Long-term impact of liming on growth and vigor of northern hardwoods

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Abstract: Sugar maple (*Acer saccharum* Marsh.) is a keystone species in the northern hardwood forest, and decline episodes have negatively affected the growth and health of sugar maple in portions of its range over the past 50+ years. Crown health, growth, survival, and flower and seed production of sugar maple were negatively affected by a widespread decline event in the mid-1980s on the unglaciated Allegheny Plateau in northern Pennsylvania. A long-term liming study was initiated in 1985 to evaluate responses to a one-time application of 22.4 Mg·ha^{-1} of dolomitic limestone in four northern hardwood stands. Over the 23-year period ending in 2008, sugar maple basal area increment (BAINC) increased significantly ($P \leq 0.05$) in limed plots from 1995 through 2008, whereas American beech (*Fagus grandifolia* Ehrh.) BAINC was unaffected. For black cherry (*Prunus serotina* Ehrh.), the third principal overstory species, BAINC and survival were reduced in limed plots compared with unlimed plots. Foliar Ca and Mg remained significantly higher in sugar maple foliage sampled 21 years after lime application, showing persistence of the lime effect. These results show long-term species-specific responses to lime application.

Résumé : L'érable à sucre (*Acer saccharum* Marshall) est une espèce clé de la forêt feuillue nordique et les épisodes de dépérissement ont eu un effet néfaste sur la croissance et la santé de cette essence dans certaines parties de son aire de répartition au cours des 50 dernières années et un peu plus. Un épisode généralisé de dépérissement, survenu au milieu des années 1980 sur le Plateau d'Alleghany qui a échappé à la glaciation dans le nord de la Pennsylvanie, a eu un effet néfaste sur la santé de la cime, la croissance, la survie ainsi que la production de fleurs et de graines de l'érable à sucre. Une expérience de chaulage a été initiée en 1985 pour évaluer la réponse à long-terme à une application unique de 22,4 Mg·ha^{-1} de chaux dolomitique dans quatre peuplements de feuillus nordiques. Pendant la période de 23 ans qui s'est terminée en 2008, l'accroissement en surface terrière de l'érable à sucre a significativement ($P \leq 0{,}05$) augmenté dans les parcelles chaulées tandis que celui du hêtre d'Amérique (*Fagus grandifolia* Ehrh.) n'a pas été affecté. Dans le cas du cerisier tardif (*Prunus serotina* Ehrh.), la troisième espèce en importance de l'étage dominant, le chaulage a réduit sa surface terrière et sa survie comparativement aux arbres dans les parcelles témoins. Le Ca et le Mg foliaires sont demeurés significativement plus élevés dans le feuillage de l'érable à sucre échantillonné 21 ans après l'application de chaux indiquant que la chaux avait un effet persistant. Ces résultats montrent que les réactions à l'application de chaux sont propres à chaque espèce.

[Traduit par la Rédaction]

Introduction

Concern for the effects of acid deposition on forest soils has led to interest in forest liming as a remedial measure. The northeastern United States has received historically high levels of acidic deposition for at least 30 years (National Atmospheric Deposition Program 2008). Significant depletion of Ca and Mg has occurred in forest soils of the northeastern United States over the last 30 to 50 years (Likens et al. 1996; Palmer et al. 2004; Bailey et al. 2005). Moreover, an imbalance in Ca, Mg, Mn, and Al has been associated with sugar maple (*Acer saccharum* Marsh.) decline in the same region (Horsley et al. 2000; Bailey et al. 2004; Hallett et al. 2006; Long et al. 2009). Extensive forest liming has been proposed as a remedial measure to mitigate these effects (Mulhollem 2002; Sharpe and Voorhees 2006). Earlier lime studies conducted in the northeastern USA and eastern Canada have used relatively low doses of lime and have been of short duration (cf. Long et al. 1997). Only a few studies have evaluated the long-term impacts of lime addition to forest soils and vegetation responses (cf. Moore et al. 2000; Moore and Ouimet 2006), and no other studies have examined the long-term response of mixed-species stands. Long-term studies of vegetation responses are needed to evaluate potential negative effects of liming before recommendations for landscape-level applications are made.

In 1985, a long-term liming study was initiated by the Pennsylvania Bureau of Forestry and the USDA Forest Service, Northern Research Station, at four sites on the Allegheny Plateau in north-central Pennsylvania. At these unglaciated, plateau-top sites, known to be low in Ca and Mg and high in Al and Mn (Bailey et al. 2005), 22.4 Mg·ha^{-1} of dolomitic

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limestone was applied in a replicated study, and effects were contrasted with those of applying no lime. The overstory was dominated by sugar maple, American beech (*Fagus grandifolia* Ehrh.), and black cherry (*Prunus serotina* Ehrh.). Previously, we reported changes in soil chemistry and growth responses over the first 8 years through 1993 (Long et al. 1997). Changes in soil chemistry were evident after the first year in the upper mineral soil. Sugar maple exhibited positive growth and crown vigor responses to liming, but American beech and black cherry showed no evidence of response to the lime treatment through 1993 (Long et al. 1997). A significant response in sugar maple crown vigor was detected after 3 years, but a significant basal area growth response was not evident until 8 years after initiation of the study.

We have continued to monitor the responses of sugar maple, American beech, and black cherry through 2008, 23 years after lime application. The primary objective of this work is to evaluate the long-term effect of lime addition on basal area growth, crown vigor, and survival of sugar maple, American beech, and black cherry. We also examine the foliar nutrition of sugar maple as an indicator of available nutrients, contrast it with black cherry foliar nutrients, and evaluate the potential effect of lime addition on sugar maple flower and seed production and its role in recruitment failure of sugar maple.

Methods

Study sites

Four blocks of the study were installed in 1985 at sites on the Susquehannock State Forest, Potter County, Pennsylvania, within the Allegheny High Plateau Section of the Appalachian Plateau Province (Harrison 1970; McNab and Avers 1994). Species composition of all four replicates was similar (Long et al. 1997). Two blocks are situated along Black Diamond Road (BDR1 and BDR2; elevation 677 m) near Inez (41°42′30″N, 78°01′30″W) and two blocks are near Cherry Springs (CS3 and CS4; elevation 716 m) (41°39′15″N, 77°49′15″W). The area has a humid, temperate climate, with daily temperature averaging 9 °C, annual precipitation averaging 1067 mm, and a growing season of about 120 days (Cronce and Ciolkosz 1983; Kingsley 1985).

Soils at these sites were formed from weathered sandstone, siltstone, and shale with a mineralogy dominated by illite and kaolinite (Goodman et al. 1958; Aguilar and Arnold 1985). Pits dug at all four blocks were used to describe these residual soils, which were in the Clymer (Typic Hapludult), Cookport (Aquic Fragiudult), Leetonia (Entic Haplorthod), Wellsboro (Typic Fragiudept), and Wharton (Aquic Hapludult) series (USDA Natural Resources Conservation Service, Soil Survey Staff 2010). No major physical limitations to forest growth such as high stone content or shallow depth to bedrock or to a perched water table were evident at these sites (Auchmoody and Walters 1992). The upper 2.5 cm of mineral soils are extremely acidic, with pH ranging from 3.7 to 4.2.

Treatment applications

The study sites were identified and laid out in the summer of 1985, and an inventory of all trees ≥ 2.5 cm diameter at breast height (DBH) was conducted. A complete block had eight 60 m × 60 m (0.36 ha) plots. Data were collected from the interior 45 m × 45 m (0.20 ha) measurement plot, leaving a 7.5 m buffer surrounding the perimeter of each plot. Lime was applied only to the interior 0.20 ha portion of the plot when the soils were dry during the autumn of 1985 using tractors equipped with conventional spreaders. Half of the plots received lime and half were left untreated. Lime was applied as a single application of commercial pulverized dolomitic limestone (Ca = 21%, Mg = 12%, Ca equivalent = 58.8) at 22.4 $\mathrm{Mg{\cdot}ha^{-1}}$. The original study also included fencing and herbicide treatments overlaid on the lime treatment, but these treatments had no significant effects on overstory responses and are not considered here (Long et al. 1997).

