Impact of forest liming on growth and crown vigor of sugar maple and associated hardwoods

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Abstract: Sugar maple (*Acer saccharum* Marsh.) has been declining across the unglaciated Allegheny Plateau in northwestern and north central Pennsylvania since the mid-1980s. A long-term study to evaluate the effects of fencing, herbicide, and liming on growth, crown vigor, and regeneration of sugar maple and associated Allegheny hardwoods was initiated in 1985. The study is a split-plot design with fencing (fence – no fence) as the whole-plot treatment and four subplot treatments: applications of herbicide (glyphosate) to control interfering vegetation, dolomitic lime (22.4 $Mg \cdot ha^{-1}$) to reduce soil acidity, dolomitic lime and herbicide, and an untreated control. Liming significantly increased diameter growth and improved crown vigor of overstory sugar maple, but did not affect growth or vigor of overstory black cherry (*Prunus serotina* Ehrh.) and American beech (*Fagus grandifolia* Ehrh.). Basal area (adjusted by covariance) of sugar maple on limed plots increased by 11% from 1986 to 1993 but only by 4% on unlimed plots. Liming increased exchangeable cations in the upper 15 cm of the soil, especially Ca and Mg, and reduced levels of exchangeable K, Al, and Mn. Changes in soil chemistry were reflected in the chemistry of overstory sugar maple foliage. Concentrations of Ca doubled on limed plots and Mg increased fourfold on limed versus unlimed plots. Liming also increased the size (in 1989 and 1992) but not the frequency of sugar maple flower and seed crops. The results demonstrate the importance of Ca and Mg nutrition in maintaining the health of sugar maple on unglaciated sites.

Résumé : Depuis le milieu des années 1980, l'érable à sucre (*Acer saccharum* Marsh.) a souffert de dépérissement sur le plateau Allegheny non soumis à la glaciation dans le nord-ouest et centre-nord de la Pennsylvanie. En 1985, une étude à long terme a été initiée afin d'évaluer les effets de protection par une clôture, d'un herbicide et du chaulage sur la croissance, la vigueur de la cime et la régénération de l'érable à sucre et des espèces feuillues compagnes. Un dispositif en tiroir avec la protection par une clôture (clôture – sans clôture) comme traitement en parcelle principale et quatre traitements en sous-parcelles : l'application d'herbicide (glyphosate) pour contrôler la végétation compétitive, de chaux dolomitique (22,4 $Mg \cdot ha^{-1}$) afin de réduire l'acidité du sol, de chaux dolomitique et d'herbicide, et un témoin non traité. Le chaulage a significativement augmenté la croissance en diamètre et amélioré la vigueur de la cime des érables à sucre de l'étage dominant, mais n'a pas affecté la croissance ou la vigueur du cerisier tardif (*Prunus serotina* Ehrh.) et du hêtre d'Amérique (*Fagus grandifolia* Ehrh.) de l'étage dominant. La surface terrière (ajustée par covariance) de l'érable à sucre dans les parcelles chaulées a augmenté de 11% de 1986 à 1993, mais seulement de 4% dans les parcelles non chaulées. Le chaulage a augmenté les cations échangeables dans les 15 premiers cm du sol, spécialement Ca et Mg, et a réduit les niveaux de K, Al et Mn échangeables. Les changements dans la chimie du sol se sont reflétés dans la chimie du feuillage de l'érable à sucre de l'étage dominant. La concentration de Ca a doublé et celle de Mg s'est accrue par un facteur de quatre dans les parcelles chaulées comparées aux parcelles non chaulées. Le chaulage a aussi amélioré la taille des fleurs (en 1989 et 1992), mais non la fréquence des floraisons et de la production de semences. Les résultats démontrent l'importance de la nutrition en Ca et Mg dans le maintien de la santé de l'érable à sucre sur les sites non soumis à la glaciation.
[Traduit par la Rédaction]

Introduction

Since the mid-1980s overstory sugar maple (*Acer saccharum* Marsh.) has been declining across the Allegheny Plateau in northern Pennsylvania, resulting in reduced stocking (Kolb and McCormick 1993; McWilliams et al. 1996). Overstory decline (sensu Manion 1991) has been related to insect damage and drought events in the mid-1960s and early 1970s and to repeated defoliation by pear thrips (*Taeniothrips inconsequens* Uzel) in the early 1980s followed by drought in 1988 (Kolb and McCormick 1993). While recent surveys of sugar maple crown condition in the northeastern and midwestern United States and eastern Canada indicate a generally healthy maple resource (Allen et al. 1992*a*), sugar maple declines are well documented in Wisconsin during the late 1950s (Giese et al. 1964), in New England during the 1960s, 1980s, and 1990s (Mader and Thompson 1969; Kelly 1988; Bauce and Allen 1991; Allen et al. 1992*b*; Wilmot et al. 1995), and in Ontario and Quebec during the 1980s (McLaughlin et al. 1987; Bernier and Brazeau 1988*a*, 1988*b*, 1988*c*; Hendershot and Jones 1989; Coté et al. 1995). These declines, like that in Pennsylvania, were characterized by a deterioration of crown condition associated with fine-twig and branch dieback that eventually resulted in mortality.

Forest liming has been used to address a variety of soil–site nutritional problems affecting northern hardwood growth and

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Table 1. Soils and stand composition at the four blocks.

	Site and soil type[a]			
	BDR1 (Clymer, Cookport, Leetonia)	BDR2 (Clymer, Cookport)	CS3 (Wellsboro, Wharton)	CS4 (Leetonia, Wellsboro, Wharton)
Total basal area pre, post-thinning ($m^2 \cdot ha^{-1}$)	33.1, 19.8	27.3, 11.0	27.5, 11.7	34.9, 17.0
% basal area pre, post-thinning				
Sugar maple	25, 21	28, 35	66, 61	31, 32
Beech	26, 19	38, 42	25, 31	10, 6
Black cherry	41, 57	15, 7	5, 8	53, 56
Other[b]	8, 4	19, 16	4, 0	6, 5
Diam. by block (cm)				
Sugar maple				
Mean diam.[c]	34.6 (65)	26.2 (103)	34.2 (112)	23.0 (202)
Range	15.0–55.6	12.7–52.9	12.8–70.3	12.6–44.2
Beech				
Mean diam.[c]	41.7 (177)	29.1 (136)	35.3 (118)	29.5 (336)
Range	15.1–99.6	12.7–61.2	12.8–70.3	12.6–63.5
Black cherry				
Mean diam.[c]	36.5 (127)	27.9 (245)	33.5 (176)	22.6 (278)
Range	15.1–56.6	12.7–56.7	12.7–70.3	12.6–49.6
Other[b]				
Mean diam.[c]	33.4 (15)	35.1 (28)	—	33.4 (16)
Range	28.0–39.9	19.0–56.7	—	13.8–49.6

[a]Cookport: Cookport channery loam, Aquic Fragiudult. Clymer: Clymer channery loam, Typic Hapludult. Leetonia: Leetonia channery loam, Entic Haplorthod. Wellsboro: Wellsboro channery silt loam, Typic Fragiochrept. Wharton: Wharton channery silt loam, Aquic Hapludult.

[b]Includes *Fraxinus americana* L., *Tsuga canadensis* (L.) Carrière, *Acer rubrum* L., *Acer pensylvanicum* L., *Betula* spp.

[c]Number of trees is in parentheses.

health, and to accelerate stand growth (Auchmoody and Filip 1973; Safford 1973; Carmean and Watt 1975; Stone and Christenson 1975; Ellis 1979; Stanturf et al. 1989). In some studies, lime treatments have been included to moderate soil acidity or augment supplies of Ca and Mg (Mader and Thompson 1969; Leaf and Bickelhaupt 1975; Safford 1973; Czapowskyj and Safford 1979; Lea et al. 1979*a*, 1979*b*, 1980; Safford and Czapowskyj 1986; Kedenburg 1987; Ouimet and Fortin 1992; Coté et al. 1995). Application rates have ranged from 0.2 to 9.0 $Mg \cdot ha^{-1}$, usually as dolomitic limestone and have been evaluated from 6 weeks to 10 years after treatment. Significant differences in nutritional status of soils and foliage have been reported frequently following lime application, though reports of positive tree-growth responses are less frequent and species specific (Safford 1973; Czapowskyj and Safford 1979; Safford and Czapowskyj 1986).

Mader and Thompson (1969) were the first to apply fertilizers as a corrective treatment for maple decline. They used diagnostic foliar analysis and regression techniques to evaluate nutrient sufficiency in healthy and declined stands in western Massachusetts. More recently, there have been efforts to develop critical foliar nutritional values for healthy sugar maple (Bernier and Brazeau 1988*b*; Kolb and McCormick 1993); Lozano and Huynh (1989) developed a diagnostic recommendation integrated system (DRIS) based on a 96-tree Ontario data set to diagnose foliar nutrient deficiencies in sugar maple. The DRIS indices for foliage were used to determine relationships to soil chemical parameters, xylem chemistry, and sugar maple crown health (Coté et al. 1993; Coté and Camiré 1995).

