Canadian Science Publishing

ARTICLE

Thirty-year effects of liming on soil and foliage chemistry and growth of northern hardwoods in Pennsylvania, USA

Robert P. Long, Scott W. Bailey, Stephen B. Horsley, and Thomas J. Hall

Abstract: The longevity of a single 22.4 Mg·ha^{-1} application of dolomitic limestone at four northern hardwood stands was evaluated over 30 years (1986–2016) to determine whether changes in soils, foliage, and tree growth were sustained on the unglaciated Allegheny Plateau in northern Pennsylvania, USA. In limed plots, soils, sampled to 45–55 cm depth, and sugar maple (*Acer saccharum* Marsh.) and black cherry (*Prunus serotina* Ehrh.) foliage had significantly ($P \leq 0.05$) greater concentrations of calcium (Ca) and magnesium (Mg) through 2016 compared with samples from unlimed plots. Ca and Mg capitals (g·m^{-2}) in the Oi through A horizons combined were greater on limed plots than unlimed plots, largely due to increases in the thickness and nutrient concentration in the A horizon. Over 30 years, sugar maple basal area increment (cm^2·year^{-1} BAINC) was greater in limed plots (30.6 cm^2·year^{-1} vs unlimed 13.3), American beech (*Fagus grandifolia* Ehrh.) BAINC was unaffected by lime application, and black cherry BAINC was reduced in limed plots compared with unlimed plots. The sustained effect of this one-time lime treatment shows the strong role of efficient nutrient cycling in forests and suggests that the benefits over a substantial portion of a stand rotation may increase the feasibility of operational liming.

Key words: forest liming, base cations, exchangeable calcium (Ca) and magnesium (Mg), percent carbon (C) and nitrogen (N), basal area increment, sugar maple, American beech, black cherry.

Résumé : La longévité d'une application unique de 22,4 Mg·ha^{-1} de calcaire dolomitique dans quatre peuplements de feuillus nordiques situés dans la partie non glacière du plateau des Alleghany dans le nord de la Pennsylvanie, aux États-Unis, a été évaluée sur une période de 30 ans (1986–2016) pour déterminer si les changements dans le sol, le feuillage et la croissance des arbres ont persisté. Dans les parcelles qui avaient été chaulées, les sols échantillonnés jusqu'à une profondeur de 45–55 cm, ainsi que le feuillage de l'érable à sucre (*Acer saccharum* Marsh.) et du cerisier tardif (*Prunus serotina* Ehrh.), avaient des concentrations de calcium (Ca) et de magnésium (Mg) significativement plus élevées ($P \leq 0,05$) jusqu'en 2016 comparativement aux échantillons provenant de parcelles non chaulées. Les capitaux en Ca et Mg (g·m^{-2}) dans les horizons Oi à A combinés étaient plus élevés dans les parcelles chaulées que dans les parcelles non chaulées, surtout à cause de l'augmentation de l'épaisseur et de la concentration des nutriments dans l'horizon A. Sur 30 ans, l'accroissement de la surface terrière (AST cm^2·an^{-1}) de l'érable à sucre était plus élevé dans les parcelles chaulées (30,6 contre 13,3 cm^2·an^{-1} dans les parelles non chaulées). L'application de chaux n'a pas eu d'effet sur l'AST du hêtre d'Amérique (*Fagus grandifolia* Ehrh.) et a réduit l'AST du cerisier tardif dans les parcelles chaulées comparativement aux parcelles non chaulées. L'effet persistant de cette application unique de chaux illustre le rôle majeur du recyclage efficace des nutriments dans les forêts et indique que les bénéfices qui perdurent pendant une partie importante de la période de révolution d'un peuplement peuvent augmenter la faisabilité du chaulage opérationnel. [Traduit par la Rédaction]

Mots-clés : chaulage en forêt, cations basiques, calcium (Ca) et magnésium (Mg) échangeables, pourcentage de carbone (C) et d'azote (N), accroissement de la surface terrière, érable à sucre, hêtre d'Amérique, cerisier tardif.

Introduction

Forest liming is used to alter soil acidity, counter effects of long-term acidic inputs, and improve the growth and health of trees (Long et al. 2011; Court et al. 2018; Jansone et al. 2020). Liming has been used to improve aquatic habitats (George et al. 2018), accelerate nitrogen (N) mineralization in organic soils (Saarsalmi et al. 2011), accelerate soil recovery from acid deposition (Lawrence et al. 2016), and enhance wildlife habitat (Pabian and Brittingham 2007). Many forest soils on unglaciated landscapes in the northeastern United States (US) have limited supplies of base cations and long-term atmospheric inputs of acid-forming inorganic sulfur and N caused mobilization and losses of base cations essential to tree growth (Bailey et al. 2005). Because of sustained base cation losses, some species such as sugar maple (*Acer saccharum* Marsh.) became more vulnerable to inciting stressors such as drought and defoliation, resulting in extensive crown dieback and mortality across unglaciated portions of northern Pennsylvania (Horsley et al. 2000).

In 1985, the Pennsylvania Bureau of Forestry and USDA Forest Service, Northern Research Station, initiated a cooperative study to test whether a single application of dolomitic lime at a rate of 22.4 Mg·ha^{-1} could enhance woody regeneration and improve tree

Received 9 September 2021. Accepted 10 December 2021.

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growth and health in four northern hardwood stands (Auchmoody 1985; Long et al. 1997). Across the unglaciated regions of northern Pennsylvania, sugar maple decline and mortality became widespread in the late 1980s and 1990s (Horsley et al. 2000). As the decline became more prevalent, the emphasis of the study shifted to the health and growth of the principal overstory trees, sugar maple, American beech (*Fagus grandifolia* Ehrh.), and black cherry (*Prunus serotina* Ehrh.), and to an assessment of the longevity of the lime treatment as measured in forest floor organic layers, soils, foliage.

Analyses through 2008 showed that lime enhanced the growth and survival of sugar maple, had no effect on American beech, and had negative effects on growth and mortality of black cherry (Long et al. 2011). By 2006, mineral soil chemistry showed sustained increases in exchangeable calcium (Ca) and magnesium (Mg) concentrations, decreased exchangeable aluminum (Al), and increased pH in limed plots. Similarly, foliar samples from overstory sugar maple and black cherry showed elevated Ca and Mg in foliage from trees on limed plots compared with trees on control plots through 2006 (Long et al. 2015). A key question remains how long the observed effects of this one-time lime application will be sustained both in soils and foliage and in the growth and health of overstory trees. Few studies have examined liming impacts with consistent sampling and analyses over 30 years for a comprehensive assessment of short- and long-term effects.

Other studies have reported varying time frames associated with lime treatment longevity. In limed European beech (*Fagus sylvatica* L.) forests in France, exchangeable Ca and Mg in the upper 15 cm of mineral soil were elevated in the first decade following lime application, but this decreased substantially after 20–30 years (Court et al. 2018). In North America, various short-term (Ouimet and Fortin 1992; Wilmot et al. 1995; Juice et al. 2006; Moore and Ouimet 2010) and long-term (Long et al. 2011; Moore et al. 2012; Moore and Ouimet 2021) studies have evaluated the impact of liming or Ca-silicate additions on soils and vegetation with a primary focus on sugar maple and associated species. In a longer-term study, dolomitic lime applications at rates of 0–50 $Mg{\cdot}ha^{-1}$ in Quebec produced increased Ca and Mg in soil and foliage still evident after 20 years (Moore and Ouimet 2021).

Other research has focused on the effects of liming on carbon (C) and N stocks in forest organic layers and mineral soils (Melvin et al. 2013; Moore et al. 2012; Paradelo et al. 2015). However, these studies frequently show contradictory responses to liming with some finding increased C and N stocks in forest floor and soil horizons and others finding decreased C and N stocks. The mechanisms driving these diverse responses are not well established.

The objectives of the 2016 sampling were to assess the longevity of lime response in soils, foliage, and tree growth. Key questions to be addressed were how long and how deep in the soil profile will elevated Ca and Mg be detected; how long will elevated Ca and Mg be detectable in sugar maple and black cherry foliage; and will the enhanced growth and health of sugar maple be sustained? Additional objectives included evaluation of the forest floor organic layers (Oi, Oe, Oa) and A horizon mineral soils by quantitatively sampling these horizons to assess liming effects on thickness, mass, and nutrient content (elements $g{\cdot}m^{-2}$) with a focus on C and N storage.

Materials and methods

Study sites

The study area lies within the unglaciated Deep Valleys Section of the Appalachian Plateaus Province (Sevon 2000). The four replicates of this study are in the Susquehannock State Forest, Potter County, Pennsylvania. Two replicates are on Black Diamond Road (BDR1 and BDR2; elevation 677 m above sea level; 41°42′30″N, 78°01′30″W) and two replicates are near Cherry Springs State Park (CS3 and CS4; elevation 716 m above sea level; 41°39′15″N, 77°49′15″W). The climate is humid, temperate with annual precipitation averaging 1125 mm, daily temperature averaging 8.2 °C, and a growing season ranging from 91 to 120 days (Pennsylvania State Climatologist 2021).

Soil pits dug adjacent to the study sites in 1985 classified a number of soil series including Inceptisols (Calvin and Hazleton, Typic Dystrudepts) and Ultisols (Cookport, Aquic Fragiudult; Hartleton, Typic Hapludult; and Wharton, Aquic Hapludult) (Soil Survey Staff 2010). The soil parent materials at these sites are residuum derived from underlying sandstone, siltstone, and shale, and the mineralogy is dominated by quartz, illite, and kaolinite (Goodman et al. 1958; Aguilar and Arnold 1985). Physical limitations such as high stone content or shallow depth to bedrock or to a perched water table were not evident at these sites (Auchmoody and Walters 1992).