All stands were thinned to about 50% relative density during the winter of 1985–1986 by removing small trees and those of inferior quality (Stout et al. 1987). Approximately two-thirds of the trees removed came from the suppressed and intermediate crown positions, and one-third came from the canopy trees. Black cherry – maple stands generally develop as stratified stands with intolerants such as black cherry, white ash (*Fraxinus americana* L.), and yellow-poplar (*Liriodendron tulipifera* L.) in the dominant crown positions and species such as sugar maple, American beech, and eastern hemlock (*Tsuga canadensis* (L.) Carr.) in the codominant and subordinate crown positions (Marquis 1980). Thinning provided abundant growing space for the residual trees and was conducted to maintain similar species composition and stand structure of the residuals on each of the eight plots in a block. After thinning, sugar maple was the most evenly distributed species across all four blocks, followed by American beech and black cherry.

Tree measurements

All residual trees were numbered and marked at breast height (1.37 m) for diameter and individual tree evaluations. Diameters were measured in the fall of each year from 1985 to 2008, except for 1991, 1992, and 1997. All trees have paint or scribe marks at DBH to assure that diameter is measured at the same position on the bole using a diameter tape or caliper. Tree crown vigor (Mader and Thompson 1969) was estimated by two observers each August from 1985 to 2008, except for 1991, 1992, 1994, and 1995, to classify tree crown condition into one of six vigor index categories. Vigor index 1 was a healthy tree with full-size foliage and no dead twigs or branches. Vigor index 2 trees had abnormally small, curled, thin, yellowish, or otherwise distorted foliage, but no dead twigs or branches. Vigor index 3 trees were similar to class 2, except for some dead or bare twigs present in the top of the crown. Vigor index 4 trees had at least two dead branches (0.9 to 1.2 m long) and twigs dead for no apparent reason that constituted less than half of the crown. More than half of the crown of vigor index 5 trees were dead branches and twigs. Vigor index 6 trees had dead crowns.

Sugar maple flower and seed crops were evaluated annually by two observers starting in 1987, with a cohort of about 200 dominant and codominant sugar maples (approximately 50 trees in each block). In some years where no flowers were present in the spring, seed crops were subsequently not rated in the fall. Flowering of sugar maple crowns was estimated each spring as the percentage of the crown with flowers present: 0%, no flowers present; 1%, trace flowering to <5% flowering; and 5% to 100%, estimated to the nearest

5% class. Seed crops were evaluated by two observers in late August or September and were assigned to one of six broad categories: 0, no seed present; 1, trace to 5% of the crown with seed; 2, 6%–25%; 3, 26%–50%; 4, 51%–75%; 5, 76%–100% of crown with seed.

Sugar maple and black cherry foliage was sampled in 2006 to evaluate foliar chemistry. Leaves from healthy dominant and codominant trees were sampled by using a shotgun to shoot sun-exposed twigs with foliage from the mid-crown during the last two weeks of August 2006. In each block, eight to nine trees each were randomly selected from limed and unlimed plots. Only healthy trees with normal foliage coloration and <10% fine twig dieback were sampled. Foliage samples were oven-dried at 70 °C, ground with a Tecator cyclotec mill (FOSS, Eden Prairie, Minnesota), and analyzed at the Northern Research Station Laboratory in Durham, New Hampshire. Dried and ground foliage was digested using a microwave-assisted acid digestion procedure (EPA Method 3052, 1996) and analyzed for Al, Ca, K, Mg, Mn, and P by inductively coupled plasma spectroscopy. Foliar N was determined by combustion with a PerkinElmer 2400 series II CHNS/O analyzer (PerkinElmer, Waltham, Massachusetts). National Institute of Standards and Technology pine needles were used as a reference standard. Percentage recovery of certifiable elements (Vogt et al. 1987) ranged from 90% for Al to 108% for Ca. Repeatability of determinations for both standards and duplicate samples, expressed as the percentage relative difference (maximum value minus minimum value expressed as a percentage of the mean), was typically less than 3%. Similar methods were used to collect and analyze 1994 foliage samples; however, trees of all vigor classes were sampled (Long et al. 1997).

Statistical methods

The study design is a randomized complete block with repeated measures. Statistical analyses were conducted with SAS version 9.2 using PROC MIXED (SAS Institute Inc. 2008) with a restricted maximum likelihood technique and the Kenward–Roger correction method for the denominator degrees of freedom (Littell et al. 2006). For growth and crown vigor repeated measures analyses, a number of different covariance structures were tested and the autoregressive order 1 covariance structure usually fit the data best based on comparisons of the corrected Akaike (AICC) and Bayesian information criteria (BIC) and residual plots. Block was considered the random effect in these mixed models. All models tested the fixed effects (lime treatment, year, lime × year), and when the lime × year interaction was significant ($P \leq 0.05$), least squares means were used to evaluate specific pairwise comparisons using the Tukey–Kramer adjustment for multiple comparisons (Littell et al. 2006; SAS Institute Inc. 2008). For growth analyses, the initial tree basal area based on the pretreatment diameter in 1985 was tested as a covariate and used with the repeated measures analyses if it was statistically significant ($P \leq 0.05$). No covariate was used for tree vigor analyses because crown health was not evaluated prior to treatment application. For growth and crown vigor analyses, dead trees were included in the analyses only up to the first year that the tree was observed as dead; in subsequent years, these trees were omitted from analyses.

Complementary log–log models were fit to analyze annual mortality data for each of the three overstory species (Allison 1995). Models were fit using PROC GLIMMIX with a binomial distribution and a complementary log–log link function (SAS Institute Inc. 2008). Independent variables in the model were lime treatment and year; an interaction term prevented model convergence. Years with zero mortality were omitted from the analyses because they frequently prevented convergence of iterative algorithms. Cumulative mortality for the duration of the study (end of the 2008 growing season) was assessed using PROC GENMOD (Flynn 1999; SAS Institute Inc. 2008). This method uses Poisson regression analyses with lime treatment and block as the independent variables to predict cumulative mortality (log-linear models) by 2008.

Sugar maple flower and seed crops were estimated annually from 1987 through 2008. These data were analyzed in a randomized complete block with repeated measures model using PROC GLIMMIX (SAS Institute Inc. 2008). Both flower and seed crop data were highly variable. Flower crop data were best modeled by the lognormal distribution with a log link function, whereas seed crop data were modeled with a gamma distribution and a log link function (Littell et al. 2006). Because of the number of zeros, highly variable data, and only four blocks, only models using the spatial power covariance structure would converge; alternative models were too complex. Where appropriate, Tukey–Kramer multiple comparison tests were used with an alpha probability level of 0.10 due to the high variability of these data.

Sugar maple foliar nutrient data were compared using t tests for means from trees sampled in limed and unlimed plots in a block ($n = 4$ for t tests). Black cherry foliar nutrient data were similarly compared, but only from two of the four blocks ($n = 2$ for t tests). Because trees were sampled differently with regard to vigor classifications (all crown vigor indices were sampled in 1994, but only healthy trees were sampled in 2006), we did not statistically compare the 1994 results with the 2006 results.

Results

Stand conditions and disturbance history

Stand conditions have changed over the course of the study (Table 1). Uneven mortality resulting from the sugar maple decline in the 1980s and 1990s and American beech mortality from beech bark disease have affected the numbers of remaining trees and stand basal areas. The CS4 block, the youngest stand, predictably showed the largest change in basal area, increasing from 17.0 $m^2 \cdot ha^{-1}$ in 1985 to 25.2 $m^2 \cdot ha^{-1}$ in 2008. Mean diameter increased for all species, whereas basal area increases were uneven across the blocks due to mortality.