Diagnostic foliar analysis and fertilization have been used to assess maple decline in areas of Ontario and Quebec where soil parent materials are deficient in K or Mg (Bernier and Brazeau 1988*a*, 1988*b*, 1988*c*; Hendershot 1991; Coté et al. 1995). The addition of small amounts of K, Ca, and (or) Mg fertilizers (0.2–0.8 $Mg \cdot ha^{-1}$) resulted in short-term improvement in indices for foliage color, transparency, and leaf size (Hendershot 1991); Coté et al. (1995) reported a 2-year improvement in diameter-growth ratio following the addition of 0.4 $Mg \cdot ha^{-1}$ K_2SO_4 + 0.4 $Mg \cdot ha^{-1}$ $CaMg(CO_3)_2$.

The current study was initiated in 1985 to evaluate treatment effects on the growth, vigor, and regeneration of sugar maple – beech (*Fagus grandifolia* Ehrh.) – black cherry (*Prunus serotina* Ehrh.) dominated stands in northern Pennsylvania. Several treatments were used to evaluate the impacts of deer browsing, interfering plants, and low soil pH. Fencing was used to exclude deer, herbicide was applied to reduce interfering plants, and lime was applied to increase soil pH and availability of N and P. Study objectives focused on (1) evaluating the effect of these treatments on the growth and vigor of residual trees after partial overstory removal, (2) determining treatment effects on regeneration establishment and growth, and (3) determining the effects of liming on soil chemistry, e.g., soil Al and soil pH, and on foliar nutrient chemistry of overstory sugar maple. In this report we present an evaluation

Table 2. Total sugar maple basal area ($m^2 \cdot ha^{-1}$) of dominant and codominant trees, by treatment, at each of the four blocks after thinning in 1985.

Block	Fence –	Fence +	Lime –	Lime +	Herb –	Herb +	Block mean
BDR1	2.82	1.73	1.53	3.02	1.97	2.58	2.28
BDR2	2.85	2.49	2.09	3.25	2.10	3.24	2.67
CS3	7.59	5.54	7.52	5.61	5.50	7.63	6.57
CS4	4.55	1.94	2.33	4.17	3.56	2.93	3.24
Mean	4.45	2.92	3.37	4.01	3.28	4.10	3.69

Note: Probability of significant differences for main factors: block, 0.025; BDR vs. CS, 0.017; BDR1 vs. BDR2, 0.617; CS3 vs. CS4, 0.018; fence, 0.055; lime, 0.348; herb, 0.238.

of lime application on soil chemistry, overstory growth and vigor, sugar maple foliar nutrient chemistry, and sugar maple and black cherry flower and seed production. Effects of the treatments on regeneration will be presented elsewhere.

Methods

Field sites

Study sites are in the Susquehannock State Forest, Potter County, Pennsylvania, within the unglaciated Allegheny High Plateau Section of the Appalachian Plateau Province (Harrison 1970; McNab and Avers 1994). Black Diamond Road (BDR), with blocks 1 (BDR1) and 2 (BDR2), is at 677-m elevation and is 2 km southeast of Inez (41°42′30 N, 78°01′30 W). Cherry Springs (CS), with blocks 3 (CS3) and 4 (CS4), is at 716-m elevation and is 0.75 km southeast of the Cherry Springs airport (41°39′15 N, 77°49′15 W). Annual precipitation averages 1067 mm, with 550 mm received during the growing season. The area has a humid temperate climate with an average daily temperature of 9°C, and the growing season averages 120 days (Cronce and Ciolkosz 1983; Kingsley 1985; McNab and Avers 1994). In winter, forests in this area are subject to ice and wind damage.

Soils at both study sites are residual, formed in material weathered from sandstone, siltstone, and shale (Goodman et al. 1958; Aguilar and Arnold 1985). Soils described from pits dug at all blocks were mixtures of Clymer, Cookport, Leetonia, Wellsboro, and Wharton series (Table 1). These are soils with a fine-loamy texture and a mineralogy dominated by illite and kaolinite. Within the study sites there are no significant physical limitations to forest growth, e.g., high stone content or shallow soil depth to bedrock or to a perched water table (Auchmoody and Walters 1992). The soils are extremely acid; the pH in the upper 2.5 cm of mineral soil ranges from 3.7 to 4.2.

Forest stands within each of the four blocks vary in species composition and stand history (Table 1). The BDR1 and BDR2 stands (blocks 1 and 2) originated following the removal of virgin eastern hemlock (*Tsuga canadensis* (L.) Carrière) and high-value hardwoods around 1890. These stands were not clear-cut, and some large old-growth hardwoods, primarily beech and sugar maple, and smaller hemlock survived the original harvest. An improvement cut during the early 1960s removed mostly sugar maple, eastern hemlock, beech, and black cherry.

The CS3 stand (block 3) was never clear-cut, though hemlock and probably high-value hardwoods were harvested about 1900. The only documented cutting in this stand was in the early 1950s. CS4 (block 4) was harvested in the early 1900s for hemlock and high-value hardwoods; a second cutting in the early 1920s removed the remaining hardwood sawlogs and chemical wood. This is the only block that was clear-cut, so it contains the youngest trees. There was no additional activity in this stand until this study.

Treatment applications

The four blocks were established in the summer of 1985, when an inventory of all trees ≥2.5 cm was conducted. Each block consists of eight 60-m^2 (0.36-ha) plots; there is a 7.5-m buffer zone around each plot. Data were collected from areas within the interior 45 m^2 (0.2 ha). Four adjacent plots (half of each block) were fenced with five-strand, high-voltage, electric fencing in the spring of 1986; the remaining four adjacent plots were unfenced. Four treatments were applied randomly to selected plots in each half block: (1) single application of commercial pulverized dolomitic limestone (Ca = 21%, Mg = 12%, CaO equivalent = 58.8) at 22.4 $Mg \cdot ha^{-1}$, (2) single foliar application of glyphosate at 2.2 kg $a.i. \cdot ha^{-1}$ in 308.5 $L \cdot ha^{-1}$ water (Horsley 1981), (3) application of lime and herbicide, (4) no lime or herbicide (control). Herbicide was applied with a backpack mist blower to the entire 0.36-ha area, including the buffer zone, during the last 2 weeks of August 1985. Lime was applied only to the interior 0.2-ha portion of the plot when the soils were dry (autumn of 1985) using tractors equipped with conventional spreaders.

During the winter of 1985–1986 all plots were thinned to about 50% relative density, primarily by removing small trees and those of inferior quality (Stout et al. 1987). Thinning was used to maintain similar species composition and stand structure of the residuals on each of the eight plots in a block and to stimulate regeneration. Thinning allowed evaluation of treatment effects for about the same number of trees in each diameter class for a given species.

Basal area of sugar maple varied among blocks and treatment plots (Table 2). The CS3 block had the greatest amount of sugar maple, 6.57 $m^2 \cdot ha^{-1}$, and BDR1 the least, 2.28 $m^2 \cdot ha^{-1}$. Basal area on limed and unlimed plots was not different ($P = 0.348$).

Tree measurements

Residual trees in all plots were numbered and marked at breast height (1.37 m) for diameter measurements. Tree vigor was estimated annually during August, and diameters were measured in October each year from 1985 to 1990 and again in 1993. Each tree was classified by two observers into one of six crown vigor classes using the rating system of Mader and Thompson (1969). To allow the numerical vigor rating to increase as tree health increased, the Mader–Thompson system was reversed: their vigor class 1 became our vigor class 6. Vigor class 6 was a healthy tree with full-size foliage and no dead twigs or branches. Class 5 trees had abnormally small, curled, thin, yellowish, or otherwise distorted foliage but no dead twigs or branches. Class 4 trees were similar to class 5 stems except that there were some dead or bare twigs present in the top of the crown. Class 3 trees had at least two dead branches (0.9–1.2 m long) and twigs dead for no apparent reason that constituted less than half of the crown. Class 2 trees had more than half of the crown in dead branches and twigs. Class 1 trees were dead but might have small living adventitious branches at the base of the crown.

Flower and seed crops of sugar maples were evaluated annually by two observers from 1987 to 1993. Flowering in the crown of individual trees was estimated each spring and rated as the percentage of crown with flowers: 0% = no flowers present, 1% = trace flowering, and 5–100% estimated to the nearest 5% class. Seed crops were evaluated in late August or September. Seed crops were placed in one of six categories: 0 = no seed present, 1 = trace to 5% of crown with seed, 2 = 6–25%, 3 = 26–50%, 4 = 51–75%, 5 = 76–100% of crown with seed.