Treatments

Plots were laid out in 1985, and an inventory of all stems ≥2.5 cm diameter at breast height (1.37 m = DBH) was conducted. At each of the four sites, a replicate consisted of eight 45 m × 45 m (0.20 ha) measurement plots with a 15 m buffer around each plot — 60 m × 60 m. In fall 1985, when soils were dry, dolomitic lime was applied to the 45 m × 45 m measurement plots. Four of the eight plots received lime and four plots were untreated. The lime was commercial pulverized dolomitic limestone (Ca = 21%, Mg = 12%, Ca equivalent = 58.8) applied in single application via tractor at a rate of 22.4 $Mg{\cdot}ha^{-1}$. All four replicates were thinned to 50% relative density in winter 1985–1986 (Stout et al. 1987). Thinning removed small and poor-quality trees with two thirds of the removals from suppressed and intermediate crown classes and one third from canopy trees. Thinning objectives included maintaining similar species composition and structure along with adequate growing space in each replication. Black cherry – sugar maple stands develop as stratified stands with shade intolerant species like black cherry, white ash (*Fraxinus americana* L.), and yellow poplar (*Liriodendron tulipifera* L.) in the dominant crown positions while sugar maple, American beech, and eastern hemlock (*Tsuga canadensis* (L.) Carr.) are in codominant or subordinate crown positions. Across all four replications, sugar maple was the most evenly distributed species after thinning followed by American beech and black cherry. Additional stand history is in supplementary S1[1].

Soil sampling and analyses

Mineral soils were sampled by depth increments starting in 1986, 1 year post treatment, continuing at irregular intervals through 2016. We report the soil chemistry results at decadal intervals, 1986, 1996, 2006, and 2016, and summarize the changes over 30 years. There were six permanently marked sample points in a rectangular 22.5 m × 11.3 m grid in the center of each plot. Sample points were at the four corners and the two mid-points on the longest sides of the rectangle. Samples were taken systematically at various distances and azimuths from each sample point to ensure each sample was from an area undisturbed by prior sampling. The sampling protocol instructed samplers to remove the organic matter and start sampling the mineral soil immediately beneath the organic layers. However, Oa and A horizons were generally thin and difficult to differentiate so that many samples started at the first clear break which was at the top of an E or B horizon. In 1986 and 1996, mineral soil samples were taken by 2.5 cm increments to a depth of 15 cm. In 2006 and 2016, samples were taken by 5 cm increments, 0–5, 5–10, and 10–15 cm. Starting in 2001 and continuing in 2006 and 2016 samples were also taken to deeper depths by 10 cm increments: 15–25, 25–35, 35–45, and 45–55 cm (only in 2006 and 2016 for this deepest

[1]Supplementary data are available with the article at https://doi.org/10.1139/cjfr-2021-0246.

sampled depth). Samples from the six sample points in a plot were composited by depth to provide six or seven sampled increments for each plot. For data analyses, the results of the 2.5 cm increment samples from 1986 and 1996 were averaged to provide data for 5 cm increments (0–5, 5–10, and 10–15 cm) (Long et al. 1997).

All soils were air-dried and sieved through a 2 mm screen. Soil samples were sent to the University of Minnesota Research Analytical Laboratory for chemical analyses. This laboratory performed analyses in all years. Soil pH was measured in a 1/1 (*v*/*v*) soil/deionized water mixture (Watson and Brown 1998). Exchangeable cations, Ca, Mg, and manganese (Mn) were measured by inductively coupled plasma spectroscopy (ICP) after extraction with 1 mol·L^{-1} NH_4OAc buffered at pH 7 (Fassel and Kniseley 1974; Dahlquist and Knoll 1978; Thomas 1982). Exchangeable Al concentrations were determined by ICP after extraction with 1 mol·L^{-1} KCl (Barnhisel and Bertsch 1982; Thomas 1982). For quality assurance and control, replicate samples were run every 17 to 20 samples and measurements all were within ±5% for the original measured value. For all 2016 soil samples, C and N content was determined by combustion on a Shimadzu TOCV and TNM-1 detector at the Forest Service Laboratory in Durham, NH. Duplicate runs were within ±5% of the original measured value for N and C content.

Quantitative forest floor and A horizon sampling

Upper soil horizons with higher organic content were added to the sampling in 2016 and sampled quantitatively by genetic horizon. These included the Oi (relatively undecomposed litter), Oe (partially decomposed fermentation layer), and Oa (well decomposed organic matter) horizons as well as the A horizon. Although the A horizon is technically considered to be a mineral horizon, the distinction between the Oa and A horizon is based on C content, with 20% C being the minimum for an Oa (Soil Survey Staff 2014), a boundary that is difficult to distinguish in the field, particularly on a pit face. Because our objective was to take a close look at organic matter dynamics, we chose more detailed methods of sampling forest floor organic layers and A horizon samples by placing a 10 cm × 10 cm frame over the soil surface and cutting a block down into the soil with a sharp knife at the same six points per plot used for sampling mineral soil horizons from small pits. Sampling ceased where the first B or E horizon was encountered, a boundary that was easy to distinguish and separate from the overlying A horizon. All of the material in each horizon within the 100 cm^2 sampling area was collected and the thickness of each horizon was measured to the nearest 0.5 cm. The presence of earthworms and charcoal was also recorded during this sampling.

The six Oi and Oe horizon samples (or less if the horizon was absent at any point) from each plot and each horizon were combined and oven-dried to constant mass at 65 °C. The oven dry weight was recorded, and the sample was ground in a Tecator Cyclotec mill (FOSS, Eden Prairie, MN). Subsamples were taken for standard elemental analyses (Ca, Mg, Al, and Mn) at the University of Minnesota Research Analytical Laboratory, St. Paul, MN, and for total C and N at the USDA Forest Service Durham, NH Laboratory. Samples were dry ashed at 485 °C and taken up in 20% HCl for analysis by ICP spectroscopy to determine total amounts (mg·kg^{-1}) of Ca, Mg, Al, and Mn (Munter and Grande 1981). Standard reference materials containing certified concentrations of elements from apple, spinach, citrus, or tomato leaves were supplied by the US National Institute of Standards and Testing (University of Minnesota Research Analytical Laboratory 2006). For QA/QC, replicate samples were run for every 12 to 15 measurements and were within ±5% of the original measured value.

The six Oa and A horizon samples (if present) from each plot were combined into one bulk sample for each horizon and air-dried. After drying, samples were sieved through a 2 mm screen. Each sample was weighed, and sub-samples were taken for chemical analyses including total C and N (USDA Forest Service Laboratory, Durham, NH) and pH and extractable cations at the University of Minnesota Research Analytical Laboratory, St. Paul, MN, using the same methods described above for mineral soils.

Foliage sampling and analyses

Overstory foliage sampling of sugar maple and black cherry was conducted in 1995, 2006, and 2016 by shooting mid-crown branches with a shotgun in early to mid-August. Foliage was not sampled in the first decade of the study. In each sample year, overstory trees (dominant and codominant crown classes) were randomly selected in a replicate from those that had healthy crowns with <10% fine twig dieback. The numbers of trees sampled varied each year: 1995 included 54 sugar maple and 35 black cherry trees, 2006 included 70 sugar maple and 64 black cherry trees, and 2016 included 94 sugar maple and 56 black cherry trees.

All foliage samples were oven-dried at 65 °C and ground in a Tecator Cyclotec mill (FOSS, Eden Prairie, MN). Samples were processed in different laboratories in different years. In 1995 and 2016, foliage samples were analyzed at the University of Minnesota Research Analytical Laboratory. The same methods used for Oi and Oe samples described above were used for foliage samples. Foliage samples from 2006 were analyzed at the Forest Service laboratory in Durham, NH, using microwave digestion (see Long et al. 2015 for detailed methods). In 2016, total foliar C and N were determined by combustion using the Shimadzu analyzer described previously. At the Forest Service's Durham Laboratory, National Institute of Standards and Technology, apple, peach, and pine foliage (NIST1515, NIST1547, and NIST1575A) reference samples were routinely measured along with project samples and yielded measured values within ±5% of certified or long-term average values.

Tree growth and mortality

In each plot, all trees were numbered and marked by scribe or paint at breast height (1.37 m = DBH) for consistent location of diameter measurements. Diameters were measured each fall from 1985 to 2016 except in 1991, 1992, 1994, and 1997. Annual diameter measurements were converted to basal area increments with the following equation:

$$\text{BAINC}\,(\text{cm}^2) = \pi\left(R_t^2 - R_{t-1}^2\right)$$

where R is the tree radius and t is the year of tree-ring formation. Tree mortality was also tallied each year to assess annual and cumulative mortality.

Statistical methods

Mineral soils

The study design is a nested randomized complete block with repeated measures. Statistical analyses were conducted with SAS 9.4 using PROC GLIMMIX (SAS Institute Inc. 2012). We used the restricted or pseudo maximum likelihood technique and the Kenward–Roger correction method for the denominator degrees of freedom (Littell et al. 2006). All analyses focused on exchangeable concentrations of Ca, Mg, Al, and Mn, and acidity (pH). Normality of the data was assessed, and alternative distributions were used when appropriate. We used the distribution which best fit the data and produced results that met model assumptions.

For the upper mineral soil horizons sampled by depth (0–5, 5–10, 10–15 cm) with data from all 4 years (1986, 1996, 2006, and 2016), the fixed effects were lime treatment, depth, and year and their interactions. Replicate was treated as a random effect. Covariance structures used for these models were the autoregressive order 1 [AR(1)] and the AR(1) with heterogeneous variance structures [ARH(1)]. The Tukey–Kramer multiple comparison method was used for pairwise comparisons of lime vs unlimed means by year and for comparisons between years. The conservative Tukey–Kramer multiple comparison method adjusts for all possible pairwise comparisons. Similar methods were used to evaluate soils sampled at deeper depths (15–25, 25–35, 35–45, 45–55 cm) in 2001, 2006, and 2016. The 45 to 55 cm depth was sampled only in 2006 and 2016. Because the sampling intervals were unevenly spaced, the spatial power [SP(POW)] covariance structure was used for these analyses.