Earlier results (Long et al. 1997) showed a wave of changes in soil chemistry through 1993 in response to lime application. These changes in soil chemistry have been sustained through the last sampling in 2006 (data not shown). Soil pH in the upper 5 cm of mineral soil has remained about 3.7 to 3.8 throughout the study in untreated plots; however, pH in limed plots averaged 6.6 in the upper 5 cm in 2006, and exchangeable Ca and Mg remain substantially elevated in limed plots (data not shown).

Drought and defoliating insects have been the major dis-

Table 1. Stand composition (excluding ingrowth) at the four blocks in 1985 and 2008.

	Block			
	BDR1	BDR2	CS3	CS4
Total basal area				
Total basal area ($m^2 \cdot ha^{-1}$), 1985, 2008	19.8, 19.8	11.0, 11.7	11.7, 14.5	17.0, 25.2
Total basal area (%), 1985, 2008				
Sugar maple	21, 25	35, 46	61, 63	32, 34
American beech	19, 8	42, 38	31, 31	6, 7
Black cherry	57, 64	7, 7	8, 6	56, 54
Other[a]	4, 3	16, 9	0, 0	5, 5
Diameter (cm)				
Sugar maple				
Mean diameter (range), 1985	34.6 (15–55)	26.3 (13–53)	34.2 (13–70)	23.0 (13–44)
Mean diameter (range), 2008	44.6 (31–70)	37.4 (19–65)	45.5 (17–86)	31.0 (14–55)
No. of trees/block, 1985, 2008	65, 49	103, 73	112, 85	202, 169
American beech				
Mean diameter (range), 1985	40.0 (29–57)	27.6 (13–50)	32.2 (13–59)	18.3 (13–34)
Mean diameter (range), 2008	45.7 (36–62)	35.2 (21–57)	40.5 (22–67)	26.1 (16–47)
No. of trees/block, 1985, 2008	47, 16	114, 70	64, 52	60, 53
Black cherry				
Mean diameter (range), 1985	47.8 (29–100)	54.0 (43–61)	55.1 (42–65)	40.0 (21–63)
Mean diameter (range), 2008	56.3 (35–113)	65.6 (56–70)	69.0 (61–78)	49.9 (27–75)
No. of trees/block, 1985, 2008	97, 79	5, 4	6, 4	118, 108
Other[a]				
Mean diameter (range), 1985	33.4 (28–40)	35.1 (19–57)	—	33.4 (14–50)
Mean diameter (range), 2008	41.2 (34–45)	46.2 (33–59)	—	42.3 (17–59)
No. of trees/block, 1985, 2008	15, 6	28, 10	—	16, 14

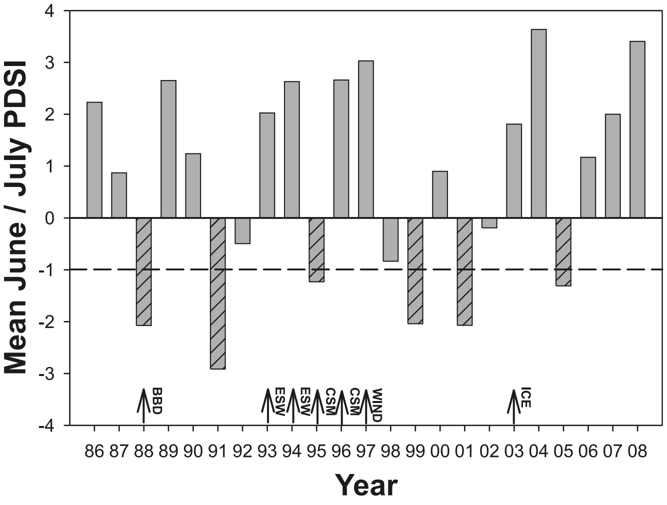
[a] Includes *Fraxinus americana* L., *Tsuga canadensis* (L.) Carrière, *Acer rubrum* L., *Acer pensylvanicum* L., and *Betula* spp.

turbance agents affecting these study sites. A severe drought in 1988 with the mean June–July Palmer drought severity index (PDSI) equal to –2.07 (Fig. 1) was followed by another severe drought in 1991, with a PDSI of –2.91 (National Oceanic and Atmospheric Administration 2010). Additional drought years with mean June–July PDSI values < –1 were 1995, 1999, 2001, and 2005.

Defoliations with moderate severity (30% to 60% of the crown defoliated) were evident in 1993 and 1994 from elm spanworm (*Ennomos subsignaria* [Hubner]), and fall cankerworm (*Alsophila pometaria* [Harris]) at all four blocks (Fig. 1). These insects defoliated American beech, sugar maple, and sometimes black cherry. In 1995 and 1996, black cherry trees received moderate mid- to late-season defoliation from cherry scallop shell moth (*Hydria prunivorata* [Ferguson]).

The beech scale insect (*Cyptococcus fagisuga* Lind.) was first detected on American beech trees in 1985, and mortality from beech bark disease was evident by 1988. This disease complex has continued to affect American beech health throughout the study. Less frequent abiotic agents such as wind and ice storms also have affected some trees. In August 1997, a wind storm damaged some buffer zone trees at both BDR1 and BDR2 blocks. An ice storm hit all four blocks in January 2003. American beech and black cherry had the most crown and fine twig injury due to ice, and sugar maple was the least affected. These stressors are difficult to quantify and have had obvious and sometimes subtle impacts on tree condition throughout the study.

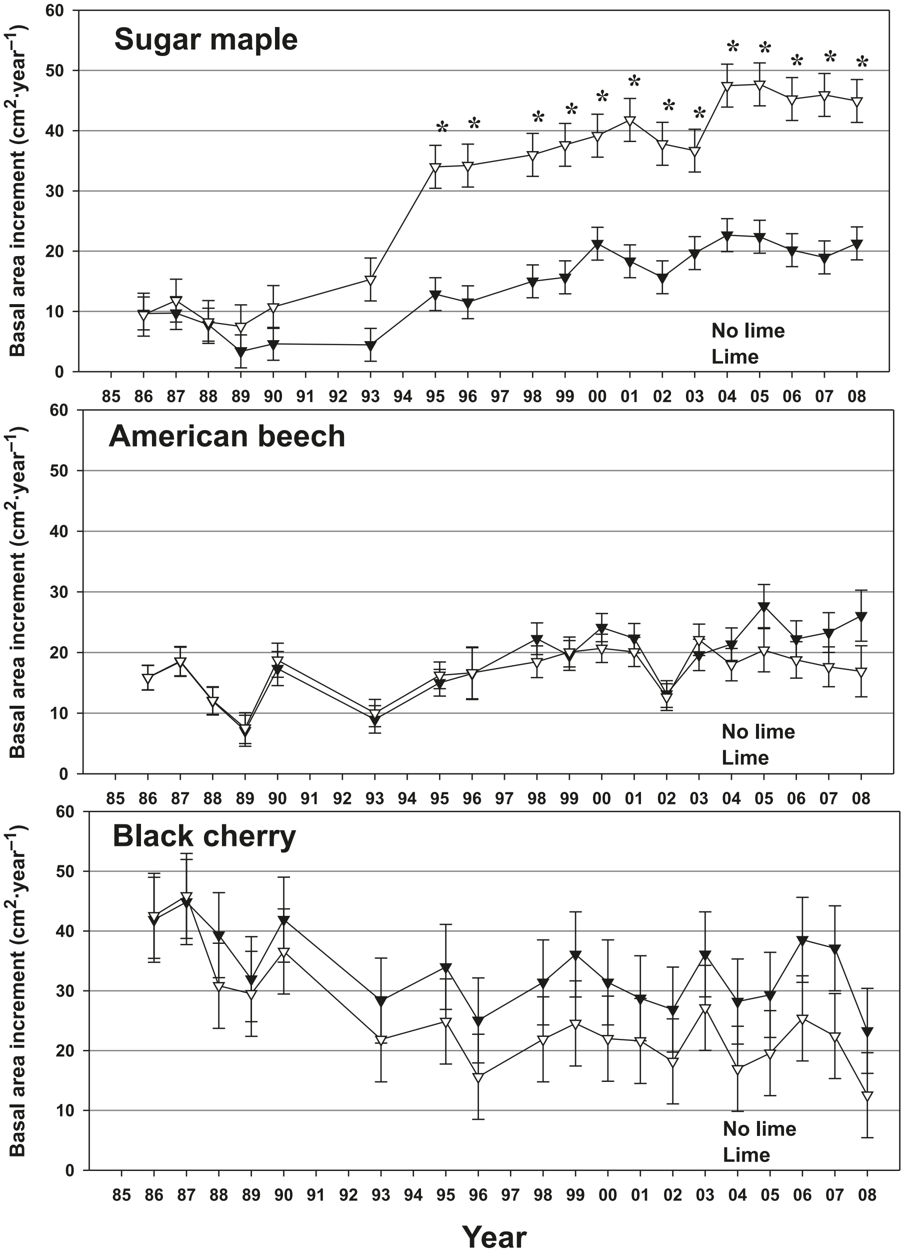
Fig. 1. Disturbance diagram showing drought (mean June–July Palmer drought severity index (PDSI) for Pennsylvania climate division 10), disease (BBD, beech bark disease initiation), defoliation (ESW, elm spanworm; CSM, cherry scallop shell moth), and ice and wind events affecting the study plots. Broken horizontal line at –1 shows the threshold for mild drought based on the PDSI; cross-hatched bars indicate the years when the PDSI < –1 (incipient drought). Years: 1986 (86) to 2008 (08).