In August 1994, a subset of 54 overstory sugar maples, 27 in limed plots and 27 in unlimed plots, were selected randomly to represent the range of crown vigor in each block (based on 1993 vigor ratings) for foliage sampling and chemical analysis. Foliage was obtained from the outer midcrown by shooting small branches and twigs. Samples were placed in paper bags, dried at 65°C, ground in a Tecator cyclotec mill, and analyzed at the University of Minnesota Research Analytical Laboratory (Munter 1982). Samples were dry ashed at 485°C and taken up in 10% HCl for analysis by inductively coupled plasma

(ICP) spectroscopy. Total milligrams per kilogram of P, K, Ca, Mg, Al, Fe, and Mn were determined. Post-dry ash boiling was used to improve the recovery of Fe and Al. Total Kjeldahl N was determined with a Lachat autoanalyzer (QuikChem method 13-107-06-2-D, Lachat Instruments, Milwaukee, WI 53218) in our laboratory.

Soil sampling and analysis

Soils were sampled near six permanently marked sampling points centered on a 22.5 by 11.3 m grid in the center of each plot. Samples were taken at increments of 2.5 cm to a depth of 15 cm. For each plot six samples were composited at 2.5-cm increments for subsequent analysis. An exception was in the first year (1986) when samples were obtained only to a depth of 10 cm. All of the samples were from areas relatively undisturbed by the lime application itself and by logging. Depending on the moisture content of the soils, samples were obtained by removing a core and dividing it into the 2.5-cm layers or by digging a small pit and extracting samples from the sidewalls at the appropriate depth. During sampling, care was taken to avoid contaminating lower depth samples with lime that was concentrated in the litter and at the mineral soil surface. Samples were air dried and sieved through a 2-mm screen and sent to the University of Minnesota Research Analytical Laboratory for analysis (Munter 1982). Soil pH was determined in a 1:1 (v/v) soil–water mixture, and extractable P (Bray-1) was determined for all samples. Major cations, K, Ca, Mg, and Mn, were determined by ICP after extraction with 1.0 M NH_4OAc. Concentrations of soil Al were determined by ICP after extraction with 1 M KCl. Soils were sampled annually in late September or early October from 1986 to 1989 and again in 1993.

Statistical analysis

The study is a split-plot design with fencing (fence – no fence) as the whole-plot treatment and the lime (L), herbicide (H), L + H, and control plots as the subplot treatments. Blocks are considered random effects and treatments fixed effects. To simplify interpretations, three-factor interaction terms were combined with error terms when nonsignificant. The conventional 0.05% level of probability was used as the nominal indicator of statistical significance; however, *P*-values >0.05 and ≤0.20 were considered worthy of additional consideration. Since the same plots were sampled repeatedly over time, we used repeated-measures analysis of variance with analysis of contrasts (Meredith and Stehman 1991; Gumpertz and Brownie 1993). The between-plot analysis tests for treatment effects averaged over time. The within-plot analysis examines time by treatment interactions (Gumpertz and Brownie 1993). Plot averaged data were used for all repeated-measures analyses. Appropriate adjustments in repeated-measures analyses were made to account for unequal time intervals for single degree of freedom contrasts.

To simplify presentation of soil chemical characteristics, average results for depths of 0–5, 5–10, and 10–15 cm are given. Separate repeated-measures analyses were conducted for each sample depth over the sampled times (1986–1989 and 1993). Preliminary analyses indicated that fencing and herbicide did not significantly ($P > 0.20$) affect soil chemical characteristics; these treatments were dropped from subsequent analyses. Within-plot single degree of freedom contrasts were used with separate analyses of limed and unlimed plots to determine whether mean chemical concentrations in subsequent years differed from the initial 1986 or 1987 mean.

Diameter measurements were converted to basal area for each tree. For analysis of total basal area in each measurement year (1985–1990 and 1993), pretreatment (1985) basal area was used as a covariate. For vigor analyses, annual vigor ratings from 1986–1990 and 1993 were used as dependent variables. Overstory sugar maples used for foliar chemistry sampling were selected randomly to represent all vigor classes (2–6) and to have about the same number of trees in each block from limed and unlimed plots. Data were averaged by block and used in an analysis of variance with block and lime as the main factors.

Results

Soil chemistry

Liming with 22.4 $Mg \cdot ha^{-1}$ of dolomitic limestone was the only treatment that significantly affected soil chemistry. Between-plot comparisons of limed and unlimed soil chemical parameters, which averaged effects across all sample times, showed significant differences for all chemical parameters at all sample depths except for P, K, and Mn concentrations at the 5–10 and 10–15 cm depths (Table 3).

The dominant feature of chemical changes in limed soils was a downward-moving wave of elemental concentration changes induced by pH or direct addition of Ca and Mg (Fig. 1). Liming increased pH, Ca, and Mg in soils at the 0–5 cm depth in 1986. There were no changes in elemental availability associated with pH in the lower two depths until 1988. Al concentration of limed plots at 0–5 cm had decreased by 1986; Mn concentration at this depth was not reduced significantly until 1988. Responses of P and K in limed plots were confined to the 0–5 cm depth, where both elements had significantly reduced exchangeable quantities. A detailed analysis of these data is planned.

Diameter and basal area growth

Between-plot analyses indicated no significant treatment-related diameter or basal area growth responses for beech or black cherry through 1993 (Fig. 2). Between-plot *P*-values for whole and subplot treatment factors (fence, lime, herbicide) were >0.43 for beech; *P*-levels for all treatments also were nonsignificant ($P > 0.16$) for black cherry. Similarly, within-plot analyses of contrasts revealed no significant time × treatment interactions ($P > 0.21$ for all contrasts) for beech or black cherry diameter or basal area growth. The results for black cherry must be interpreted with caution, since seven plots had no black cherry present in the overstory. For sugar maple, diameter and basal area growth responded only to lime treatment. Separate analyses of dominant–codominant and intermediate–suppressed crown classes produced similar results, so subsequent analyses combined all crown classes for analyses of growth and vigor.

For sugar maple diameter (trees alive at the end of each measurement year, mortality not included), between-plot repeated-measures analysis indicated that lime was the only significant ($P = 0.049$) whole or subplot treatment effect (Table 4). Mean total diameter (adjusted for the initial diameter by analysis of covariance) in limed plots increased by 6% (1.8 cm) from 1986 to 1993 compared with only 1.5% (0.5 cm) in unlimed plots. The difference in diameter growth between limed and unlimed sugar maples became significant in 1993, though these differences approached significance by 1990 ($P = 0.088$) (Table 4).

For surviving trees, trends in cumulative basal area increment were similar to those for diameter (Fig. 2, Table 4). Cumulative basal area growth (adjusted by covariance) for sugar maples in limed plots was 89 cm^2 for 1986–1993 (12.7 $cm^2 \cdot year^{-1}$) versus 31 cm^2 (4.4 $cm^2 \cdot year^{-1}$) in unlimed plots. No increase in basal area growth was observed in unlimed plots between 1990 and 1993 because of mortality of some large trees during this period. The death of these larger trees reduced the mean basal area per tree in unlimed plots.

Table 3. Mean soil chemical characteristics (SE) for samples from limed and unlimed plots averaged over all sample times, and probability that means are significantly different (all values are in mg·kg^{-1}, except pH).

	Sample depth (cm)[a]	Between-plot means[b]		
		No lime	Lime	*P*
pH	0–5	3.77 (0.03)	5.38 (0.06)	<0.001
	5–10	3.94 (0.04)	4.30 (0.04)	0.001
	10–15	4.12 (0.04)	4.45 (0.03)	<0.001
Ca	0–5	337.4 (24.0)	2023.0 (61.9)	<0.001
	5–10	50.3 (4.0)	174.9 (17.6)	<0.001
	10–15	40.0 (4.1)	96.0 (12.6)	<0.001
Mg	0–5	49.6 (4.4)	362.7 (24.9)	<0.001
	5–10	9.5 (0.7)	102.8 (8.7)	<0.001
	10–15	7.5 (0.6)	59.2 (6.0)	<0.001
P	0–5	16.2 (2.0)	14.6 (0.9)	0.031
	5–10	5.6 (1.3)	5.0 (0.5)	0.640
	10–15	4.3 (1.1)	4.2 (0.5)	0.922
K	0–5	163.2 (12.5)	118.6 (7.6)	0.006
	5–10	42.1 (5.2)	40.0 (4.0)	0.554
	10–15	38.4 (4.9)	34.5 (3.8)	0.277
Mn	0–5	44.3 (2.4)	24.8 (2.5)	<0.001
	5–10	23.3 (4.7)	18.2 (2.8)	0.145
	10–15	14.8 (3.1)	10.5 (1.8)	0.106
Al	0–5	347.6 (45.8)	134.3 (22.3)	<0.001
	5–10	509.9 (51.3)	405.1 (51.2)	0.010
	10–15	542.8 (43.4)	428.2 (43.8)	0.008

[a]No samples taken from 10–15 cm depth in 1986.
[b]Between-plot *P*-values assess probability that limed and unlimed means are the same when averaged over all time periods.