Forest floor and A horizon analyses

Quantitative forest floor samples (Oi, Oe, Oa, and A horizons) were analyzed as a nested randomized complete block design. For the Oi and Oe horizons, lime treatment effects on thickness, mass, and total elemental concentrations of Ca, Mg, Al, Mn, N, and C in these horizons were evaluated in models with lime treatment as a fixed effect and replicate and plot nested in lime treatment as a random effect. For Oa and A horizons, the same model was used to determine lime treatment effects on horizon thickness and mass and on exchangeable concentrations of Ca, Mg, Al, and Mn, and total N and C. Acidity, measured as pH, and extractable cations were evaluated for Oa and A horizons. Because inherent differences among these genetic horizons may yield insight into nutrient retention processes, all analyses were conducted separately for each horizon.

To better understand where nutrients are stored in the forest floor and A horizons, measured element concentrations were multiplied by horizon mass per 100 cm^2 to express the data as an element capital ($g \cdot m^{-2}$) of Ca, Mg, Al, Mn, N, and C. Oi and Oe horizons were analyzed through total digestion because decomposition is the primary process making metal cations available in these horizons, which turnover rapidly. Oa and A horizons were analyzed through salt extraction because cation exchange on longer lived organic exchange sites is the primary process making metal cations available in these horizons. Together, the total metal cation concentrations in the Oi and Oe horizons and exchangeable metal cations in the Oa and A horizons approximate the readily available supplies. The sum of each element stored in all four horizons was calculated and similarly analyzed.

Foliage

Similar methods using SAS PROC GLIMMIX (SAS Institute Inc. 2012) were used to analyze foliar element concentrations (Ca, Mg, Al, Mn, N) in samples from 1995, 2006, and 2016. For these analyses, the fixed effects were lime and year and the lime × year interaction with replicate as the random effect. Separate analyses were used for sugar maple and black cherry. Because of uneven distribution of black cherry, samples were available only from the BDR1 and CS4 replicates, since there were too few black cherry in the other two replicates.

Tree growth and mortality

For the tree growth analyses, DBH measurements were converted to annual basal area increments (BAINC, $cm^2 \cdot year^{-1}$). The initial basal area from 1985 diameter measurements was used as a covariate when significant and all annual data were used except in years trees were not measured: 1991, 1992, 1994, and 1997. The data were analyzed as a nested randomized complete block with repeated measures using methods like those described above for soils analyses (SAS 9.4; SAS Institute Inc. 2012). All models tested the fixed effects of lime, year, and the lime × year interaction with replicate as the random effect. The Tukey–Kramer multiple comparison method with adjusted probabilities for all pairwise comparisons was used to compare BAINC means between limed and unlimed plots for each year (Littell et al. 2006).

Annual mortality was recorded each year. Cumulative mortality by the end of the 2016 growing season was assessed using PROC GENMOD (Flynn 1999; SAS Institute Inc. 2012). Lime treatment, replication and their interaction were independent variables used to predict cumulative mortality with Poisson regression analyses using log-linear models.

Results and discussion

Mineral soils

The 30-year results from this study confirm the sustained impact of the one-time 22.4 $Mg \cdot ha^{-1}$ dolomitic lime application in these four northern hardwood forest stands. In mineral soils, exchangeable Ca and Mg were significantly ($P \leq 0.05$) elevated through the soil profile to a depth of 45–55 cm in limed plots (Fig. 1). In limed plots, exchangeable Ca showed a pattern of increased concentrations through 2016 at all three sample depths (0–5, 5–10, and 10–15 cm). By 2016, exchangeable Ca in the upper 5 cm averaged 0.5 $cmol_c \cdot kg^{-1}$ in unlimed plots and 11.4 $cmol_c \cdot kg^{-1}$ in limed plots. In the upper 5 cm of limed plots, exchangeable Ca concentrations increased, peaking in 2006 and showing a slight but non-significant ($P = 0.99$) decline by 2016. Exchangeable Mg in limed plots showed a similar pattern in the upper 5 cm, with a significant ($P \leq 0.01$) decrease in 2016 — 5.4 $cmol_c \cdot kg^{-1}$ compared with 8.4 $cmol_c \cdot kg^{-1}$ in 2006. In limed plots only, exchangeable Mg concentrations decreased slightly but non-significantly in the 5–10 cm ($P = 0.99$) and 10–15 cm ($P = 0.89$) depths in 2016 compared to 2006 concentrations in limed plots.

Comparisons with other North American studies show similar trends, but these studies lack the longevity of our study. In soils, long-term responses to liming show exchangeable Ca and Mg were variable and are affected by different site histories, parent materials, and historical deposition rates. Fifteen-year results at the Lake Clair Watershed study in Quebec show that a liming rate of 20 $Mg \cdot ha^{-1}$ produced exchangeable Ca of 3.9 $cmol_c \cdot kg^{-1}$ and Mg concentrations of 4.8 $cmol_c \cdot kg^{-1}$ in the upper 10 cm of mineral soil (Moore et al. 2012). At Hubbard Brook Experimental Forest in New Hampshire, 1028 $kg \cdot ha^{-1}$ (0.41 Mg $Ca \cdot ha^{-1}$) of pelletized wollastonite ($CaSiO_3$) was applied in 1999 and monitored over 11 years (Johnson et al. 2014). There was a progressive downward migration of Ca, but exchangeable Ca in the upper 10 cm of mineral soil peaked in 2006 at about 3 $cmol_c \cdot kg^{-1}$, just 7 years after application (Johnson et al. 2014). The lower application rate compared with our study and the slower dissolution of Ca-silicate versus carbonate minerals may account for this small increase and early peak. European studies show similar outcomes with greater Ca and Mg concentrations in the upper 15 cm of mineral soils in limed plots for the first 15 years post-liming but no detectable differences thereafter (Court et al. 2018).

In the Woods Lake watershed liming study, $CaCO_3$ was applied at the rate of 6.89 $tons \cdot ha^{-1}$ (2.76 Mg $Ca \cdot ha^{-1}$) (Melvin et al. 2013). After 19 years, exchangeable Ca was significantly ($P < 0.01$) elevated through the soil profile to a depth of 40 cm, but most of the exchangeable Ca was in the Oe and Oa layers (Melvin et al. 2013). At the 5 cm depth, exchangeable Ca was about 2 $cmol_c \cdot kg^{-1}$ in limed catchments compared with about 0.6 $cmol_c \cdot kg^{-1}$ in control catchments. The longevity of this response also is supported by increased foliar Ca in litter that averaged about 1.6% in limed catchments compared with 0.9% in the controls.

Soil acidity also was affected by lime treatment. In our study, by 2016 soil pH in the upper 5 cm was 3.7 in unlimed plots and was significantly greater, 6.2, in limed plots (Fig. 1). Soil pH was significantly greater in limed plots compared with unlimed plots at 5–10 and 10–15 cm depths starting in 1996 and continuing to 2016. Both exchangeable Al and Mn decreased significantly in limed plots compared with unlimed plots, though pair-wise comparisons were not significant at all depths and in all sample years (Fig. 1).

Starting in 2001, we assessed changes at greater depths by sampling additional 10 cm increments to 45 cm (15–25, 25–35, and 35–45 cm), and then in 2006 and 2016 samples also were obtained from the 45–55 cm depth (Fig. 2). Exchangeable Ca and Mg showed sustained increases in concentration in limed plots through the soil profile as deep as 45–55 cm with significant ($P \leq 0.05$) pair-wise differences between limed and unlimed plots at all sampled

Fig. 1. Least squares means and standard errors from repeated measures analysis of lime treatment effects on soil exchangeable Ca, Mg, Al, Mn, and pH sampled in 1986, 1996, 2006, and 2016 in the upper 15 cm of mineral soil (0–5, 5–10, 10–15 cm). Tukey–Kramer pairwise comparisons with significant ($P \leq 0.05$) differences between lime and no lime treatments are noted by an asterisk (*).