Basal area increment

Disturbance events likely interacted with the lime treatment and affected growth responses for all three species, but these disturbances are not readily quantifiable (Figs. 1 and 2). Sugar maple basal area increment (BAINC) in unlimed plots was lowest from 1989 to 1993 when two droughts and two defoliations occurred. Repeated measures analysis of cova-

Fig. 2. Least squares means of mean annual basal area increment (BAINC; cm^2·year^{-1}) for sugar maple, American beech, and black cherry, 1986 (86) to 2008 (08). Asterisks indicate a significant ($P \leq 0.05$) pairwise difference based on the Tukey–Kramer adjustment for multiple comparisons because of year × lime treatment interaction. Pairwise comparisons were not significantly different for American beech or black cherry, but black cherry BAINC averaged across all time periods was 25.3 cm^2·year^{-1} in limed plots, significantly ($P = 0.026$) less than the BAINC of 33.4 cm^2·year^{-1} in unlimed plots.



riance showed a significant lime treatment × year interaction for sugar maple BAINC (Table 2; Fig. 2). Sugar maple BAINC was responsive to liming and also was affected by drought and defoliation disturbances. Sugar maple BAINC was significantly greater for limed trees starting in 1995 and continuing through 2008 using pairwise comparisons and the Tukey–Kramer multiple comparison adjustment (Fig. 2). Sugar maple BAINC averaged across all years (1986–2008) was 31.1 cm^2· year^{-1} in limed plots and only 14.5 cm^2·year^{-1} in unlimed plots. American beech BAINC decreased by 1989 following the 1988 drought and decreased again by 1993 in response to elm spanworm defoliation. In contrast to sugar maple, American beech BAINC showed no significant response to lime treatment (Table 2; Fig. 2); however, the lime treatment effect, averaged across all time periods, approaches statistical significance ($P = 0.061$; Table 2). American beech trees in unlimed plots averaged 18.6 cm^2·year^{-1}, whereas trees in limed plots averaged 16.9 cm^2·year^{-1}. Decreasing black cherry BAINC from 1990 through 1996 was related to defoliations and drought events in that time period. Black cherry had a significant, but negative, growth response to lime treatment when averaged over the entire 1986–2008 period (Table 2; Fig. 1). Black cherry basal area increment averaged 33.4 cm^2·year^{-1} in unlimed plots and only

Table 2. Fixed-effects *F* statistics, associated probability levels, and model covariance structure for repeated measures analyses of growth, expressed as annual basal area increment (BAINC), and of crown vigor (VIGOR) for sugar maple, American beech, and black cherry for 1986 to 2008.

Species	Lime	Year	Lime × year	Covariance structure[a]
BAINC				
Sugar maple				
F statistic	102.8	13.7	3.2	AR(1)
P level	<0.001	<0.001	<0.001	
American beech				
F statistic	4.3	11.9	0.6	ARH(1)
P level	0.061	<0.001	0.822	
Black cherry				
F statistic	73.4	10.9	1.0	AR(1)
P level	0.026	<0.001	0.475	
VIGOR				
Sugar maple				
F statistic	54.2	17.8	3.9	AR(1)
P level	<0.001	<0.001	<0.001	
American beech				
F statistic	<0.1	34.3	0.4	ARH(1)
P level	0.951	<0.001	0.963	
Black cherry				
F statistic	4.8	69.5	0.2	AR(1)
P level	0.068	<0.001	0.981	

[a] Covariance structures: AR(1), first-order autoregressive with homogeneous variances; ARH(1), autoregressive order 1 with heterogeneous variances. Other covariance structures that were evaluated: compound symmetry, Toeplitz, and spatial power law.

25.3 cm^2·year^{-1} in limed plots. There was no significant lime treatment × year interaction for black cherry (Table 2). This negative effect of lime was not evident in analyses through 1993 (Long et al. 1997).

Crown vigor

Sugar maple crown vigor index has fluctuated throughout the study (Fig. 3). The significant lime treatment × year interaction (Table 2; Fig. 3) showed that mean crown vigor index of limed trees was improved (lower mean crown vigor index rating) compared with unlimed trees by 1990. This difference stayed statistically significant through 1999 based on pairwise comparisons (Fig. 3). Limed sugar maple mean crown vigor index after 1999 was improved, although not significantly, averaging 2.4 compared with 3.3 for unlimed trees.

American beech crown vigor index was not affected by lime treatment and averaged about 3.2 through 2008 (Table 2; Fig. 3). Mean American beech crown vigor index increased dramatically, indicating decreased crown health, by 1996 for all American beech trees. Crown health declined because of beech bark disease, which was first detected in the plots in 1986 and which affected trees regardless of lime treatment. Since 1996, there have been few large fluctuations in American beech crown health, and beech bark disease has continued to cause poor American beech crown condition in many plots.

Black cherry mean crown vigor index has decreased over the course of the study without regard to lime treatment (Table 2; Fig. 3). Crown vigor index increased (decreased crown health) in response to elm spanworm defoliations in 1993 and 1994 and continued to deteriorate in 1995 and 1996 because of cherry scallop shell moth defoliations. Crown vigor index of black cherry has not shown signs of improvement since about 2000. Over the entire study, black cherry crown vigor index has averaged 3.2 in limed plots and 3.1 in unlimed plots; this difference was not statistically significant (Table 2).

Starting in 1997, we also evaluated crown vigor using protocols developed by the North American Maple Project (NAMP) (Millers et al. 1991). Although these protocols provide a finer resolution for crown condition estimates, we found no major differences from the results presented using the Mader and Thompson (1969) system, and thus these results are not presented here.

Mortality

Annual mortality for each of the three overstory species was analyzed with complementary log–log models. For sugar maple, 2003 was omitted because of zero mortality. Annual mortality rates reported here are biased upward by omitting the zero years and should be interpreted with that limitation (Fig. 4).