Vigor and survival

Vigor responses followed a similar pattern, with significant responses to liming only for sugar maple (Fig. 3). Between-plot repeated-measures analysis indicated a significant ($P < 0.001$) lime treatment effect. Averaging across all sample times, there were no significant site differences for sugar maple vigor between BDR and CS blocks; initial 1985 vigor was not a significant covariate, so all means are unadjusted. Mean vigor decreased gradually in unlimed plots, from 5.1 in 1986 to 3.0 in 1993. In limed plots, mean vigor increased from 5.1 in 1986 to 5.3 in 1989 and then decreased to 5.1 in 1990 and 4.4 in 1993.

Within-plot analysis of contrasts for the time × lime interactions revealed that crown vigor of sugar maple responded rapidly to lime treatment. By 1988, average vigor in limed plots was 5.2 and was significantly ($P = 0.001$) greater than average vigor (4.8) in unlimed plots. Despite the 1988 drought, sugar maple vigor increased in limed plots through 1989, while vigor in unlimed plots continued to decline (Fig. 3). Sugar maple vigor decreased in both limed and unlimed plots in 1990 and 1993, reaching its lowest point in 1993 at 4.4 in limed plots and 3.0 in unlimed plots. This conspicuous decrease was related to the elm spanworm (*Ennomos subsignarius* Hubner) defoliations occurring in all blocks at this time. There was some indication of site effects only in 1993, with overall mean sugar maple vigor averaging 3.5 in the CS blocks, significantly ($P = 0.001$) less than that in the BDR blocks (4.0).

A pattern of decreased vigor over time was noted for both beech and black cherry (Fig. 3), though none of the treatments significantly ($P < 0.05$) affected the vigor of these species. Beech vigor decreased from 5.6 in 1985 to 3.5 in 1993 on unlimed plots, and from 5.6 in 1985 to 3.6 in 1993 on limed plots. Beech bark disease is present in all four blocks and may contribute to this decrease. For black cherry, mean vigor also decreased from 5.5 in 1985 to 3.8 in 1993, but was essentially the same in limed and unlimed plots (Fig. 2). Defoliation by elm spanworm in all blocks during 1992 and 1993 may largely account for the decreased vigor of all three species in 1993.

Comparison of numbers of trees in 1993 and 1986 showed that sugar maple survival was higher on limed plots and beech survival was higher on herbicide-treated plots; black cherry survival (98%) was unaffected by treatments. Sugar maple survival averaged 88% over all crown classes and treatments; separate examination of the combined dominant–codominant and intermediate–suppressed crown classes revealed significant differences in mortality attributable to lime treatment for both groupings. Average survival of dominant–codominant sugar maple was 84% on unlimed plots and 97% on limed plots ($P = 0.030$). Average survival of intermediate–suppressed was 80% on unlimed plots versus 92% on limed plots ($P = 0.059$).

Survival of American beech (all crown classes) was 84% on plots not treated with herbicide and 90% ($P = 0.065$) on herbicide-treated plots. Separate analyses of surviving dominant–codominant and intermediate–suppressed trees showed similar though nonsignificant ($P > 0.182$) herbicide effects.

Foliar chemistry

Midcrown foliage sampled from overstory sugar maples in August 1994 indicated nutritional differences associated with liming. Trees in limed plots (number of plots = 10; number of trees = 27) had significantly greater amounts of Ca and Mg than trees in unlimed plots (number of plots = 12, number of trees = 27) (Table 5). Concentrations of Ca in foliage from limed trees were more than double those observed from unlimed trees; Mg concentrations were more than 4 times greater in foliage from limed trees than from unlimed trees. Foliage from limed trees also had significantly less K, Mn, Al, and Fe than foliage from unlimed trees. Levels of Mn in foliage from

Fig. 1. Mean exchangeable Ca, Mg, P, K, Mn, KCl-extractable Al, and pH determined from soils sampled in limed and unlimed plots from 1986 to 1989 and in 1993. Vertical lines indicate ±1 SE limits.

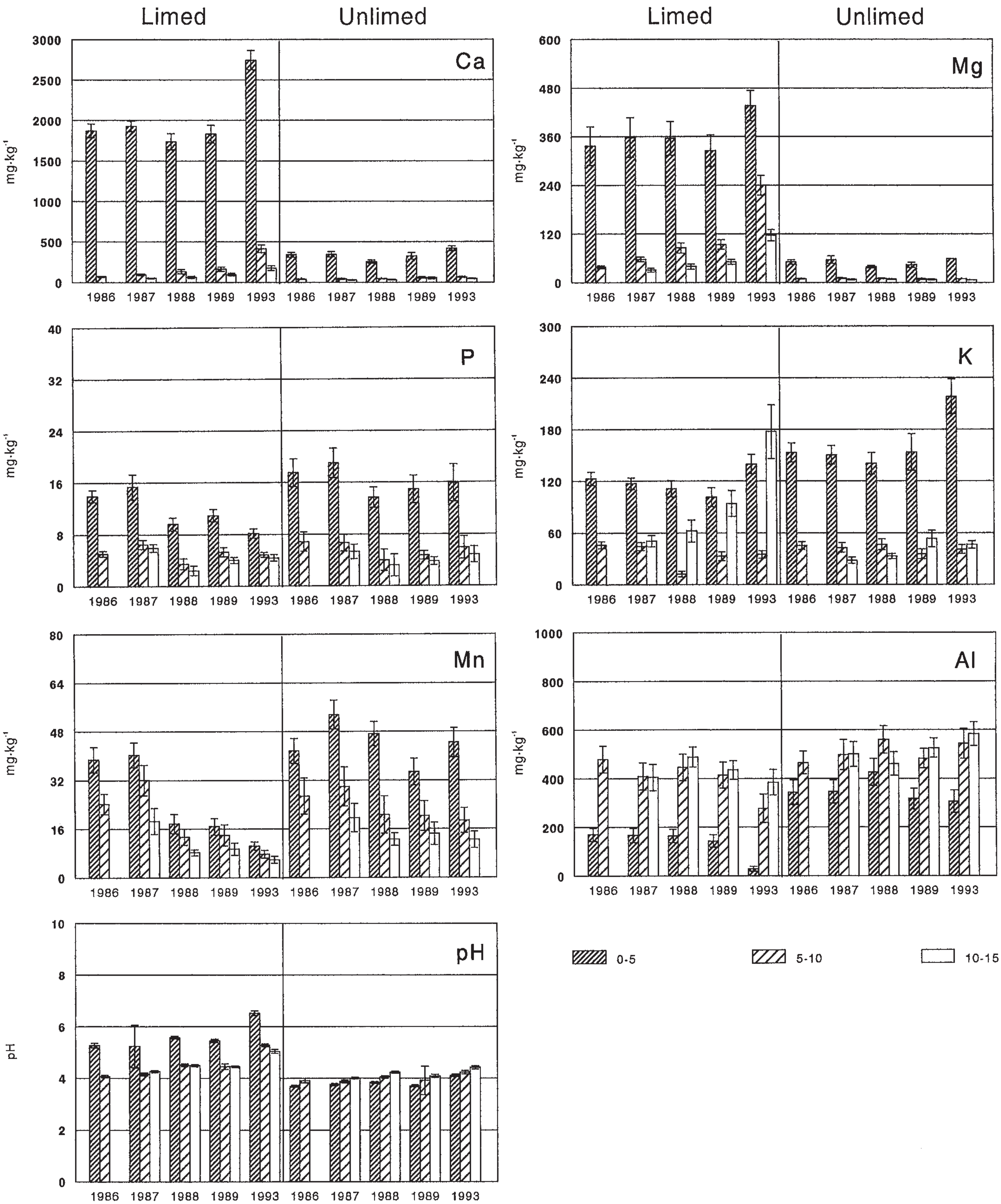


Fig. 2. Mean basal area per tree in limed (broken lines) and unlimed (solid lines) plots from 1986 to 1993. Plotted values are corrected by covariance analysis for differences in initial basal area.