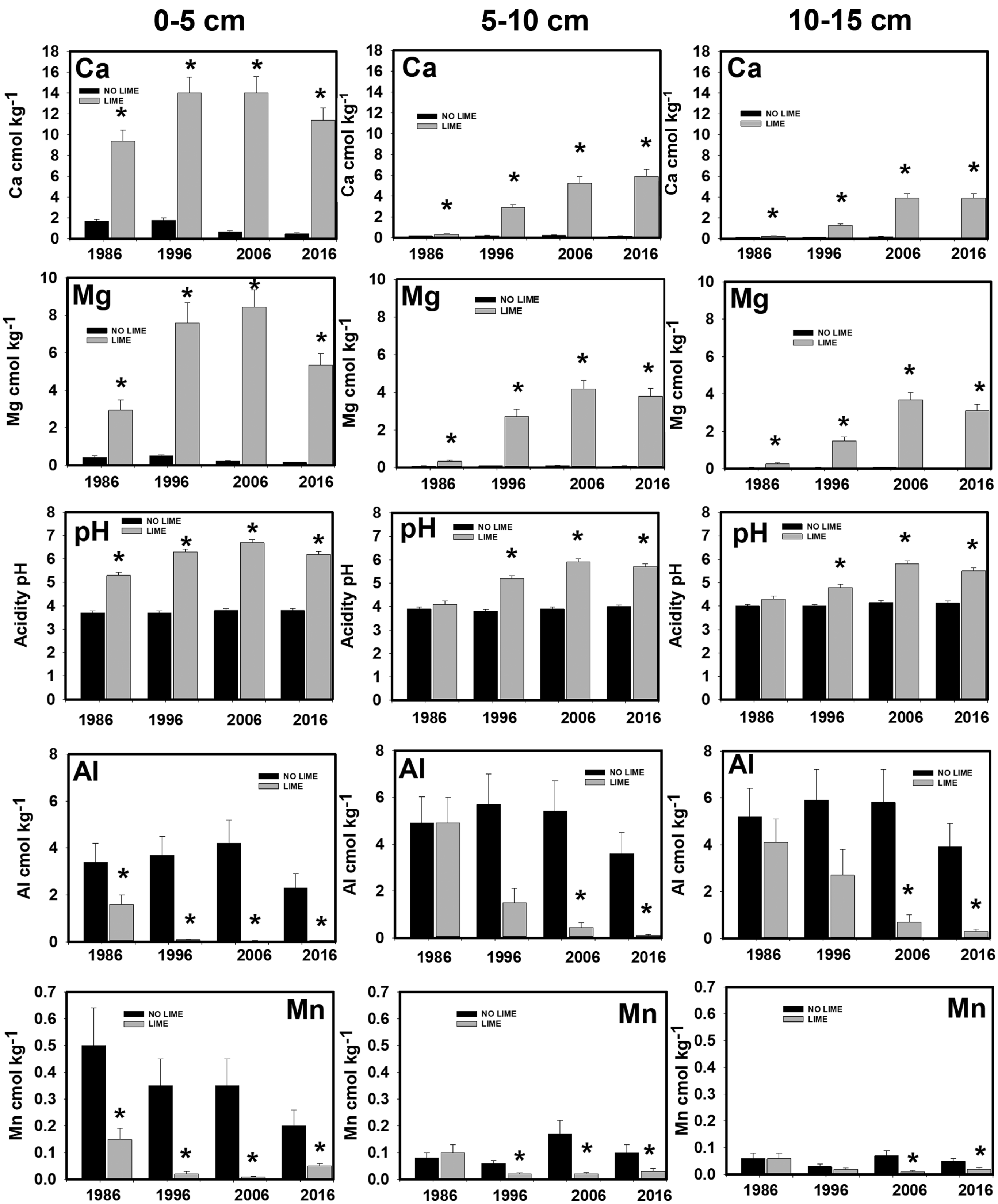
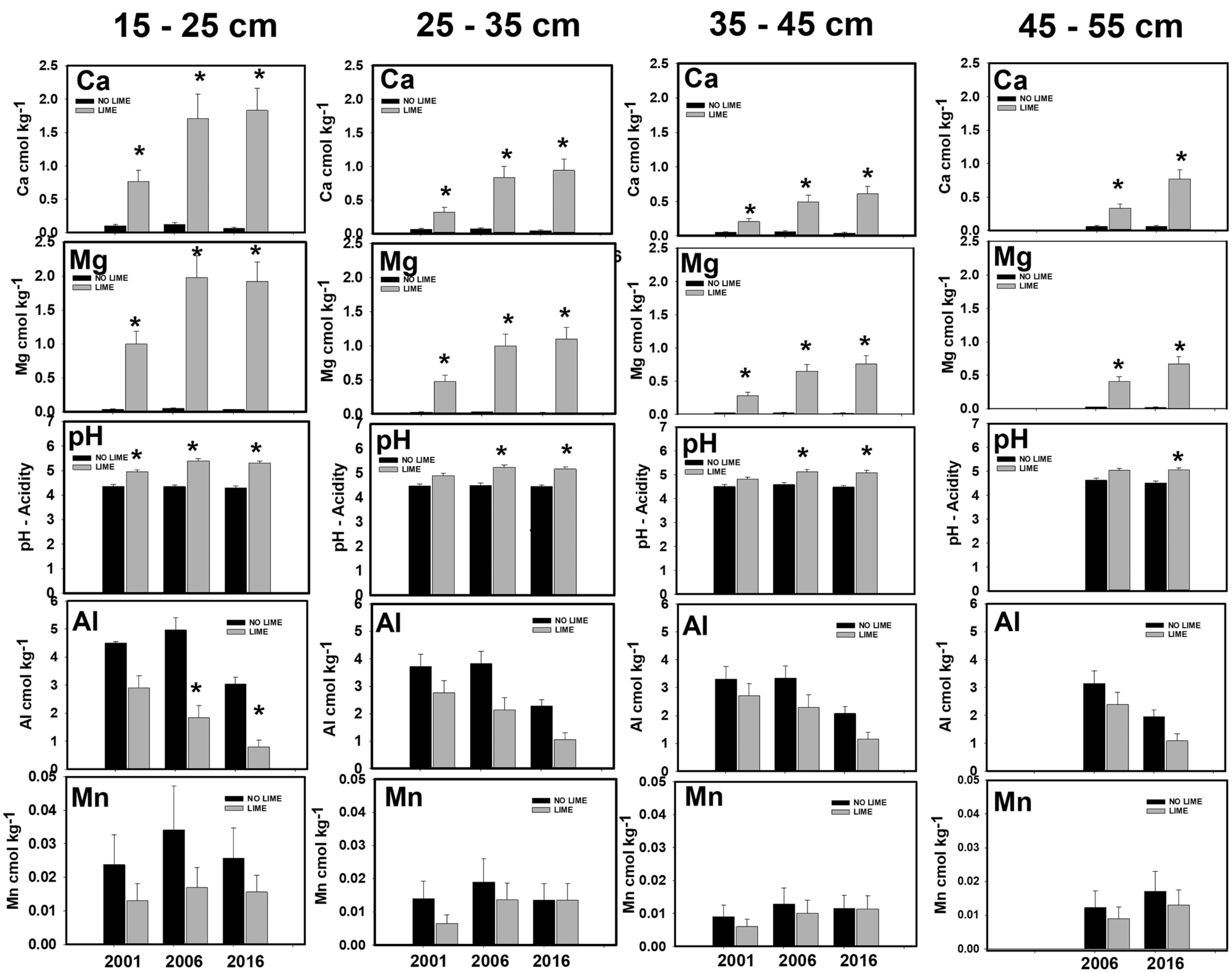


Fig. 2. Least squares means and standard errors from repeated measures analysis of lime treatment effects on exchangeable Ca, Mg, Al, Mn, and pH in deeper horizons (15–25, 25–35, 35–45, and 45–55 cm) sampled in 2001, 2006, and 2016. Tukey–Kramer pairwise comparisons with significant ($P \leq 0.05$) differences between lime and no lime treatments are noted by an asterisk (*).



depths (Fig. 2). Exchangeable Mg showed a similar pattern of increasing concentration as deep as 45–55 cm. Changes in pH in these deeper horizons in limed vs unlimed plots have not been as great or as consistent, but in 2016 pH increased to 4.63 in limed plots. Exchangeable Al showed a pattern of reduced concentrations in limed plots, but not all differences were significant. For exchangeable Mn, there were no significant lime effects at these deeper horizons through 2016.

Examining the trajectory of soil nutrient concentrations gives insights into the longevity of this lime treatment and some indication of future trends. Exchangeable Ca and Mg concentrations have increased through the soil profile to 45–55 cm and continued to increase through 2016. The upper 15 cm of mineral soils have more stable concentrations of Ca and Mg, but the deeper horizons show continued increases. We expect these increased concentrations to be maintained. Soil pH was consistently greater in limed plots and peaked in 2006 at 6.7 in the upper 0–5 cm layer. At deeper layers, pH has stabilized at about 5.0 in limed plots and 4 to 4.5 in unlimed plots. Exchangeable Al and Mn were significantly reduced in limed plots, but these changes were only significant in the upper 15 cm (Mn) or 25 cm (Al) of mineral soil. Al and Mn have decreased in deeper horizons, but differences with control plots were not significant.

In 2016, total C and N concentrations were determined in all mineral soils sampled by depth increments. N concentration was 0.14% in limed plots and was significantly ($P < 0.01$) greater than 0.10% in unlimed plots (Fig. 3). Carbon concentration was 2.1% in soils from limed plots, significantly greater ($P < 0.01$) than 1.7% in unlimed plots. Carbon concentration varied with depth and lime treatment, but depth was not significant ($P = 0.60$), which supports that sampling started at the top of E and B horizons and that A horizons were not included in the pit samples. These results show that liming increases concentrations of C and N through the soil profile to a depth of 45–55 cm. Total C and N concentrations were only measured in soils in 2016, so there are no earlier data to provide comparisons or to contrast trajectories on limed vs unlimed plots.

Forest floor organic and A horizons

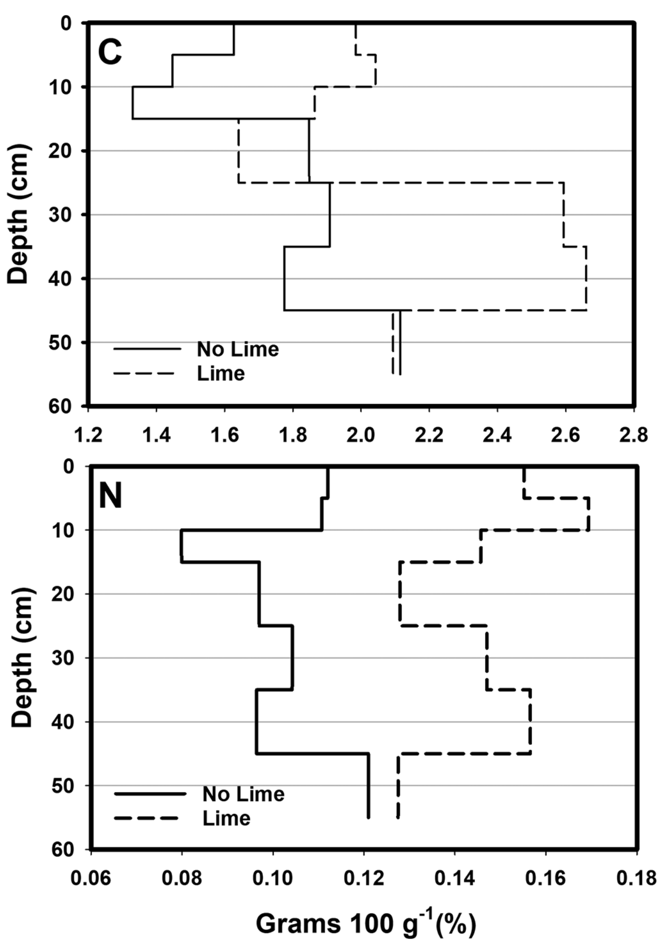
Lime treated plots had greater thickness and mass of Oi, Oe, and Oa horizons although these differences were not statistically significant (Table 1). However, lime treatment significantly increased the thickness and mass of the A horizons (Table 1). A horizons from

Table 1. Least squares means (standard errors) in no lime (NL) and limed (L) plots for thickness, mass per area, and total elemental concentrations of Ca, Mg, Al, Mn, and %N and %C in Oi and Oe layers and for exchangeable concentrations of Ca, Mg, Al, and Mn, and acidity (pH) and total concentrations of %N and %C in each horizon along with the probability (*P*) that the means are significantly different.