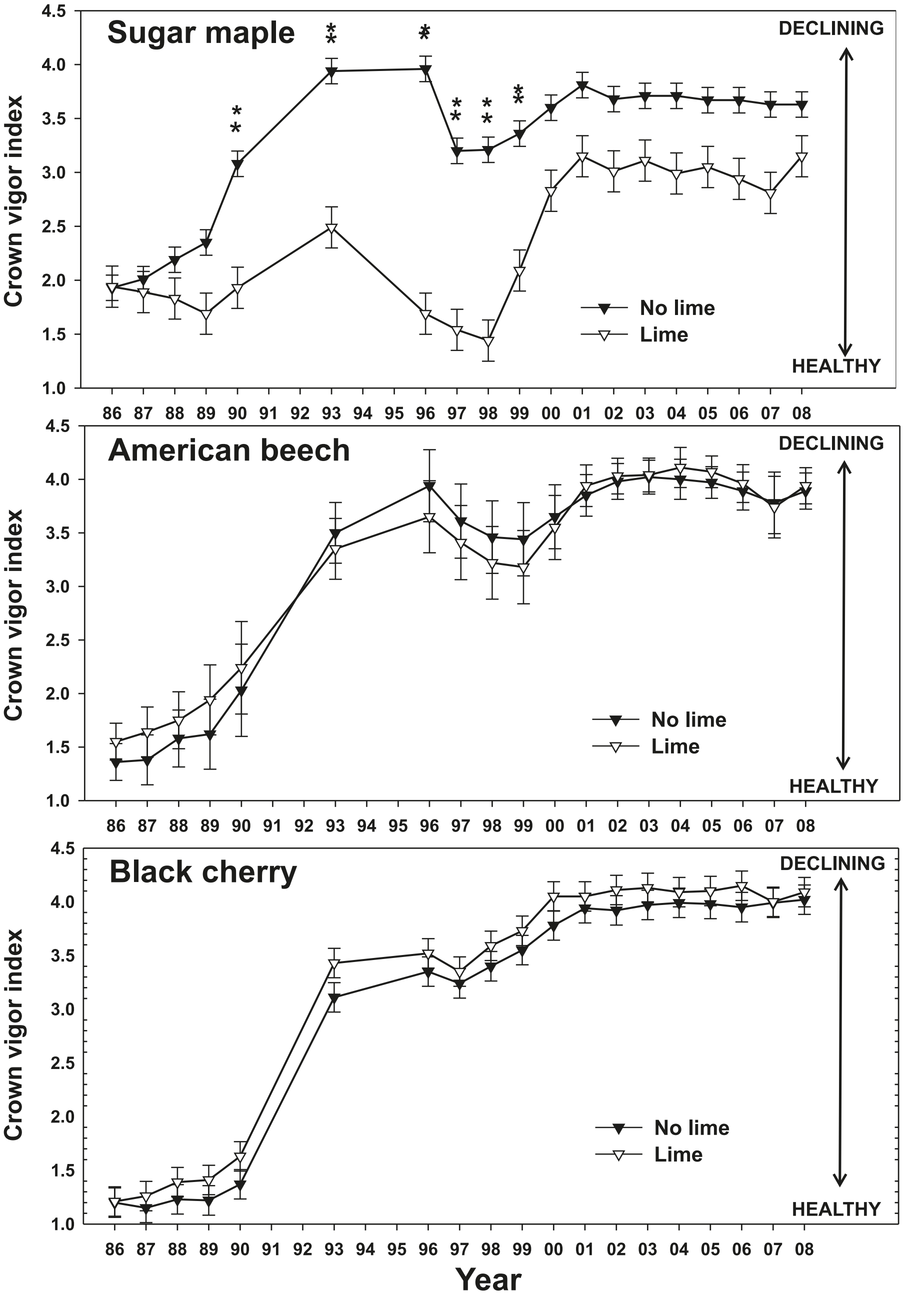
For sugar maple, both lime treatment and year were significant predictors of annual mortality ($P < 0.001$ for both factors). In limed plots, least squares means of annual mortality averaged 0.5% per year, whereas in unlimed plots, mortality averaged 1.3% per year from 1986 to 2008. The greatest mortality rate for sugar maple was 2.3% annually for the period 1991–1993, which included both drought and defoliation events. The least squares mean mortality for 1993 was 6.9%, but this value was adjusted (divided by three) because mortality data were not collected in 1991 and 1992. The next greatest mortality rate was in 1990 (1.7%) following the 1988 drought. The years 1987 and 1986 had the lowest mortality (0.18% for both years). Because of model complexity (models would not converge), it was not possible to evaluate the lime treatment × year interaction.

American beech analyses omitted the years when no beech trees died (1986, 1988, and 2005). Lime treatment was not a significant factor ($P = 0.781$) affecting American beech mortality; annual mortality was 1.5% in unlimed plots and 1.6% in limed plots. Year was highly significant ($P < 0.001$). The greatest mortality rate was in 1997, when the mean mortality was 5.3% (least squares mean) and the lowest mortality rate was in 1987 (0.35%).

Black cherry annual mortality analyses omitted the years 1986–1988, 2002, 2003, 2007, and 2008, when no trees died. Black cherry annual mortality was significantly ($P = 0.002$), but negatively, affected by lime treatment. Least squares mean annual mortality was 1.7% in limed plots compared with 0.5% in unlimed plots.

Cumulative mortality by 2008 was evaluated using Poisson regression with lime treatment and block as the independent variables. Sugar maple cumulative mortality (Table 3; Fig. 4) was significantly affected by lime treatment, with 14.0% (least squares means) mortality in limed plots compared with 33.9% in unlimed plots. American beech mortality was unaffected by lime treatment, but block differences were significant. Most American beech mortality occurred at BDR1 and

Fig. 3. Least squares means of mean crown vigor index (1 (healthy) to 6 (dead)) for sugar maple, American beech, and black cherry, 1986 (86) to 2008 (08). Asterisks indicate a significant ($P \leq 0.05$) pairwise difference based on the Tukey–Kramer adjustment for multiple comparisons.



BDR2 (66.0% and 39.5%, respectively) compared with CS3 and CS4 (18.8% and 13.3%, respectively). Black cherry mortality was significantly affected by both lime treatment and block, though only two blocks, BDR1 and CS4, were used in the analyses because of low representation of the species at the other two replicates. Mortality in limed plots was 21.2% compared with only 6.1% in unlimed plots, whereas BDR1 had 17.3% mortality compared with only 7.5% mortality in CS4 plots.

Sugar maple flower and seed crops

Flower and seed crops have been highly variable throughout the study (Fig. 5). During the 22 years that sugar maple flower and seed crops have been rated (1987–2008), there were eight years in which there was no production to very small flower (<1% of the crown with flowers) and seed crop production: 1990, 1991, 1993, 1997, 2001, 2004, 2005, and 2007. These years were omitted from the statistical analyses. For both flower and seed crops, there were significant lime × year interactions ($P < 0.001$ for both flower and seed crop analyses). Pairwise comparisons, adjusted by the Tukey–Kramer method, showed significantly ($P \leq 0.10$) larger flower crops for trees in limed plots versus unlimed plots in 1992, 1996, 1998, 1999, 2002, and 2008. The largest flower crop during the study occurred in 2006 when average flower cover was about 95% on limed tree crowns and 82% on un-

Fig. 4. Cumulative mortality (% dead trees, unadjusted) by year for sugar maple, American beech, and black cherry, 1986 (86) to 2008 (08).