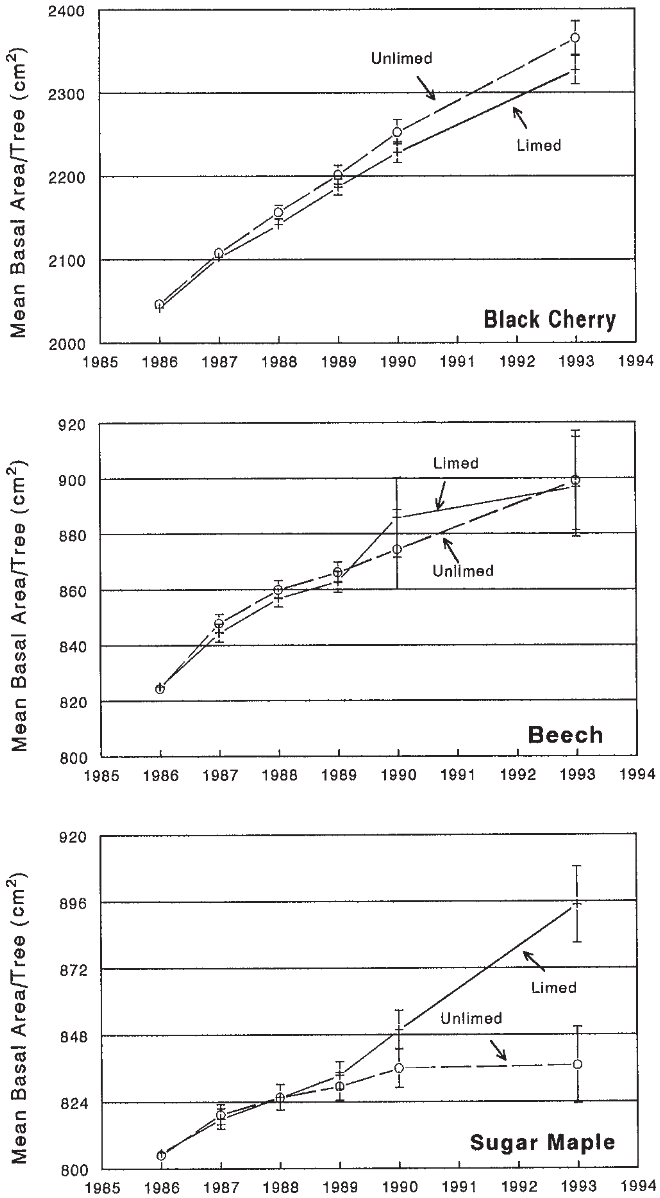
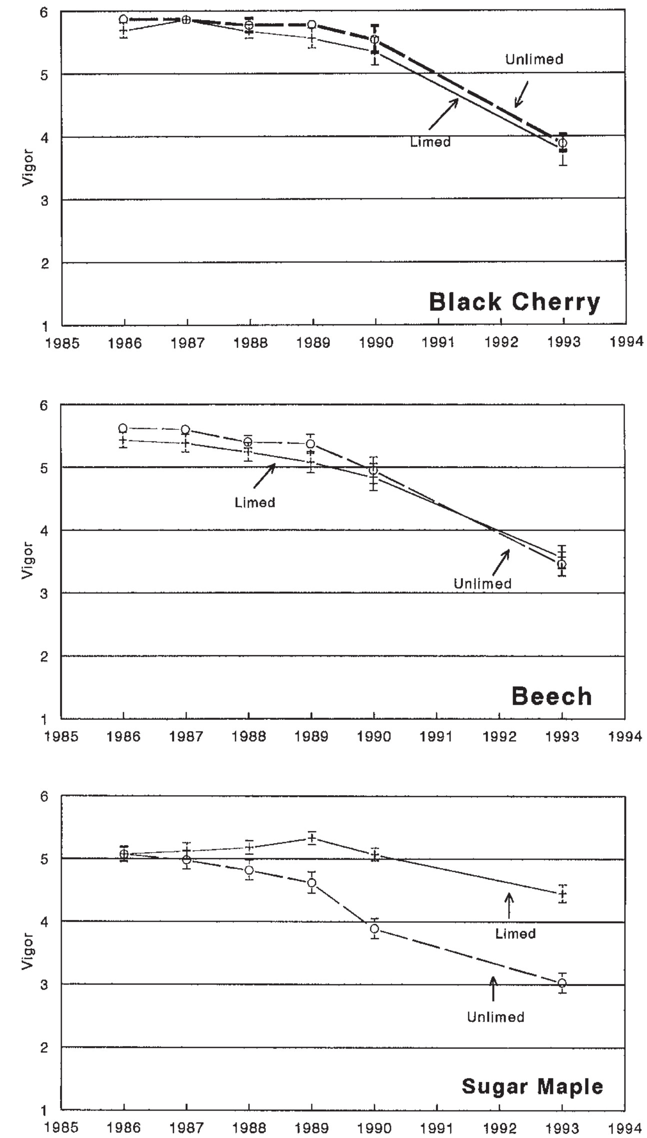


Fig. 3. Mean vigor ratings in limed (solid lines) and unlimed (broken lines) plots (vigor scale: 1 (dead) to 6 (healthy)).



limed trees were less than half those in foliage from unlimed trees. Foliar P was higher in limed trees, though not significantly so. Foliar N apparently was unaffected by liming and was similar in limed and unlimed trees. The Ca/Al molar ratio, frequently used as an indicator of stress, was calculated for all foliage samples and was significantly higher in limed trees than in unlimed trees.

Foliar Ca and Mg nutrition also varied depending on tree vigor, primarily for unlimed trees (data not shown). Concentrations of Ca were greatest for unlimed trees of the highest vigor classes, 5611 $mg \cdot kg^{-1}$ in class 5 and 6 trees, significantly ($P < 0.05$) greater than the 3621 $mg \cdot kg^{-1}$ in class 4 trees. Similarly, Mg was 902 $mg \cdot kg^{-1}$ for unlimed class 5 and 6 trees, significantly greater than the 455 $mg \cdot kg^{-1}$ for class 4 trees.

Correlations between soil and foliar nutrients provide additional insights into nutrient relationships. Soil chemical concentrations from all sampled horizons (0–15 cm) were averaged for 1993 and compared with plot-averaged foliage samples from 1994 (Table 6). There were significant positive correlations between soil K, Ca, Mg, Mn, and Al and corresponding foliar chemical concentrations. The dominant effect of soil pH on the availability of nutrients is shown by the significant correlations of pH with all foliar nutrients except N. Soil pH was positively correlated with foliar P, Ca, and Mg, and negatively correlated with K, Mn, Fe, and Al. Correlations of 1993 vigor estimates with soil chemical constituents revealed a negative correlation between vigor and soil Al concentrations, while soil Ca and Mg were positively correlated with vigor. The foliar Ca/Al ratio was positively correlated with soil Ca and negatively correlated with soil Al. This ratio also was correlated with 1993 vigor ($r = 0.64$, $P = 0.001$), suggesting that low Ca/Al ratios are associated with low sugar maple vigor.

Table 4. Repeated measures analysis of variance *P*-values for sugar maple mean diameter, mean cumulative basal area increment, and vigor responses associated with the between-plot main factor, lime, and the within-plot single degree of freedom contrasts for lime × time.

Dependent variable	Between-plot[a] lime treatment	Within-plot contrasts for lime × time[b]				
		86 vs. 87	86 vs. 88	86 vs. 89	86 vs. 90	86 vs. 93
Mean diam./tree	0.049	0.708	0.919	0.453	0.088	0.007
Mean cum. BAI/tree	0.004	0.118	0.116	0.007	0.002	<0.001
Mean vigor	<0.001	0.069	0.001	<0.001	<0.001	<0.001

Note: Only trees alive at the end of each year from 1986 to 1993 are included.
[a]Between-plot *P*-values test whether lime treatment effects were significant averaged over all time periods from 1986 to 1993.
[b]Within-plot *P*-values for single degree of freedom contrasts of the lime × time interaction from the initial year (1986), compared with each subsequent measurement year.

Table 5. Mean elemental concentrations (mg·kg^{-1}) of foliage sampled from mature sugar maples (1994) in limed and unlimed plots, and probability that means are equal.

	Unlimed		Limed		
Parameter	Mean[a]	SE	Mean[a]	SE	*P*-level
N	16 005	302	15 584	685	0.598
P	1 058	50	1 361	156	0.188
K	7 136	261	4 811	231	0.036
Ca	4 031	208	8 777	474	0.002
Mg	617	61	2 655	151	0.001
Mn	2 548	218	1 148	88	0.002
Al	38.4	1.5	25.4	0.9	0.004
Fe	59.3	3.3	45.9	1.4	0.009
Ca/Al[b]	75.0	4.6	233.3	7.8	<0.001

[a]Means were calculated by averaging values from limed and unlimed plots in each replication ($n = 4$).
[b]Ca/Al is the molar ratio of Ca to Al from concentrations detected in foliage.

Mean basal area increment (MBAI) of sampled trees (1986–1993) was examined to evaluate relationships between growth, vigor, and foliar nutrients (Table 6). MBAI was positively correlated with vigor, foliar Ca and Mg concentrations, and the Ca/Al ratio, and negatively correlated with foliar Al and Mn.