	Oi[a]		Oe[a]		Oa[b]		A[b]	
	No lime	Lime	No lime	Lime	No lime	Lime	No lime	Lime
Thickness (cm)	0.99 (0.11)	1.28 (0.14)	0.73 (0.08)	0.95 (0.08)	1.26 (0.18)	1.50 (0.24)	1.75 (0.24)	3.13 (0.42)
NL vs L	$P = 0.053$		$P = 0.070$		$P = 0.447$		$P = 0.005$	
Mass (g·100 cm^{-2})	7.34 (0.51)	8.54 (0.54)	6.6 (0.97)	7.60 (1.24)	29.9 (8.6)	28.6 (8.9)	96.3 (18.6)	182.1 (35.5)
NL vs L	$P = 0.122$		$P = 0.535$		$P = 0.909$		$P = 0.016$	
Ca	9282 (521)	16829 (945)	5388 (956)	11376 (2270)	5.1 (0.8)	31.0 (5.2)	1.9 (1.8)	18.3 (1.8)
NL vs L	$P < 0.001$		$P = 0.019$		$P < 0.001$		$P < 0.001$	
Mg	1059 (121)	2786 (316)	724 (159)	2270 (564)	1.2 (0.2)	13.4 (1.9)	0.5 (0.09)	7.2 (1.5)
NL vs L	$P < 0.001$		$P = 0.006$		$P < 0.001$		$P < 0.001$	
Al	647 (1170	1027 (187)	2099 (358)	2323 (502)	0.63 (0.27)	0.04 (0.02)	1.42 (0.34)	0.03 (0.010
NL vs L	$P = 0.083$		$P = 0.710$		$P = 0.001$		$P < 0.001$	
Mn	5591 (564)	1761 (177)	4784 (1315)	2196 (628)	1.27 (0.22)	0.81 (0.17)	0.38 (0.09)	0.17 (0.01)
NL vs L	$P < 0.001$		$P = 0.010$		$P = 0.139$		$P = 0.146$	
pH	NA		NA		3.73 (0.12)	4.86 (0.14)	3.63 (0.70)	5.99 (0.01)
NL vs L	NA		NA		$P < 0.001$		$P < 0.001$	
%N	1.73 (0.06)	1.54 (0.06)	2.07 (0.07)	1.81 (0.08)	18.6 (1.5)	16.8 (1.6)	7.1 (0.9)	6.3 (0.9)
NL vs L	$P = 0.027$		$P = 0.012$		$P = 0.371$		$P = 0.244$	
%C	48.99 (0.62)	45.72 (0.62)	43.89 (1.0)	40.54 (1.28)	32.8 (2.3)	34.4 (2.6)	11.9 (1.6)	10.5 (1.6)
NL vs L	$P < 0.001$		$P = 0.044$		$P = 0.605$		$P = 0.242$	

Note: *P* values of ≤0.05 indicate a significant difference between unlimed and limed plots.
[a]Oe and Oi concentrations of Ca, Mg, Al, and Mn are total elemental concentrations (mg·kg^{-1}).
[b]Oa and A concentrations of Ca, Mg, Al, and Mn are exchangeable concentrations (cmol$_c$·kg^{-1}).

Fig. 3. Total C and N concentrations (g·100 g^{-1}) in mineral soils sampled by depth increments in 2016 to a depth of 45–55 cm in limed and unlimed plots.



limed plots were almost 80% thicker (3.1 cm vs 1.8 cm) and almost twice the mass (182.1 g·100 cm^{-2} vs 96.3 g·100 cm^{-2}) of A horizons from unlimed plots. Ca and Mg concentrations (cmol$_c$·kg^{-1}) were significantly ($P \leq 0.05$) greater in limed plots for all four horizons. Total Al concentration was not significantly affected by lime treatment in Oi and Oe horizons, but exchangeable Al was reduced significantly in Oa and A horizons by liming. Exchangeable Mn was not affected by liming in the Oa and A horizons, but total Mn concentration was significantly reduced in Oi and Oe horizons (Table 1). For Oi and Oe horizons, total %N and %C concentrations were significantly greater in samples from unlimed plots compared with limed plots. Similar increased total %N and %C concentrations were found in unlimed plots for Oa and A horizons, but none of these differences were statistically significant (Table 1). All Oa horizon samples had >20% C concentrations while all A horizon samples had <20% C indicating that they were properly designated in the field.

To estimate storage on a mass per area basis (g·m^{-2}), element capital means were determined (Table 2). There was significantly more Ca and Mg in all horizons from limed plots compared with unlimed plots. Also, Al and Mn in the Oi and Oe were greater in unlimed plots than limed plots on a concentration and mass per area basis. Al concentration was significantly reduced in limed plots in the Oa and A horizons while Mn concentrations and mass were not significantly different between limed and unlimed plots in the Oa and A horizons. Total mass per unit area of N and C in unlimed and limed plots was not significantly different in Oi and Oe horizons, contrary to their patterns based on concentrations (Tables 1 and 2). Both N and C mass in A horizons from limed plots were significantly greater than mass in unlimed plots (Table 2), while concentrations did not differ significantly.

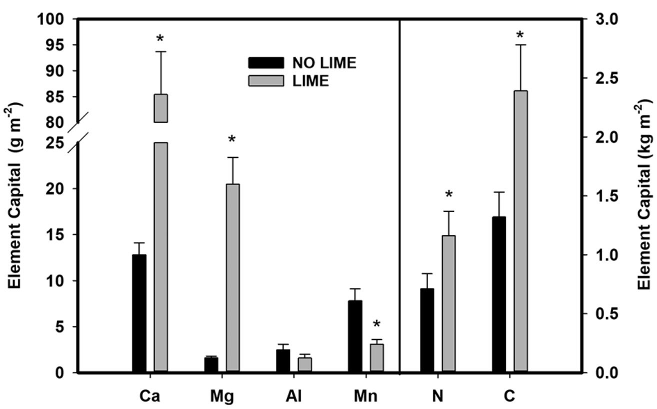
Mean mass (g·m^{-2}) of elements stored when all four layers (digestible concentrations in Oi and Oe and exchangeable concentrations in Oa and A horizons) were summed highlight major differences (Fig. 4). Limed plots had significantly ($P \leq 0.05$) greater amounts of Ca, Mg, N, and C than observed in unlimed plots. The large differences in N and C amounts between unlimed and limed plots are driven by amounts sequestered in the A horizon from limed plots (Table 2). Total mass of Al and Mn were reduced in limed plots compared with unlimed plots. On a total mass per

Table 2. Least squares means (standard errors) in no lime (NL) and limed (L) plots for total element capital of Ca, Mg, Mn, Al, N, and C in Oi, Oe, Oa, and A horizons along with the probability (*P*) that the means are significantly different.

	Oi (*N* = 32)		Oe (*N* = 26)		Oa (*N* = 21)		A (*N* = 32)	
Element	No lime	Lime	No lime	Lime	No lime	Lime	No lime	Lime
Ca ($g \cdot m^{-2}$)	6.60 (0.66)	15.0 (0.68)	1.5 (0.3)	6.5 (1.0)	1.09 (0.50)	5.23 (2.52)	2.24 (0.49)	58.9 (12.7)
NL vs L	$P < 0.001$		$P = 0.033$		$P = 0.007$		$P < 0.001$	
Mg ($g \cdot m^{-2}$)	0.73 (0.06)	2.51 (0.21)	0.16 (0.28)	1.40 (0.22)	0.16 (0.07)	1.36 (0.65)	0.39 (0.08)	15.33 (3.38)
NL vs L	$P < 0.001$		$P = 0.028$		$P = 0.002$		$P < 0.001$	
Al ($g \cdot m^{-2}$)	0.47 (0.10)	0.88 (0.19)	0.99 (0.12)	1.25 (0.23)	0.056 (0.044)	0.003 (0.002)	0.86 (0.27)	0.05 (0.02)
NL vs L	$P = 0.102$		$P = 0.253$		$P = 0.008$		$P < 0.001$	
Mn ($g \cdot m^{-2}$)	4.43 (0.53)	1.38 (0.17)	1.93 (0.44)	1.12 (0.45)	0.63 (0.19)	0.16 (0.21)	0.72 (0.24)	0.79 (0.26)
NL vs L	$P < 0.001$		$P = 0.016$		$P = 0.052$		$P = 0.704$	
N ($g \cdot m^{-2}$)	13.0 (0.83)	12.9 (0.83)	7.1 (1.9)	7.7 (1.8)	310.5 (77.6)	126.2 (82.3)	451.9 (79.4)	1050.7 (182.1)
NL vs L	$P = 0.958$		$P = 0.709$		$P = 0.031$		$P < 0.001$	
C ($g \cdot m^{-2}$)	359.4 (25.7)	385.1 (27.2)	149.2 (44.1)	178.7 (39.1)	533.6 (129.1)	305.8 (140.8)	759.8 (110.2)	1741.8 (246.1)
NL vs L	$P = 0.481$		$P = 0.514$		$P = 0.161$		$P < 0.001$	

Note: *P* values of ≤0.05 indicate a significant difference between unlimed and limed plots.

Fig. 4. Least squares means of total element mass ($g \cdot m^{-2}$) of Ca, Mg, Al, and Mn, and total mass ($kg \cdot m^{-2}$) of C and N in Oi, Oe, Oa, and A horizons quantitatively sampled in 2016. Asterisks (*) indicate a significant ($P \le 0.05$) difference between limed and unlimed plots.



square meter basis for Oi, Oe, Oa, and A horizons, Ca mass in limed plots was 6 times greater, 85.4 $g \cdot m^{-2}$, compared with Ca in unlimed plots, 12.8 $g \cdot m^{-2}$ (Fig. 4). Magnesium mass in limed plots was more than 12 times greater, 20.5 $g \cdot m^{-2}$, compared with unlimed plots, 1.6 $g \cdot m^{-2}$. This suggests that even after 30 years, elevated Ca and Mg are being cycled through foliage back into the forest floor, with low amounts of leaching losses, thus maintaining elevated levels. This process will likely continue.