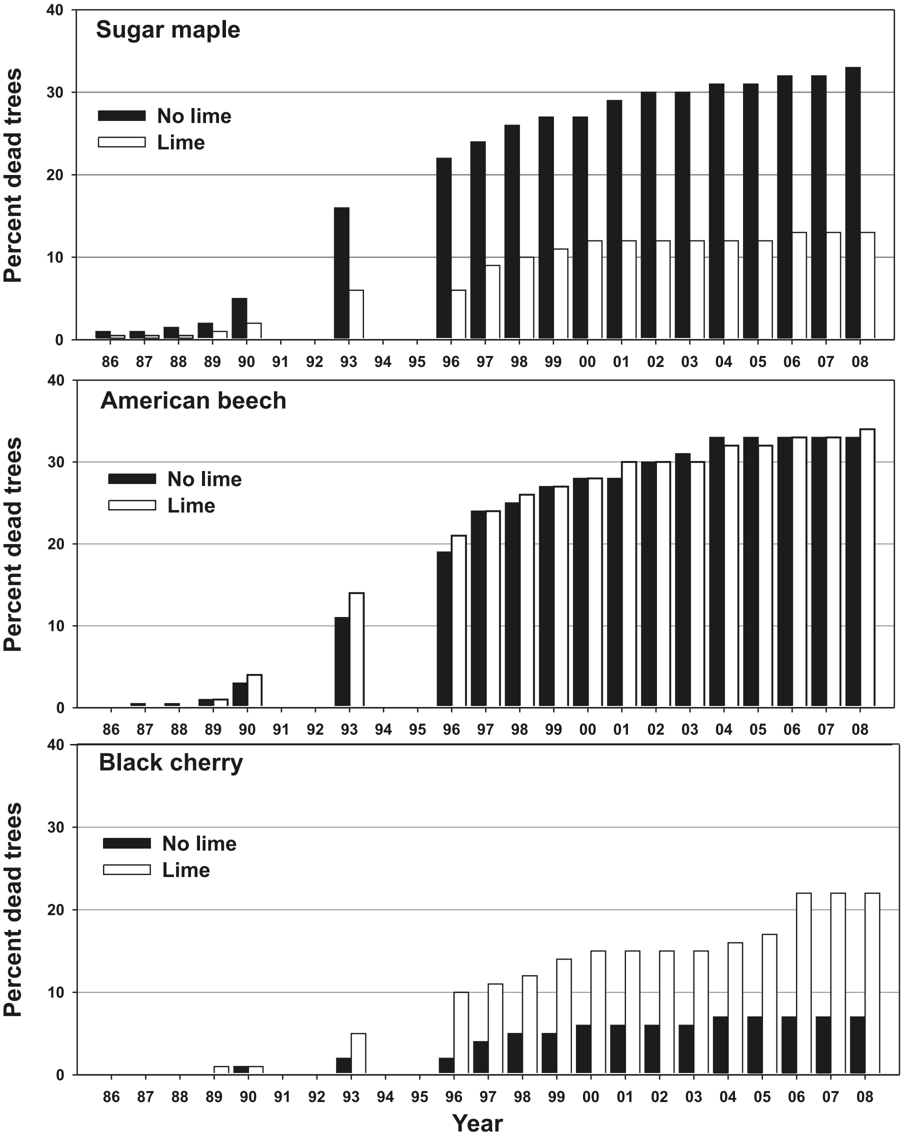


Table 3. χ^2 statistic, probability levels, and least squares means percentage mortality for Poisson regression analyses of cumulative mortality (1985–2008) in relation to lime treatment and block for sugar maple, American beech, and black cherry.

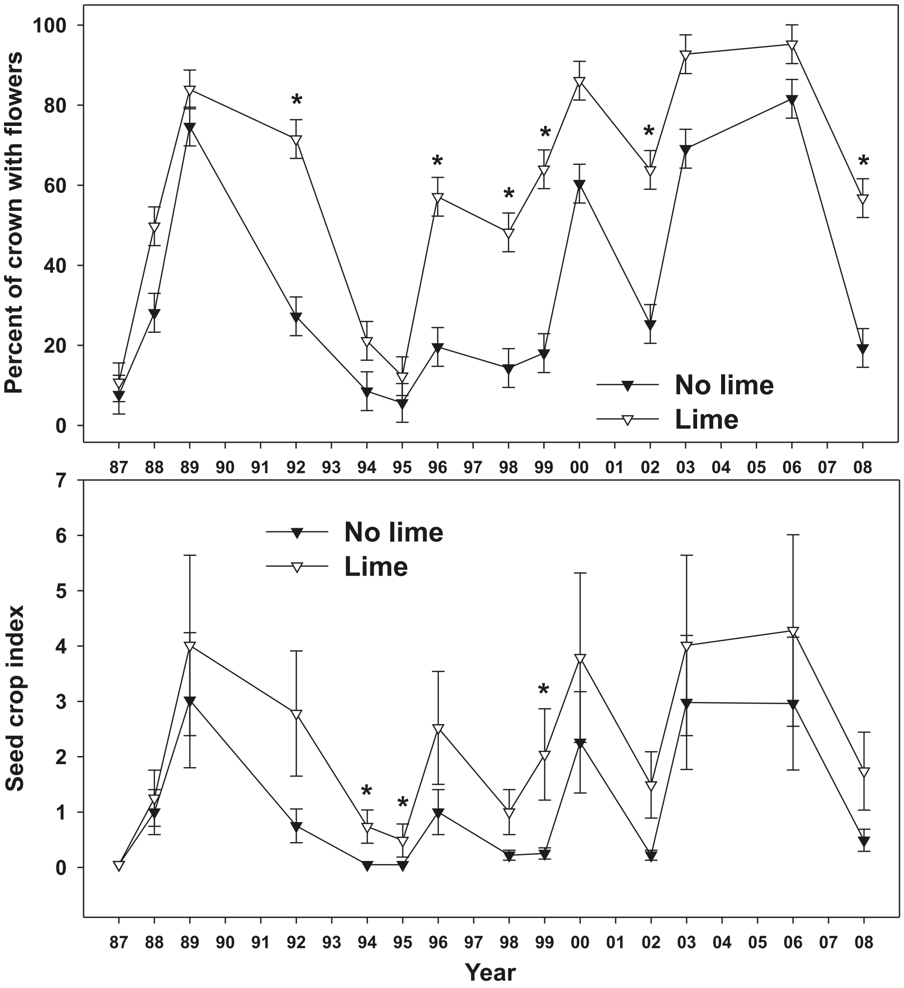
	χ^2 (probability level)		Least squares means % mortality (no. of trees)	
Species	Block	Lime treatment	Lime	No lime
Sugar maple	4.49 (0.213)	19.6 (<0.001)	14.0 (35)	33.9 (72)
American beech	27.1 (<0.001)	0.01 (0.923)	28.7 (36)	28.1 (50)
Black cherry	4.78 (0.029)	10.0 (0.002)	21.2 (20)	6.1 (8)

limed tree crowns, although these means were not significantly different ($P > 0.989$). Seed crops, rated on a scale of 1 to 5, were much more variable, and only in 1994, 1995, and 1999 were seed crops significantly ($P \leq 0.10$) greater on limed versus unlimed trees (Fig. 5). Lime treatment increased the size of the flower and seed crops but did not affect the frequency of these reproductive stages.

Sugar maple and black cherry foliage chemistry

Sugar maple foliar nutrients sampled in 2006 showed sustained changes in nutrient concentrations in response to lime application 21 years earlier. The 2006 results were very similar to results from 1994, despite differences in sampling methodology (Long et al. 1997). Ca and Mg remained significantly greater in foliage from limed trees versus unlimed trees (Table 4). Foliar K, Al, Fe, and Mn were all significantly reduced in limed trees versus unlimed trees, and N and P were unaffected by lime treatments (Table 4). Foliar Ca in limed trees, 9519 mg·kg^{-1}, was more than double the Ca concentrations in unlimed trees, 3913 mg·kg^{-1}. Similarly,

Fig. 5. Least squares means of sugar maple flower and seed crops. Years with trace or no flower crops were omitted from analyses (1990, 1991, 1993, 1997, 2001, 2004, 2005, 2007). Asterisks indicate a significant ($P \leq 0.10$) pairwise difference based on the Tukey–Kramer adjustment for multiple comparisons. Years: 1986 (86) to 2008 (08).



there was a more than fourfold increase in foliar Mg concentrations in limed trees versus unlimed trees. Foliar K concentration in limed trees, 6133 mg·kg^{-1}, was still significantly less than in unlimed trees, 7657 mg·kg^{-1}. Mn concentration was only 426 mg·kg^{-1} in limed trees compared with 2946 mg·kg^{-1} in unlimed trees.