Sugar maple and black cherry flower and seed crops

Flower and seed crops were rated annually from 1987 to 1993. Black cherry produced moderate to abundant flower and seed crops annually (data not shown), though neither flower nor seed crops were related to treatments in any year.

The only years with abundant sugar maple seed crops were 1989 and 1992 (Table 7). Liming was related to increased flower production in 1988, 1989, and 1992 (Table 7). The 1988 flower crop resulted in a modest seed crop with few new seedlings in 1989. In 1989, mean flowering was 89% of the available crown in limed plots and 76% in unlimed plots. The mean seed crop was 3.8 for limed trees and 2.8 for unlimed trees. In 1992, lime treatment significantly affected flower and seed crops. Mean flowering was approximately 75% of the available crown on limed plots compared with only 23% on unlimed plots. Similarly, the mean seed-crop index was 2.8 on limed plots, indicating seed was present on 6–50% of the available crown. On unlimed plots, mean seed production was only 0.6, indicating seed was present only in trace amounts or up to 5% of the available crown.

Discussion

Soil chemistry

Liming changed soil reaction and nutrient availability in the upper 15 cm of the soil profile. The observed values were the net effect of at least three factors: (1) direct elemental addition, (2) pH, and (3) fixation. Direct addition of lime increased exchangeable Ca and Mg. As early as 1986, at the 5–10 cm depth, exchangeable Ca nearly doubled and Mg was 4 times greater on limed than on unlimed plots (Fig. 1). A year later, similar changes were evident for Mg at the 10–15 cm depth. Exchangeable levels of both cations continued to increase with depth over time; Mg moved through the profile more rapidly than Ca (Fig. 1).

Acidity of the upper 15 cm of soil was influenced by the addition of lime within 1 year after application. Soil at 0–5 cm was affected most, with less change in acidity at 5–10 and 10–15 cm. Exchangeable Al and Mn decreased as pH increased (Fig. 1).

Contrary to expectations, both P and K decreased following lime application, most notably at 0–5 cm. Decreased soil K may be related to Mg and Ca displacement of K ions from exchange sites or to fixation of K due to excess $CaCO_3$ (Brady 1974; Cote et al. 1995). The decrease in soil P probably is related to the formation of insoluble Ca phosphates or to increased P uptake by vegetation (Brady 1974); similar decreases were reported by Ward and Bowersox (1970) and Coté et al. (1995).

In this study, the significant response of sugar maple growth and vigor to liming suggests that Ca and (or) Mg are limiting to sugar maple growth. The health of overstory sugar maple appears "normal" on nearby glaciated sites in Pennsylvania and southern New York, near our study areas (Heisey and Kish 1993). At three southern New York sites with soils derived from glacial till, exchangeable Ca and Mg ranged from 178 mg·kg^{-1} to 554 and 33 to 57 mg·kg^{-1}, respectively, in the upper 10 cm of mineral soil (Stanturf and Stone 1994). In our study, Ca averaged 200 mg·kg^{-1} and Mg was 30 mg·kg^{-1} in the 0–10 cm layer. The differences in glacial history and parent materials may account for some of the observed differences in soil nutrient status.

Growth and vigor responses

The greatest increase in sugar maple growth from liming has occurred since 1990 (Fig. 2). Mean annual basal area increment for limed trees from 1986 to 1993 was 12.7 cm^2·year^{-1},

Table 6. Pearson correlation coefficients and probability levels for correlations between mean soil chemical characteristics (average of values from 0–15 cm) and mean foliar nutrient concentrations or vigor rating; 54 trees were sampled on 22 plots, and all correlations are based on plot means ($n = 22$).

		Foliage									
Soil	Statistic	N	P	K	Ca	Mg	Mn	Fe	Al	Ca/Al	Vigor
Ca	*r*	–0.290	0.415	–0.421	0.850	0.926	–0.811	–0.760	–0.816	0.939	0.517
	P	0.190	0.055	0.051	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.014
Mg	*r*	–0.288	0.325	–0.440	0.793	0.903	–0.780	–0.730	–0.810	0.907	0.541
	P	0.193	0.139	0.040	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.009
P	*r*	0.123	0.076	0.378	–0.142	–0.273	0.396	0.226	0.197	–0.211	–0.083
	P	0.585	0.738	0.082	0.529	0.220	0.068	0.311	0.379	0.347	0.712
K	*r*	–0.290	–0.255	0.541	–0.535	–0.559	0.280	–0.030	0.183	–0.502	–0.345
	P	0.191	0.251	0.009	0.010	0.007	0.206	0.893	0.415	0.017	0.116
Mn	*r*	0.210	–0.134	0.417	–0.523	–0.606	0.627	0.352	0.494	–0.595	–0.219
	P	0.349	0.551	0.053	0.012	0.003	0.002	0.108	0.019	0.003	0.328
Al	*r*	–0.205	–0.293	0.214	–0.605	–0.634	0.410	0.354	0.444	–0.628	–0.585
	P	0.360	0.186	0.339	0.003	0.001	0.058	0.106	0.039	0.002	0.004
pH	*r*	–0.315	0.448	–0.470	0.865	0.911	–0.767	–0.696	–0.750	0.931	0.503
	P	0.153	0.037	0.027	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.017
MBAI[a]	*r*	–0.084	0.285	–0.212	0.509	0.489	–0.385	–0.334	–0.497	0.518	0.504
	P	0.710	0.198	0.342	0.015	0.021	0.077	0.128	0.019	0.013	0.017

[a]Mean basal area increment.

slightly less than 14 $cm^2 \cdot year^{-1}$ reported for nondeclining sugar maple in New York (Stanturf et al. 1989). Unlimed sugar maple grew only 4.4 $cm^2 \cdot year^{-1}$ during this period. Growth responses from lime alone are infrequent in the world literature; in previous work with sugar maple and other northern hardwoods, application of lime alone has not always promoted growth. Several factors may have contributed to inconsistent results: (1) nutrients were not limiting, (2) the amount of lime applied was insufficient, and (or) (3) responses were evaluated too soon after application. Safford (1973) reported a 19% increase in relative basal area growth of sugar maple 8 years after application of 1.12 $Mg \cdot ha^{-1}$ of dolomitic limestone compared with the control; however, he attributed this increase, in part, to higher pretreatment growth rates of the treated trees. In New York, relative basal area growth of sugar maple was 30% below that of controls when evaluated 2 years after treatment with 9 $Mg \cdot ha^{-1}$ dolomitic limestone (Lea et al. 1979*c*). This negative response likely was due to lime-induced deficiency of other nutrients and (or) premature evaluation of growth responses. In northwestern Pennsylvania, Leaf and Bickelhaupt (1975) applied 4.4 $Mg \cdot ha^{-1}$ of dolomitic limestone to a mixed sugar maple – black cherry stand. Three years after application, there were no significant increases in basal area growth. Growth response in this study probably was evaluated too soon after lime application to detect significance.

Coté et al.(1995) reported a 13% increase in sugar maple radial growth for the 5-year period following fertilization with 0.8 $Mg \cdot ha^{-1}$ $K_2SO_4 + CaMg(CO_3)_2$ compared with controls. Growth response was positive the same year that fertilizer was applied, suggesting that this rapid response was due to correction of a K deficiency or to enhanced Ca or Mg availability associated with the fertilizer formulation. Rapid growth response to lime is inconsistent with previously reported responses to unincorporated lime. A 0.4 $Mg \cdot ha^{-1}$ application of lime only ($CaMg(CO_3)_2$) in Coté et al.'s (1995) study resulted in a 20% growth suppression over the 5-year period for treated sugar maple compared with controls. The amount of lime may have been insufficient to produce a positive response or the additional Mg may have induced a K deficiency as noted by Coté et al. (1995).

In the Lake States, both pole- and sawlog-size sugar maple were unresponsive to N–P–K additions, though pole-size trees did show a trend of increased growth that was not statistically significant (Stone 1980; Stone et al. 1982). Moreover, other research has indicated that sugar maple is unresponsive to N–P–K additions when foliar N is greater than 2% (Carmean and Watt 1975). In western Massachusetts severe maple decline was associated with sites where both foliar N (<19 000 $mg \cdot kg^{-1}$) and Ca (<7000 $mg \cdot kg^{-1}$) were low (Mader and Thompson 1969). Application of 4.48 $Mg \cdot ha^{-1}$ dolomitic limestone to declining trees in mid-July resulted in no discernible effect on foliar chemistry evaluated in September of the same year. The absence of changes in foliar chemistry in response to liming likely was a result of an insufficient time period for chemical changes to occur in the soil system.