In limed plots, quantitative forest floor sampling showed an increase in the A horizon thickness that is notable since this part of the soil profile has the highest root density, with likely effects on tree nutrition. This suggests a mechanism whereby the efficient recycling by vegetation is acting to conserve nutrients on the limed plots. While liming affected A horizon thickness, a similar effect has been attributed to decreased acid deposition from 1997 to 2017 (Bailey et al. 2021). The Bailey et al. (2021) study in unmanaged forest stands on the Allegheny National Forest, found signs of soil recovery from acid deposition with increased Ca and Mg concentrations in the Oa and A horizons, decreased Al concentrations and increased thickness of the Oa and A horizons over a 20-year interval (1997–2017). In the present study, the forest floor and A horizons were only sampled in 2016. Thus, we cannot compare trajectories on limed and unlimed plots to see how native recovery from acidification by itself may have affected the differences noted between treatments.

Long-term changes of C and N storage were not an early focus of our study, but 2016 sampling allows some assessment of potential treatment effects and comparisons with other studies. For example, the Woods Lake Watershed liming study found forest floor C and N stocks were greater in limed catchments compared with controls in the Oe and Oa horizons (Melvin et al. 2013). We found no significant differences in %C concentrations in limed plots compared with unlimed plots (Table 1) and no significant differences based on C and N mass per area (Table 2). In our study, A horizon concentrations of C and N were not significantly different between unlimed and limed plots. However, on a mass basis, limed plots had more than twice as much N and C due to increases in horizon thickness and mass (Table 2). In mineral soils sampled by depth, both %C and %N showed significantly greater concentrations in limed plots in 2016. This contrasts with the Woods Lake results that found no significant lime effects on C and N concentrations in mineral soils (Melvin et al. 2013).

Melvin et al. (2013) concluded that liming reduced decomposition rates leading to increased C and N stocks in forest floor organic layers. We found no evidence of this effect in our study. Our study, with different vegetation, on unglaciated soils, and over longer time (30 years) provides a sharp contrast. From our quantitative forest floor sampling mineral soil, A horizons showed a dramatic lime effect being significantly thicker and with greater mass and Ca and Mg concentration in limed plots compared with unlimed plot samples, and significantly greater mass of N and C stored in this horizon (Table 2). The Melvin et al. (2013) study found Oa horizons more commonly in the Adirondacks while in our study Oa horizons were identified in only 21 of the 32 plots with 14 Oa horizons in unlimed plots and 7 in limed plots. In the Adirondacks, the soils were dominantly Spodosols, where Oa horizons are generally thicker and directly overlay an E or B horizons, providing a sharper break in C content at the base of the O horizons. In our study, in a warmer climate than the Adirondacks and with Inceptisols and Ultisols, the break between the O horizons and mineral soils is less distinct, with Oa and A horizons commonly both present and representing a gradient in concentration of well decomposed organic matter mixing with mineral matter.

The presence of earthworms also was noted during forest floor sampling. Of the 192 sampling points only five points yielded a total of six earthworms. These were all at the BDR1 replicate in plots 1, 2, 5, and 6. All of these plots received the lime treatment. No other earthworms were found and, in general, the low pH of soils in this study suggests that earthworm activity is likely to be limited (Ross et al. 2021). Charcoal was found in two samples from two plots in the CS4 replication suggesting some but limited evidence for past fires (see supplementary material S1[1] for details of land use history). Earthworm activity and fire history

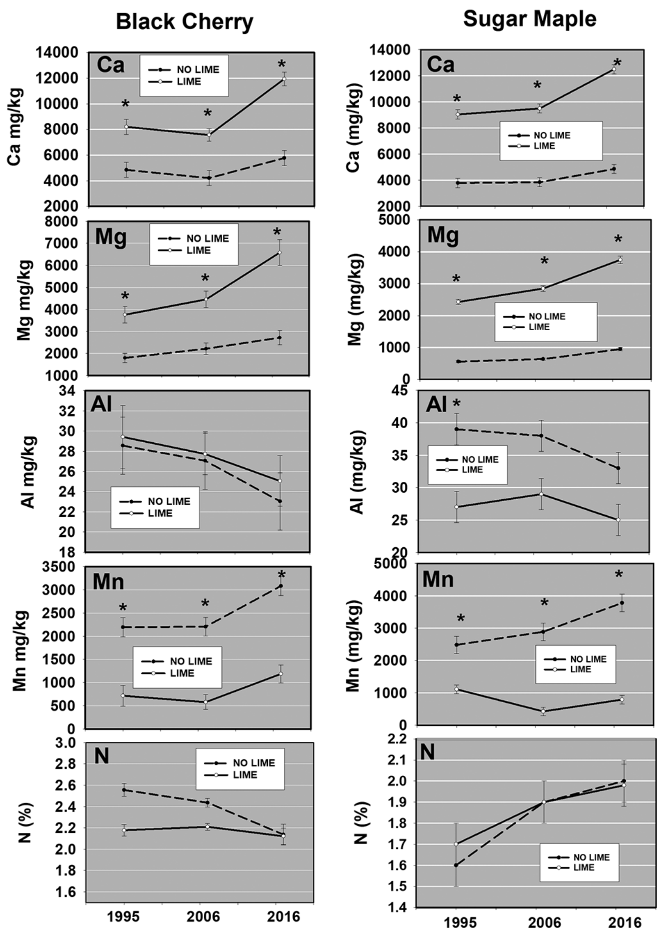


Fig. 5. Black cherry and sugar maple foliar concentrations of Ca, Mg, Al, Mn, and N from samples taken in 1995, 2006, and 2016. Tukey–Kramer pairwise comparisons with significant ($P \leq 0.05$) differences between lime and no lime treatments are noted by an asterisk (*).

do not appear to play a major role in the soil differences we observed between limed and unlimed plots.

Foliage chemistry

Overstory foliage of sugar maple and black cherry was not sampled until 1995, 9 years after the start of the study. Starting in 1995 and continuing in 2006 and 2016, sugar maple foliar nutrients displayed the sustained effect of the one-time lime application (Fig. 5). Both Ca and Mg concentrations in sugar maple foliage from limed plots were significantly ($P < 0.01$) greater in 2016 compared with foliage from unlimed plots (Fig. 5). Both Ca and Mg show continued upward concentration trends through 2016 in trees from limed plots. Foliar Al in limed plots was significantly reduced in foliage from unlimed plots in 1995, but not in 2006 or 2016. Foliar Mn concentrations were significantly greater in unlimed plots compared with limed plots in all three sample years showing reduced Mn availability in limed plots. Foliar N concentrations show a trend of increasing concentrations in trees from limed and unlimed plots and no significant lime treatment effects. These were the major differences observed in foliar nutrients and other nutrients such as phosphorus and potassium showed no response to liming.

In other long-term liming studies, foliar nutrients, primarily Ca and Mg, show a long-lasting effect of liming. In Quebec, at the

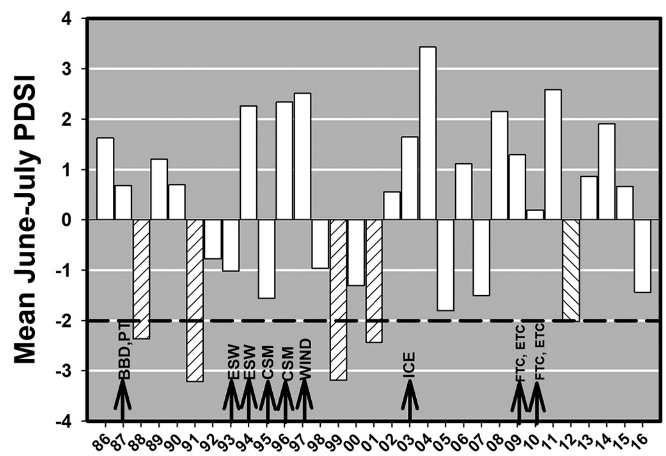


Fig. 6. Disturbance diagram showing drought (mean June–July Palmer Drought Severity Index (PDSI) for Pennsylvania climate division 10), disease (BBD, beech bark disease), defoliation (PT, pear thrips; ESW, elm spanworm; CSM, cherry scallop shell moth; FTC, forest tent caterpillar; ETC, eastern tent caterpillar), and wind and ice events affecting the study plots. The broken horizontal line at −2 is the threshold for moderate drought and includes the cross-hatched bars in 1988, 1991, 1999, 2001, and 2012.

Duchesnay Experimental Forest, the 20 $t \cdot ha^{-1}$ lime treatment sustained increased foliar Ca and Mg 20 years post-treatment (Moore and Ouimet 2021). In France, beech (*Fagus sylvatica* L.) foliage had greater concentrations of Ca and Mg 25 years after a 7 $Mg \cdot ha^{-1}$ lime application (Forey et al. 2015) and other research found similar responses after 40 years using variable liming rates (Court et al. 2018).

Black cherry foliage chemistry showed some similar patterns to sugar maple foliage chemistry (Fig. 5 — note the Y-axis scales are different for most elements). Both Ca and Mg concentrations in black cherry were significantly greater in foliage from limed plots compared with unlimed plots in all sampled years. Foliar Mn concentrations were reduced significantly in limed plots compared with unlimed plots in all sampled years, the same pattern seen for sugar maple foliage. However, black cherry foliar Al was unaffected by lime treatments in all three sampled years. Black cherry foliar N showed a decreasing trend, opposite of sugar maple, and no significant lime treatment effect.