In 1994, sugar maple foliage was sampled without regard to crown vigor index, making statistical comparisons between 1994 and 2006 difficult. Despite this difference in sampling method, Ca and Mg concentrations were similar in 1994 and 2006, with 2006 values slightly higher for trees from limed plots (Table 4). Foliar N concentration also was greater in both limed and unlimed plots in 2006 samples compared with 1994 samples. Al, Fe, and P concentrations were similar in both time periods in both limed and unlimed plots. Foliar K concentration, which was potentially deficient in the 1994 foliage from limed plots, increased to 6133 mg·kg^{-1} in 2006 compared with 4811 mg·kg^{-1} in 1994. Another major change since 1994 was the decreased foliar Mn concentration for trees in limed plots. Mn concentration was 426 mg·kg^{-1} in 2006 compared with 1148 mg·kg^{-1} in 1994.

Black cherry foliage chemistry reflected similar responses to lime treatment. Both Ca and Mg concentrations in limed trees were almost double those from unlimed trees (Table 4). As with sugar maple, foliar Mn concentrations were reduced in limed black cherry foliage compared with foliage from unlimed trees. There were no significant differences in foliar P, K, Al, Fe, and N concentrations for black cherry in limed and unlimed plots in 2006, but Fe and Al concentrations were reduced in foliage from limed plots in 1994. Both Mn and N concentrations were marginally reduced in foliage from limed plots in 1994, but Mn shows a significantly reduced concentration, 627 mg·kg^{-1}, in 2006 for black cherry.

Discussion

Growth and vigor responses

The long-term impact of a single 22.4 Mg·ha^{-1} application of dolomitic lime remained evident after 23 years in these four northern hardwood stands in north-central Pennsylvania. Major effects of the lime treatment were the sustained increase in sugar maple BAINC in limed plots compared with unlimed plots and the more recent detection of a negative growth response of black cherry to lime application. American beech growth was unaffected by lime treatment. These results were obtained in a large plot (0.20 ha) experiment us-

Table 4. Sugar maple and black cherry mean foliage element concentrations (in mg·kg^{-1} (standard error)) and *t* test probability levels for comparisons based on means from each block in limed and unlimed plots in 2006 and 1994.

	Sugar maple[a]			Black cherry[b]		
Element	No Lime	Lime	*t* test *P* level	No Lime	Lime	*t* test *P* level
2006[c]						
Ca	3 913 (191)	9 519 (549)	<0.001	4 952 (72.7)	8 485 (354)	0.010
Mg	646 (39)	2 855 (113)	<0.001	2 279 (1.7)	4 688 (359)	0.094
P	1 140 (61)	1 268 (119)	0.373	1 380 (19)	1 420 (27)	0.343
K	7 657 (204)	6 133 (93)	<0.001	11 821(1038)	8 226 (753)	0.107
Al	38.3 (1.2)	29.7 (1.1)	0.002	26.6 (3.0)	30.2 (4.1)	0.560
Mn	2 946 (221)	426 (76)	<0.001	2 160 (70)	627 (77)	0.005
Fe	58.6 (3.6)	43.8 (1.0)	0.008	53.4 (0.9)	50.9 (0.8)	0.175
N	19 329 (356)	18 906 (172)	0.326	23 979 (585)	21 972 (372)	0.101
1994[d]						
Ca	4 031 (208)	8 777 (474)	0.002	5 734 (78)	8 768 (256)	0.008
Mg	617 (61)	2 655 (151)	0.001	1 924 (38)	3 873 (307)	0.024
P	1 058 (50)	1 361 (156)	0.188	1 453 (42)	1 414 (79)	0.706
K	7 136 (261)	4 811 (231)	0.036	13 759 (877)	10 186 (692)	0.086
Al	38.4 (1.5)	25.4 (0.9)	0.004	28.1 (3.1)	27.3 (1.0)	0.815
Mn	2 548 (218)	1 148 (88)	0.002	2 100 (334)	629 (208)	0.065
Fe	59.3 (3.3)	45.9 (1.4)	0.009	60.6 (0.9)	55.6 (1.6)	0.113
N	16 005 (302)	15 584 (685)	0.598	25 260(1020)	21 421 (179)	0.066

[a] For all sugar maple *t* tests, $n = 4$.

[b] For all black cherry *t* tests, $n = 2$.

[c] For sugar maple, 33 trees were sampled in unlimed plots and 37 in limed plots; for black cherry, 33 trees were sampled in unlimed plots and 31 in limed plots.

[d] For sugar maple, 27 trees were sampled in unlimed and limed plots for a total of 54 trees; for black cherry, 20 trees were sampled in unlimed plots and 15 in limed plots.

ing 49–169 trees per block and are supported by a regional study of untreated stands showing that sugar maple BAINC was less on sites with low base cation nutrition (based on foliar analyses in the 1990s) starting in the 1970s compared with sites having adequate base cation nutrition (Long et al. 2009). Conversely, black cherry growth in the regional study was greater on low base cation sites compared with higher base cation nutrient sites (Long et al. 2009). These results corroborate the responses observed in our long-term liming study.

Average sugar maple BAINC has remained greater for limed trees compared with unlimed trees over 23 years. Growth for limed trees since 2004 has averaged >40 cm^2·year^{-1}, a large increase over values observed in the first 8 years of the study when BAINC averaged 12.7 cm^2·year^{-1} for limed trees (Fig. 2). Similar growth results were observed in Quebec over 10 years, where sugar maple BAINC averaged 14.0 cm^2·year^{-1} for limed trees treated with up to 50 tonnes·ha^{-1} of dolomitic lime, whereas unlimed trees had mean BAINC of 5.4 cm^2·year^{-1} (Moore and Ouimet 2006). However, the increased growth in the Quebec study was not sustained; it peaked in 1999 at about 22 cm^2·year^{-1} and then decreased to about 12 cm^2·year^{-1} in 2004, the last year that data were evaluated. The reason for the difference in results is unclear. That overall growth rates were not as great in Quebec as those observed in Pennsylvania may be explained by differences in stand age and density, site, and climatic and, perhaps, genetic factors.

Sugar maple trees in limed plots have maintained elevated BAINC despite the background of disturbance events that could negatively impact growth (Fig. 1). The droughts of both 1988 and 1991 affected growth, as did the defoliations in 1993 and 1994. Subsequent droughts in 1999 and 2001 were not as severe as the 1991 drought, and no additional defoliations occurred through 2008. As stresses have abated to some degree, both limed and unlimed trees have sustained BAINC increases, though at a much higher level in limed trees.

American beech BAINC was unaffected by lime applications, but results may be obscured by the effects of beech bark disease. However, black cherry BAINC was negatively impacted by lime applications. The negative effect of lime on growth was not evident in earlier analyses and may be related to longer-term nutrient imbalances caused by lime application. This result must be interpreted cautiously as black cherry was analyzed on only two of the four blocks, BDR1 and CS4, because of the small number of trees on BDR2 and CS3 (four remaining black cherry trees on each block). Black cherry mean BAINC on unlimed plots was 33.4 cm^2·year^{-1}, or 32% greater than mean BAINC of limed trees, 25.3 cm^2·year^{-1}. However, black cherry BAINC response in this study is consistent with that in Long et al. (2009) based on native differences in site quality.

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

Sugar maple mean crown vigor was the first variable to respond positively to lime application in the 1990s, despite the drought and defoliation events during that period (Figs. 1 and 3). Mean sugar maple crown vigor index was significantly improved (lower crown vigor index) from 1990 to 1999 for trees on limed plots compared with trees on unlimed plots. Although limed trees have had healthier crown vigor since 1999, the pairwise comparison with unlimed trees showed that the differences are not statistically significant (Fig. 3). Similar crown vigor may reflect, in part, the absence of a major defoliation of sugar maple since 1994 and an improvement in the carbohydrate status of unlimed trees. The rating system (Mader and Thompson 1969) used since the beginning of the study and the stress history and gradual aging of the stands also provide partial explanations. Under the Mader and Thompson rating system, any tree with two or three dead branches (dead branch must be 0.9 to 1.2 m long) was rated as vigor index 4. As all trees have aged and acquired injuries from drought, defoliation, ice, and wind, most now meet these criteria.