The absence of a beech growth response to liming noted in our study also has been reported in previous studies. Lea et al. (1979*c*) found no significant growth response by beech to fertilization or liming 2 years after application. Similarly, Safford (1973) found no significant growth response by beech 8 years after application of 1.12 $Mg \cdot ha^{-1}$ of dolomitic limestone. Black cherry growth did not respond to lime application in the study conducted by Leaf and Bickelhaupt (1975). However, N–P–K fertilization studies have shown black cherry growth responses to N application in Ontario and New York (Ellis 1979; Stanturf et al. 1989), and to N + P fertilizers in northwestern Pennsylvania (Auchmoody 1982). Our results indicate that beech and black cherry growth are not limited by Ca and Mg nutrition in north central Pennsylvania.

Sugar maple vigor responded similarly to liming, but did not maintain an upward trend after 1989 (Fig. 3). Decreased vigor probably was related to drought and defoliation events

Table 7. Mean flower and seed crop ratings for approximately 200 trees evaluated each year, and probability that means are equal.

	Flower crops[a]			Seed crops[b]		
	Unlimed	Limed	*P*-level	Unlimed	Limed	*P*-level
1987	2.8	6.7	0.122	<0.1	0.2	0.105
1988	21.8	49.1	<0.001	0.8	1.3	0.026
1989	76.5	88.6	0.011	2.8	3.8	0.002
1990[c]	—	—	—	—	—	—
1991	<0.1	0.2	0.034	—	—	—
1992	23.1	75.1	<0.001	0.6	2.8	<0.001
1993[c]	—	—	—	—	—	—

[a]Flower crops represent percent of crown with flowers present (estimated to the nearest 5% class).

[b]Seed crops estimated in broad classes, where 0 = no seed, 1 = trace to 5%, 2 = 6–25%, 3 = 26–50%, 4 = 51–75%, 5 = 76–100% of the crown with seed.

[c]There were insufficient amounts of flowers or seeds for ratings in these years.

mentioned previously. During 1993, when the last diameter measurements and vigor estimates were made, there was light to moderate defoliation from elm spanworm in all stands. This was reflected in lower mean vigor for all three overstory species. We speculate that in the absence of drought and defoliation, sugar maple on limed plots would have continued to improve in overall vigor. The change in sugar maple vigor over time (Fig. 3) shows the deterioration of trees on unlimed plots by 1990, while trees on limed plots remained vigorous. By 1993, trees on both unlimed and limed plots had decreased significantly in vigor, though sugar maple on limed plots had higher vigor than those on unlimed plots. American beech and black cherry also were affected by elm spanworm defoliations; vigor of both species declined from 1990 to 1993. Overstory beech was affected by beech bark disease at all four blocks. Beech scale, *Cryptococcus fagisuga* Lind. (=*Cryptococcus fagi* Baer), was first identified in the BDR blocks during 1985, and beech mortality was evident by 1988.

Foliar chemistry

The effect of liming on sugar maple foliar chemistry was apparent in 1994, 9 years after application (Table 5). Comparing our results with the range of values for putative "healthy" trees compiled by Kolb and McCormick (1993) indicates that liming increased foliar concentrations of Ca (8777 $mg \cdot kg^{-1}$) and Mg (2655 $mg \cdot kg^{-1}$) into the putative healthy range for sugar maple (Ca 5000 – 21 900 $mg \cdot kg^{-1}$; Mg 1100–4000 $mg \cdot kg^{-1}$).

Foliar P levels of limed trees remained within the putative healthy range compiled by Kolb and McCormick (1993) (800–1800 $mg \cdot kg^{-1}$); however, K in foliage from limed plots decreased to 4811 $mg \cdot kg^{-1}$, below the healthy range (5500–10 400 $mg \cdot kg^{-1}$). Reduced foliar K likely was due to antagonism between K and Mg (Schneider and Zech 1990–1991); a similar response to lime was observed for sugar maple foliage in southern Quebec (Coté et al. 1995). K deficiency also may result from lime-induced K fixation by excess $CaCO_3$ (Brady 1974) or from a dilution effect associated with increased leaf size. Vector analysis of concentration, content, and growth response data could provide a better understanding of the mechanism of K reduction (Timmer and Stone 1978).

Foliar N did not differ ($P = 0.59$) in limed (15 584 $mg \cdot kg^{-1}$) and unlimed (16 005 $mg \cdot kg^{-1}$) trees. Nitrogen values were at or slightly below the lower limit of the healthy range (16 000 – 23 200 $mg \cdot kg^{-1}$) for sugar maple and were slightly lower than values reported for nearby stands in 1991 (Kolb and McCormick 1993). Increased pH in limed soil resulted in reduced foliar concentrations of Al (25 $mg \cdot kg^{-1}$) and Mn (1148 $mg \cdot kg^{-1}$). Concentrations of both elements in the foliage of limed trees were near or within the healthy range (Al 32–60 $mg \cdot kg^{-1}$; Mn 632–1630 $mg \cdot kg^{-1}$) compiled by Kolb and McCormick (1993).

Additional comparisons using these putative healthy ranges indicated that overstory sugar maple sampled on unlimed plots in 1994 were deficient in Ca (4031 $mg \cdot kg^{-1}$) and Mg (617 $mg \cdot kg^{-1}$), as were trees sampled in the same vicinity on the Susquehannock State Forest in 1991 (Kolb and McCormick 1993). Sugar maple dieback in the Lower Laurentians of Quebec was related to low Mg levels in soils derived from granite and syenite (Bernier and Brazeau 1988*c*). In Quebec, foliar Mg averaged 600 $mg \cdot kg^{-1}$ and was accompanied by conspicuous interveinal chlorosis, symptomatic of Mg deficiency. These symptoms or their precursors, a light green and mottled appearance, were observed infrequently on foliage from unlimed plots in our study. Other studies of declining and non-declining sugar maple and limed and unlimed trees have reported Mg concentrations ranging from 800 to 4500 $mg \cdot kg^{-1}$ in foliar samples (Ouimet and Fortin 1992; Fyles et al. 1994; Coté et al. 1995; Wilmot et al. 1995).

Mean foliar P levels, 1058 $mg \cdot kg^{-1}$, were within the range for healthy trees (800–1800 $mg \cdot kg^{-1}$), as were foliar K concentrations (7136 $mg \cdot kg^{-1}$) from unlimed plots. Foliar Al was slightly higher (38 $mg \cdot kg^{-1}$) in trees on unlimed plots compared with limed plots (25 $mg \cdot kg^{-1}$), but well within the healthy range. Foliar Mn for trees on unlimed plots in our study were much higher (2548 $mg \cdot kg^{-1}$) than the upper limit of the healthy range and were similar to Mn levels observed in sugar maple foliage from other stands in this area (Kolb and McCormick 1993; Heisey 1995). High foliar Mn levels have been associated with acidic soils with large amounts of available Al and Mn in soil solution and macronutrient deficiencies of Ca in soils and foliage (Hoyle 1969). In yellow birch (*Betula alleghaniensis* Britt.), foliar Ca increased and Mn and Al decreased in response to dolomitic limestone application in a pot study (Hoyle 1969). Hoyle (1972) described the symptomology of Mn toxicity in yellow birch grown in pot culture; however, evidence of Mn toxicity in field-grown trees has not been reported for any northeastern hardwood species.

The molar ratio of Ca/Al in foliage has been used as an indicator of Al stress in trees. Cronan and Grigal (1995) reported that foliar Ca/Al molar ratios of 14 or less were well correlated with conditions of Al stress in laboratory studies. However, data from field studies have not consistently corroborated this relationship (Cronan and Grigal 1995). Foliar Ca/Al molar ratios in our study averaged 75 in unlimed plots and 233 in limed plots (range 34–335) and are not indicative of Al stress based on laboratory results (e.g., Thornton et al. 1986). Other studies (Bernier and Brazeau 1988*c*; Wilmot et al. 1995) show significant differences in the Ca/Al ratio and overstory health of sugar maple. In Vermont, low-quality sites with high amounts of crown dieback had Ca/Al molar ratios averaging 108, while high-quality sites with low crown dieback had ratios of 168 (Wilmot et al. 1995). In southern Quebec, the Ca/Al molar ratio for declining sugar maple ranged from 82 to 203, with most trees showing symptoms associated with Mg deficiency (Bernier and Brazeau 1988*c*). Similarly, representative overstory sugar maples with <20% crown dieback had Ca/Al molar ratios of 167 and 80 in two other stands sampled in the Susquehannock State Forest in 1991 (Kolb and McCormick 1993).

These results suggest that the laboratory threshold ratio of 14 rarely is observed under field conditions for overstory sugar maple. Results of our study and others suggest that a Ca/Al ratio of 110 or less may be associated with declining sugar maple. The mechanisms of Al toxicity or interference with nutrient uptake are well established (Cronan and Grigal 1995; Foy et al. 1978). However, whether Al toxicity directly injures dividing apical root cells and inhibits nutrient uptake or whether Al occupies exchange sites and blocks Ca or other cation uptake without producing root injury is unknown and warrants further study.