Stand structure, tree growth, and disturbance history

In the 30 years since the start of the study, stand composition of the initial cohort of trees has changed, with increased basal area per hectare, and a decrease in the percent of basal area with American beech, particularly in BDR1 and BDR2 replications (Table 3). About the time the study was initiated in 1985, beech bark disease became prevalent in these plots and beech mortality was first recorded in 1987. At the same time, there was a light defoliation from pear thrips (*Taeniothrips inconsequens* Uzel). Over the course of the study, many beech have died because of the disease complex — both scale insect infestation and infection by *Neonectria* fungi. Other major disturbances, including droughts and defoliations, also affected the growth and survival of overstory trees (Fig. 6). These include severe droughts early in the study in 1988 and 1991 and defoliations from elm spanworm (*Ennomos subsignarius* Hübner), forest tent caterpillar (*Malacosoma disstria* Hübner), and cherry scallop shell moth (*Hydria prunivorata* Ferguson). All of these disturbances influenced tree growth responses. See supplementary material S1[1] for a summary of stand and disturbance histories.

Sugar maple BAINC growth in limed plots, using Tukey–Kramer pairwise comparisons, did not become significantly different from trees in unlimed plots until 1995 (Fig. 7). The forest tent caterpillar

Table 3. Stand composition (excluding ingrowth) at the four replications in 1985 and 2016.

	Replication			
	BDR1	BDR2	CS3	CS4
Total basal area 1985, 2016 ($m^2 \cdot ha^{-1}$)	19.8, 20.6	11.0, 12.3	11.7, 14.8	17.0, 26.5
% Total basal area 1985, 2016				
Sugar maple	20, 27	35, 49	61, 64	32, 34
American beech	19, 9	42, 34	31, 31	6, 8
Black cherry	57, 62	7, 8	8, 5	56, 53
Other[a]	4, 3	16, 9	0, 0	5, 6
Diameter (cm)				
Sugar maple				
Mean diam. (range) 1985	34.6 (15–55)	26.2 (13–53)	34.2 (13–70)	23.0 (13–44)
Mean diam. (range) 2016	47.2 (32–74)	40.7 (20–70)	48.2 (18–91)	33.7 (15–59)
No. of trees 1985, 2016	65, 49	103, 70	112, 79	202, 149
American beech				
Mean diam. (range) 1985	40.0 (29–57)	27.6 (13–50)	32.2 (13–59)	18.3 (13–34)
Mean diam. (range) 2016	47.4 (38–65)	37.5 (22–53)	42.8 (24–75)	28.8 (17–51)
No. of trees 1985, 2016	47, 15	114, 58	64, 48	60, 49
Black cherry				
Mean diam. (range) 1985	47.8 (29–100)	54.0 (43–61)	55.1 (42–65)	40.0 (21–63)
Mean diam. (range) 2016	58.6 (36–115)	68.6 (59–72)	67.8 (61–74)	52.2 (29–77)
No. of trees 1985, 2016	97, 73	5, 4	6, 3	118, 102
Other[a]				
Mean diam. (range) 1985	33.4 (28–40)	35.1 (19–57)	—	33.4 (14–50)
Mean diam. (range) 2016	43.8 (36–48)	48.4 (34–62)	—	45.9 (17–62)
No. of trees 1985, 2016	15, 6	28, 9	—	16, 14

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

defoliations in 2009 and 2010 reduced the BAINC of sugar maple in both limed and unlimed plots, but trees in limed plots recovered quickly and were growing significantly greater by 2012 (Fig. 7). Sugar maple in limed plots continued to increase BAINC growth, peaking in 2015 at 50.7 $cm^2 \cdot year^{-1}$ compared with 18.2 $cm^2 \cdot year^{-1}$ in unlimed plots. Lime treatments had no significant effect on American beech BAINC growth (Table 4). Black cherry BAINC growth was significantly reduced by liming (Fig. 7). Pairwise comparisons with least squares means did not detect significant differences but averaged across all years there was a significant lime effect. Black cherry BAINC in limed plots averaged 22.8 $cm^2 \cdot year^{-1}$ compared with 27.5 $cm^2 \cdot year^{-1}$ in unlimed plots (Fig. 7; Table 4). The eastern tent caterpillar (*Malacosoma americanum* Fabricius) defoliations primarily affected black cherry from 2008 to 2010. These early season defoliations were evident in reduced growth of all three overstory species in 2009 and 2010 regardless of lime treatment.

The long-term differential growth responses of the three overstory species were unanticipated but consistent since the mid-1990s. The influence of exogenous disturbances such as droughts and defoliations moderated responses to lime treatments but allowed real time assessments of disturbance impacts. Drought events in 1988 and 1991 likely delayed any growth response to lime application. However, by 1995 sugar maple BAINC was significantly greater in limed plots. Heavy defoliation by forest tent caterpillar in 2009 and 2010, the most severe defoliations during the study, caused a major decrease in BAINC of sugar maple in limed and unlimed plots, but by 2012, sugar maple BAINC in limed plots had recovered quickly. The sustained 30-year effect of the lime treatment on sugar maple BAINC highlights the importance of base cation nutrition for sugar maple and is supported by other research linking base cation levels to sugar maple growth on both glaciated and unglaciated landscapes (Long et al. 2009).

Comparisons with growth responses in other studies are not straight-forward because of different stand and climatic conditions. At Duchesnay in Quebec, sugar maple BAINC over 19 years was 15 $cm^2 \cdot year^{-1}$ after a one-time treatment of 800 $kg \cdot ha^{-1}$ of calcitic lime ($CaCO_3$) in 1990 (Ouimet et al. 2017). In another study in the Duchesnay Experimental Forest, sugar maple BAINC peaked at about 25 $cm^2 \cdot year^{-1}$ five years after dolomitic lime application of 20 $Mg \cdot ha^{-1}$ and remained elevated over the entire 15-year study (Moore et al. 2012). At the 20-year post-treatment point, the 20 $Mg \cdot ha^{-1}$ treated trees had BAINC about 180% greater than in untreated trees (Moore and Ouimet 2021). Despite the defoliation disturbances that affected sugar maple BAINC in our study, the average 30-year BAINC in limed plots was 30.6 $cm^2 \cdot year^{-1}$, more than double the 13.3 $cm^2 \cdot year^{-1}$ BAINC in unlimed plots.

Table 4. Analysis of variance F test (probability levels) statistics for repeated measures models testing lime treatment effects on basal area increment, BAINC ($cm^2 \cdot year^{-1}$) of sugar maple, American beech, and black cherry from 1986 to 2016.

Species	Lime	Year	Lime × Year
Sugar maple	122.05 (<0.001)	18.6 (<0.001)	4.22 (<0.001)
American beech	1.66 (0.218)	11.06 (<0.001)	0.87 (0.643)
Black cherry	31.17 (<0.001)	12.74 (<0.001)	0.83 (0.678)

Mortality

Cumulative mortality of sugar maple in unlimed plots was 42.3% compared with just 14.9% in limed plots (Table 5; Fig. 8). From the late 1980s to about 2000, sugar maple mortality increased steeply in unlimed plots, then plateaued until the forest tent caterpillar defoliations in 2009 and 2010. Sugar maple mortality in limed plots has remained stable with only a slight increase from the most recent defoliations. Cumulative American beech mortality was not affected by lime treatment (P = 0.522) through 2016. There was a significant replication effect and most of the beech mortality occurred at BDR1 and BDR2. Cumulative black cherry mortality showed a significant ($P < 0.01$) negative effect of lime application (Table 5; Fig. 8). By 2016, black cherry mortality in limed plots was 30.4% compared with 8.7% in unlimed plots.

Fig. 7. Least squares means and standard errors of mean basal area increment (BAINC; $cm^2 \cdot year^{-1}$) for sugar maple, American beech, and black cherry from 1986 to 2016. Asterisks (*) indicate a significant ($P \leq 0.05$) pairwise difference based on the Tukey–Kramer adjustment for multiple comparisons. Pairwise comparisons were not significant for American beech or black cherry, but black cherry BAINC averaged across all time periods was 22.8 $cm^2 \cdot year^{-1}$ in limed plots significantly ($P < 0.001$) less than the BAINC of 27.5 $cm^2 \cdot year^{-1}$ in unlimed plots.