Mortality

Mortality patterns for all three overstory species show that the greatest rate of mortality occurred from 1988 to 2001, when multiple droughts and defoliations occurred (Fig. 4). Starting in 2000, the mortality rate leveled off for sugar maple and American beech in both limed and unlimed plots, but increased abruptly in 2006 for black cherry in limed plots (Fig. 4). Reasons for this increase are not evident but may be related to the drought conditions (mean June–July PDSI = –1.31) that prevailed in 2005.

Beech bark disease has caused American beech mortality to be more than 30% (unadjusted) in both limed and unlimed plots during the course of the study (Fig. 4). Sugar maple mortality also is more than 30% on unlimed plots but is substantially lower (14%) on limed plots. Mortality of black cherry remains the lowest of the three overstory species, with unlimed plots having the lowest mortality (6.1%) over the 23 years of the study, whereas mortality on limed plots was 21.2%.

Earlier research conducted in all 32 plots of this study showed that liming increased the frequency and abundance of *Armillaria* rhizomorphs in soils and dead wood of sugar maple, beech, birch (*Betula* spp.), and black cherry (Marçais and Wargo 2000). However, liming also increased the vigor of sugar maple by increasing starch reserves and decreasing levels of stress-indicating polyamines and soluble sugars, perhaps making sugar maple more resilient and black cherry less resilient to fungal activity (Wargo et al. 2002). Black cherry has been shown to grow less on high base cation sites than on low base cation sites (Long et al. 2009).

Foliage chemistry

Foliar chemistry may provide some insights into the differential behavior of sugar maple and black cherry in response to liming. The effects of liming on sugar maple foliage chemistry remained apparent in 2006, when the last samples were taken, 21 years after lime application. Increased foliar concentrations of Ca and Mg and reduced concentrations of Al and Mn were maintained for sugar maple foliage from limed trees. Foliar Ca concentrations for limed sugar maple, 21 years after lime application, were 9519 mg·kg^{-1}, similar to those reported from Quebec for sugar maple limed at 20 Mg·ha^{-1} (foliar Ca = 9424 mg·ha^{-1}) 10 years after lime application (Moore and Ouimet 2006). Similarly, foliar Mg was 3178 mg·kg^{-1} for Quebec sugar maple compared with 2855 mg·kg^{-1} in our study (Table 4).

Foliar Ca–Al ratios (Ca:Al) have been proposed as a measure of acidification stress on trees, though Al is not well transported to foliage of sugar maple (Cronan and Grigal 1995; Marschner 1995). In our study, foliar Al was significantly lower in sugar maple foliage from limed plots in both sampling periods (Table 4). However, molar Ca:Al calculated from the foliar concentrations were well above (generally > 60) the foliar Ca:Al threshold of 12.5 proposed by Cronan and Grigal (1995). Research at Hubbard Brook Experimental Forest in New Hampshire also showed that root tissue Ca:Al (1.3 to 4.6) were well above proposed threshold of 0.1 to 0.2 (Cronan and Grigal 1995; Juice et al. 2006).

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

For black cherry, high foliar Mn levels may not have negative effects. Controlled studies with seedlings grown in sand culture showed that treatment with elevated Mn (1000 μmol·L^{-1}) did not significantly affect CO_2 exchange, electron transport, chlorophyll *a* + *b* content, or total seedling biomass compared with controls grown with 5 μmol·L^{-1} Mn (St. Clair and Lynch 2005). However, sugar maple seedlings grown at the elevated Mn level had significantly less chlorophyll *a* + *b*, reduced CO_2 exchange, and a reduced electron transport rate but no significant reduction in total biomass compared with seedlings grown in the control treatment (St. Clair and Lynch 2005).

In addition to Ca, Mg, Mn, and Al, black cherry may be influenced by N and K. Black cherry foliar N and K levels were reduced by liming in both 1994 and 2006, though differences were not statistically significant. Black cherry is a high N demanding species (Auchmoody 1982). Based on fertilization studies with N–P–K additions in sapling black cherry stands, these reductions of N and P in limed plots may be sufficient to impact black cherry growth (Auchmoody 1982). Although no specific K requirement has been established for black cherry, the lowest foliar K level in untreated sapling stands was 9200 mg·kg^{-1}, which is 1000 mg·kg^{-1} higher than that observed in foliage from black cherry in limed plots. Similarly, the lowest N concentration from untreated sapling black cherry foliage was 24 300 mg·kg^{-1}, whereas black cherry foliage in our limed plots was about 22 000 mg·kg^{-1} in 1994 and 2006. Deficiencies of both N and K in limed plots may account for the reduced black cherry growth. Developing the optimal nutrient requirements for black cherry with compositional nutrient diagnosis or some other system could clarify this issue (Parent and Dafir

1992). Additional studies are needed to elucidate the differential effects of nutrition on growth of different species.

Sugar maple flower and seed crops

Lime treatment has increased the size, but not the frequency, of sugar maple flower and seed crops (Fig. 5). Flower and seed crops do not occur as frequently in northern Pennsylvania as in New England and the Lake States (Long et al. 1997). Seed crops rated as good or larger occurred about every three years in Wisconsin (Curtis 1959) and New Hampshire (Graber and Leak 1992). Based on a mean threshold value of 70% of the crown with flowers, limed trees produced significant flower crops in 1989, 1992, 2000, 2003, and 2006. Four of these five years followed a drought event (1988, 1991, 1999, and 2005) when the mean June–July PDSI was more negative than –1 (National Oceanic and Atmospheric Administration 2010). That 2003 does not fit this pattern is probably a limitation of the PDSI, which is calculated on an entire climate division (Pennsylvania climate division 10) and did not capture the dry conditions in Potter County during the 2002 growing season. The effect of lime on flower crop size is dramatic; however, seed crops were significantly larger in limed plots only in 1994, 1995, and 1999. Seed crops were more difficult to estimate and much more variable, making detection of treatment effects problematic. Forest inventory data have shown that between 1989 and 2004, the proportion of sugar maple in the 5 to 25 cm diameter classes in Pennsylvania decreased, suggesting recruitment failure for sugar maple (McWilliams et al. 2007). The lack of adequate seed production accounts, in part, for the poor recruitment of sugar maple in many parts of Pennsylvania.

Conclusions

Sugar maple health is affected by both nutritional and stress factors. The decline disease hypothesis of Manion (1991) proposes that decline results from interactions among specifically ordered, but interchangeable, factors. For sugar maple, we have previously shown that sugar maple health is related to interactions of base cation nutrition and stress events; however, all species do not respond in the same manner to these factors (Horsley et al. 2000). Long et al. (2009) proposed a model integrating these factors for sugar maple. American beech, however, does not appear responsive to base cation nutrition, and black cherry responds differently from sugar maple (Long et al. 1997, 2009).

These results show that a single application of 22.4 $\mathrm{Mg \cdot ha^{-1}}$ of dolomitic lime has had a sustained effect on sugar maple crown vigor, growth, and flower and seed production over 23 years. American beech has been unaffected by lime treatment, and black cherry growth and survival has been negatively impacted by lime treatment. These results highlight the importance of species-specific responses to lime application. Liming has been proposed to remediate acidic soil conditions and base cation depletion resulting from long-term inputs of atmospheric deposition (Mulhollem 2002; Sharpe and Voorhees 2006). Such treatments may benefit some species, have no effect on others, and have negative effects on still others. Only a small number of species common to the northern hardwood forest have been evaluated. Additional species and rates of liming should be studied before widespread liming is recommended.

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