Correlations of soil and foliar chemistry

Soils on the unglaciated Allegheny Plateau sites typically have low pH, high amounts of exchangeable Al and Mn, and low concentrations of exchangeable Ca and Mg. These relationships may contribute to nutritional problems associated with maple decline throughout this area. The minimum nutrient requirements for maintaining sugar maple health are not well established. Various procedures have been used to derive "critical" leaf nutrient concentrations (Coté et al. 1993; Kolb and McCormick 1993; Lozano and Huynh 1989). Coté et al. (1993) used seven fertilizer formulations to improve sugar maple vigor in southern Quebec. Modified critical leaf nutrient concentrations derived from these treatments were 2000 $mg \cdot kg^{-1}$ for N, 8700 $mg \cdot kg^{-1}$ for Ca, and 1200 $mg \cdot kg^{-1}$ for Mg in trees growing between the 50 and 90th percentiles (Coté et al. 1993). Unlimed trees in our study were deficient in N, Ca, and Mg using these values. Values compiled by Kolb and McCormick (1993) from a review of published foliar elemental concentrations for putative healthy trees provide wider ranges in association with healthy sugar maple; unlimed trees were deficient in N, Ca, and Mg using these values. Application of Lozano and Huynh's (1989) DRIS indices for sugar maple to Quebec data confirmed deficiencies of P, K, and Mg noted previously (Bernier and Brazeau 1988*a*, 1988*b*, 1088*c*). Lozano and Huynh's (1989) equations were used to calculate DRIS indices for our trees and indicated a deficiency of both Ca (–20) and Mg (–17) for our unlimed sugar maple. For limed trees, P (–17), K (–42), and Ca (–16) had negative indices, while a large positive index for Mg (51) suggested antagonism between Mg and the other cations (F. Lozano, personal communication). Nitrogen was not deficient in this analysis. DRIS indices of 20 and 24 were obtained for unlimed and limed trees, respectively.

Flower and seed crops

Sugar maple seed supply on the unglaciated portion of the Allegheny Plateau appears to be less than that found in other areas of the species range. Both the frequency and the size of seed crops are smaller than those reported for forests in the Lake States and New England. During the 31 years between 1965 and 1995 for which records are available, there have been only four area-wide sugar maple seed crops (1967, 1972, 1989, 1992), or one seed crop every 7–8 years (Grisez 1975; Bjorkbom 1979; J.C. Bjorkbom, unpublished; S.B. Horsley, unpublished); by contrast, good or better seed crops occurred about once every 3 years in Wisconsin (12 years (1947–1958), Curtis 1959; 26 years (1949–1974), Godman and Mattson 1976) and in New Hampshire (11 years (1971–1981), Graber and Leak 1992). Lime had no effect on seed-crop frequency of sugar maple or black cherry in our study. That lime did not alter sugar maple seed-crop frequency suggests that factors other than Ca, Mg, or a change in soil acidity are required for flower initiation in this species. Each of the area-wide seed crops produced during the past 31 years has occurred the year following a summer drought (1966, 1971, 1988, 1991) where the average June–July Palmer Drought Severity Index (PDSI) was less than –1.00 (NOAA 1995).

Other factors

A range of other factors have been implicated in efforts to determine causal factors associated with sugar maple decline. Nutrient deficiencies, particularly of base cations, seem to be a common thread in other maple decline events as well. The early work of Mader and Thompson (1969) in western Massachusetts noted deficiencies of N, Ca, and Mg in declining sugar maple trees. Low soil and foliar concentrations of Ca and Mg were associated with declining sugar maple in Vermont (Wilmot et al. 1995). Research in Quebec has implicated sites with deficiencies of Mg, K, Ca, and P and impairment of root function associated with low winter snow cover and deep soil freezing in the early 1980s (Bernier and Brazeau 1988*a*, 1988*b*, 1988*c*; Ouimet and Camiré 1995; Robitaille et al. 1995). The work of Kolb and McCormick (1993) and the present study link sugar maple decline with low soil and foliar concentrations of Ca and Mg in Pennsylvania.

Soils with low base cation exchange capacity are common in northern Pennsylvania, particularly on the unglaciated portion of the Allegheny Plateau (Levine and Ciolkosz 1988), though we presently lack detailed knowledge of variability within the landscape, particularly with elevation, slope position, and differences in soil parent materials. Northwestern and north central Pennsylvania receive substantial atmospheric inputs of SO_4 (>25 $kg \cdot ha^{-1} \cdot year^{-1}$) and NO_3 (>15 $kg \cdot ha^{-1} \cdot year^{-1}$) (Lynch 1990); deposition loads of this magnitude have resulted in accelerated cation leaching in other ecosystems (Johnson and Fernandez 1992). Cation leaching undoubtedly is occurring in the forests of northern Pennsylvania, though we do not know the magnitude and nature of these changes. Moreover, without complete nutrient budgets, including soil and litter chemistry, nutrient inputs and outputs, leaching and biomass accumulation, it is not possible to identify the biogeochemical processes responsible for cation dynamics.

In addition to the inherent low content of Ca and Mg at our sites, the supply of soil nutrients and water to vegetation in these acid soils may be reduced further by factors that impair root function. Extreme drought events and insect defoliation were associated with the initiation of maple decline in Pennsylvania stands in the mid-1960s (Kolb and McCormick 1993). In Quebec, deep soil freezing was associated with impaired root function and crown dieback symptomatic of maple decline; surficial freezing and drought were associated with temporary crown transparency but not crown dieback (Robitaille et al. 1995). Although snowfall during the decade of the 1980s frequently was lower than normal in northwestern and north central Pennsylvania (NOAA 1995), soils in this region typically do not freeze (Carter and Ciolkosz 1980; L.R. Auchmoody, unpublished). Thus, freezing injury to roots probably is not a factor in decline of sugar maple in Pennsylvania. Interference by Al^{3+} with Ca and Mg uptake, either by cation binding or by toxicity to roots, also has been reported as impairing root function (Cronan and Grigal 1995). Thornton et al. (1986) demonstrated impaired function of roots of sugar maple seedlings in laboratory solution culture, but there has been no demonstration of Al toxicity to sugar maple roots under field conditions.

Armillaria also has been associated with sugar maple decline (Wargo and Harrington 1991 and references therein; Bauce and Allen 1992). *Armillaria* is present at all of our sites, though the species has not been determined (P. Wargo and B. Marcais, personal communication). Trees that already are stressed typically are attacked by *Armillaria*, though virulence is species dependent. Stresses such as drought and defoliation, which decrease root starch supplies, increase reducing sugars and alter composition of amino acids and phenolic defensive compounds that have been associated with *Armillaria* infection (Garraway et al. 1991; Wargo and Harrington 1991).

Nutrient deficiencies may contribute to the complex series of stress events that ultimately lead to *Armillaria* infection. For example, Ellsworth and Liu (1994) correlated reduced net photosynthesis in sugar maple trees with low foliar Ca and Mg concentrations; McLaughlin et al. (1991) and McLaughlin and Kohut (1992) have made similar observations in red spruce (*Picea rubens* Sarg.). Both nutrient deficiencies and drought also have been associated with increased soluble nitrogen supply, which resulted in higher survival of early instar larvae of defoliating insects and increased herbivory (White 1984; Jones and Coleman 1991). Pupal weight of *Malacosoma disstria* L., a defoliator in Quebec sugar maple forests, was higher when pupae were fed foliage from declining compared with healthy sugar maples (Lorenzetti et al. 1993). Thus, nutrient deficiency may have an indirect link with other factors that increase susceptibility to *Armillaria* infection.

Conclusions

The cause of sugar maple decline has been difficult to determine because of the ephemeral nature of decline episodes and the fact that decline seems to occur as a result of the interaction of several factors, some of which vary temporally. Historical accounts of sugar maple decline generally have reported a temporary increase in mortality followed by a period of recovery and improved health (Giese et al. 1964; Robitaille et al. 1995). For example, sugar maple decline reported in Quebec in the 1980s has been followed by gradually improving crown condition and growth (Allen et al. 1992*a*; Payette et al. 1996).

Our data do not allow precise determination of the sequence of interactions involving drought, defoliation, nutrient status, or other extreme events necessary to promote sugar maple decline. The continued incidence and severity of maple decline in this region coupled with the failure to adequately regenerate these stands reinforce the need for a comprehensive understanding of the important relationships affecting maple health. However, our study has demonstrated the importance of Ca and Mg nutrition in the dynamics of sugar maple health. Liming has been shown to reverse some of the negative consequences of sugar maple decline, resulting in increased tree vigor, growth, and seed production.

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