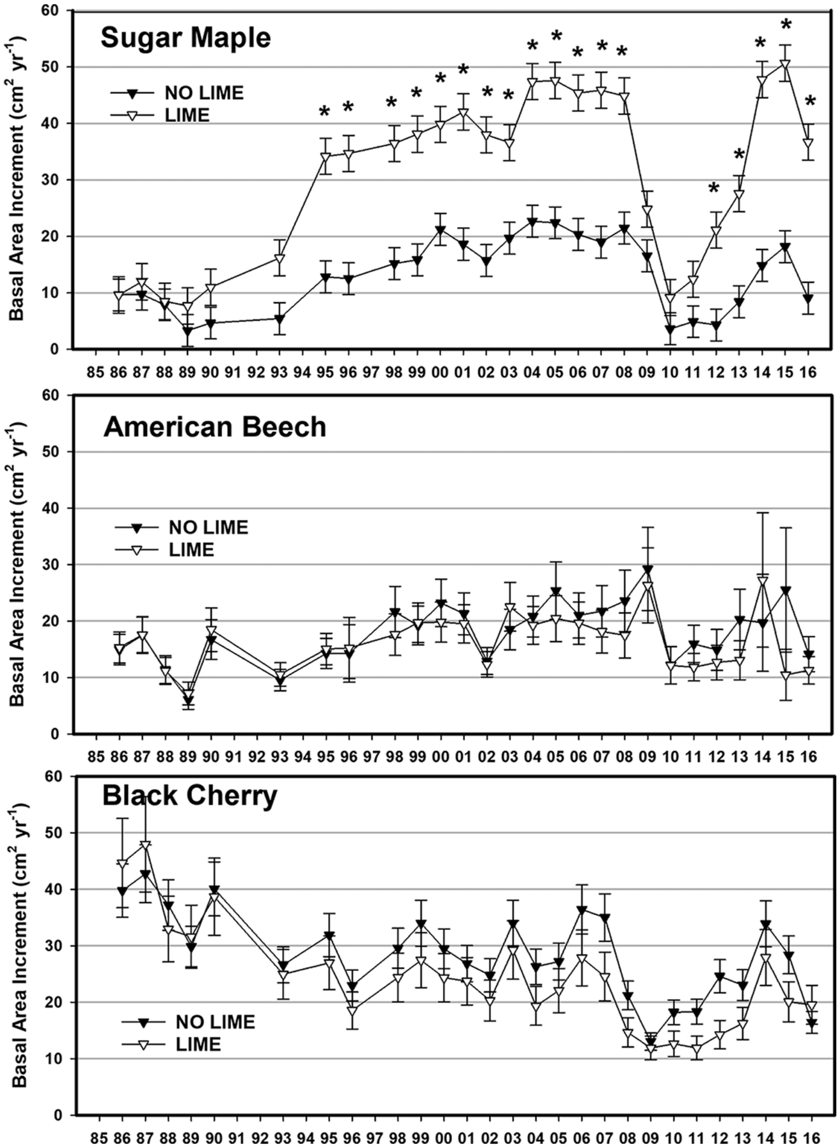


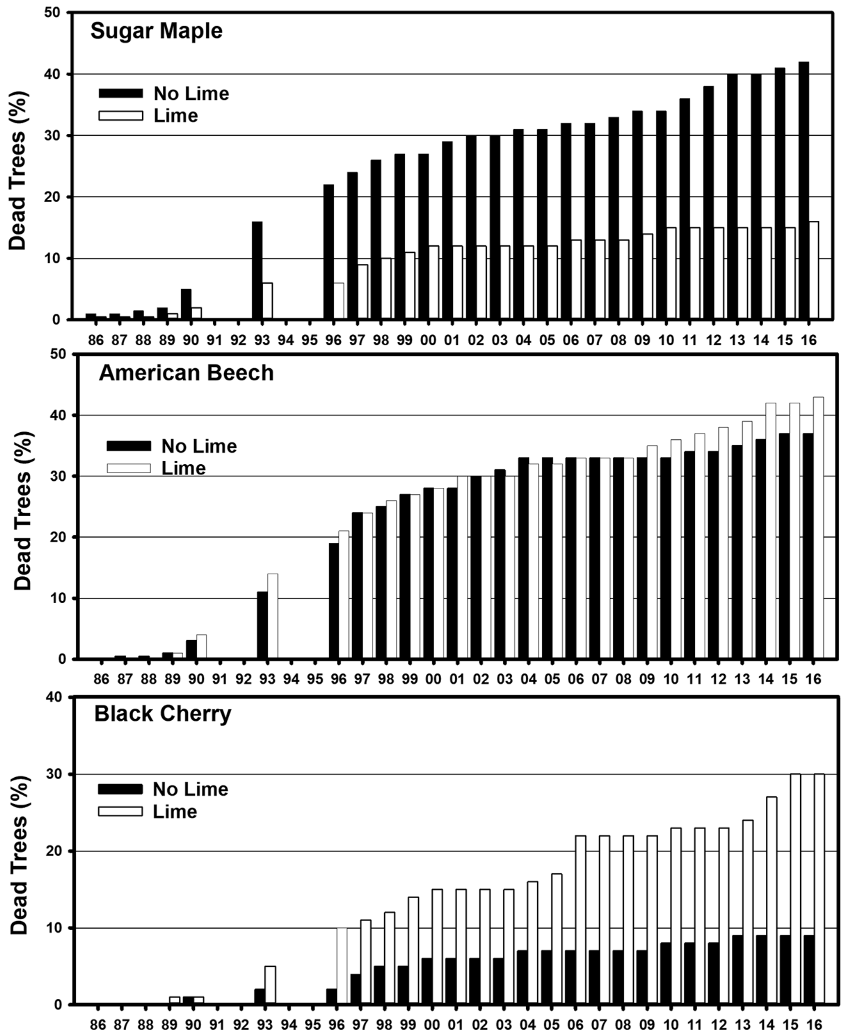
Table 5. Chi-square (χ^2) statistic, probability levels, and least squares means (standard error) of percentage mortality for Poisson regression analyses of cumulative mortality (1986–2016) in relation to lime treatment and replication for sugar maple, American beech, and black cherry.

	χ^2 (probability level)			% Mortality (S.E.)	
Species	Replication	Lime	Replication × Lime	Lime	No Lime
Sugar maple	1.39 (0.708)	26.77 (<0.001)	2.04 (0.565)	14.9 (2.9)	42.3 (4.7)
American beech	22.14 (<0.001)	0.03 (0.853)	0.42 (0.937)	35.5 (5.9)	34.1 (5.3)
Black cherry	4.37 (0.037)	14.79 (<0.001)	0.73 (0.394)	30.7 (5.8)	8.0 (2.7)

Liming and forest management

While liming has proved beneficial in many circumstances, the differential responses of the overstory species in our study suggest that attention to species composition and management objectives is necessary. Black cherry growth and mortality over 30 years showed a negative response to this large lime application. Notably, other factors are likely affecting black cherry including substantial decreases in amounts of nitrate nitrogen deposition (Royo et al. 2021). A lower liming rate may have benefitted sugar maple without having deleterious effects on black cherry.

Fig. 8. Cumulative mortality (number of dead trees, unadjusted, expressed as a percent) by year for sugar maple, American beech, and black cherry from 1986 to 2016.



Managers and researchers have applied lime to address a range of management objectives. In northern France, acid deposition impacts led to the liming studies in five pure beech stands (Court et al. 2018). Foliar levels of Ca and Mg were increased over 15 to 20 years post-liming, but concentrations decreased after this period though limed plots retained higher amounts of foliar Ca and Mg compared with controls (Court et al. 2018). In our study, foliar Ca and Mg continued to increase over 30 years in both sugar maple and black cherry foliage. With substantial decreases in acidic deposition in northeastern North America, a few areas are showing modest increases in Ca and (or) Mg in organic horizons and soils, indicative of recovery from acidic deposition (Bailey et al. 2021; Lawrence et al. 2021). Lime application could accelerate recovery in some circumstances (Lawrence et al. 2016).

Managers have implemented operational liming on the Monongahela National Forest, with aerial lime applications of 10 $Mg \cdot ha^{-1}$ to restore base cations on 323 ha with soils formed from the base-poor Pottsville formation and impacted by acidic deposition (USDA Forest Service 2011). Watershed liming has been shown to increase bird and snail abundance on two 100 ha forested watersheds in Pennsylvania (Pabian and Brittingham 2007; Pabian et al. 2012). Lime sand was applied at a rate of 4.5 $Mg \cdot ha^{-1}$ near Gifford Run in the Moshannon State Forest, and changes in bird and snail abundance persisted up to 5 years after lime treatment in the two replications of the study. In the Washington and Jefferson National Forests, an aquatic restoration project has focused on the Saint Mary's Wilderness, where seven streams were treated with 209 Mg of lime sand distributed over the streams to improve aquatic habitats in 1999, 2005, and 2013 (Lieberman et al. 2013). Water chemistry, brook trout numbers, and macroinvertebrate diversity all have improved from this lime treatment (Lieberman et al. 2013). While some risks are always present, watershed liming would increase Ca availability and prevent or decrease the mobilization of Al, helping both terrestrial and aquatic ecosystems. However, clear targets for restoration have not been established for many ecosystems and this should be considered carefully. Our study clearly shows that liming provided long-term nutrition necessary for the health and growth of sugar maple but had negative effects on black cherry.

Liming as a forest management tool may have different effects depending on the amount, form, and frequency of the application (Schaaf and Hüttl 2006). Differences in the composition of the liming materials, including particle size and purity may affect the solubility and the rapidity of the response in soils and vegetation. Climate and site factors such as the deposition history and management history may affect the response to a lime application. More thorough research should be conducted to determine optimal liming rates which will vary based on the soil chemistry, deposition history, and nutritional requirements of target species. Canadian researchers recommend liming rates of 1–3 Mg·ha^{-1} for sugar maple but also caution that liming may promote earthworm invasion (Moore et al. 2015). An important finding from our study is the need for long-term monitoring. In our work, some soil chemical parameters showed rapid changes (Long et al. 2015) but tree growth responses were not evident until 8 to 10 years post-treatment. In a number of studies, liming effects may not have been detected because monitoring was stopped before lime had time to alter soil chemistry and affect vegetation. In a meta-analysis of 350 trails, 27% were only monitored for 4 years or less, perhaps not detecting changes that could have become evident with monitoring over a longer time (Reid and Watmough 2014).

The sustained effect of this treatment over 30 years and trends indicating further improvements in nutrient cation concentrations and the development of the A horizon suggests that this could be an important management tool. It also suggests that the forest, absent major disturbances, and perhaps enhanced by lower levels of atmospheric acid deposition, has a strong ability to tightly conserve nutrient supplies in the rooting zone. And, where effects of a single treatment may last three decades or more, the economic feasibility of liming as a management tool may be more positive.

Acknowledgements

This cooperative study was initiated in 1985 by B. Towers (PA DCNR) and the late L. Auchmoody (USDA Forest Service). We gratefully acknowledge their foresight and careful design of this study. Dr. S. Stout, former Northern Research Station Project Leader, provided enduring support for maintaining the study through 2016. Many people provided critical assistance over the 30-year period, especially P. Lilja and other personnel from the Susquehannock State Forest. Key Forest Service support was provided by D. Saf, E. Wiltsie, J. Smithbauer, J. Hanson, G. Sanford, E. Baxter, and R. Garrison. We thank the Pennsylvania Bureau of Forestry for funding the 30-year sampling and for providing logistical support and field personnel. Field assistance in 2016 from: J. Altemus, G. Gilmore, W. Laubscher, R. Lusk, G. Peters, B. Regester, P. Smith, and T. Tomon is gratefully acknowledged. Data entry and laboratory analyses were provided by C. Weldon, J. Merriam, J. Hislop, and S. Auger. We gratefully acknowledge long-term invaluable advice and assistance from Forest Service Mathematical Statistician J. Stanovick. We thank Drs. D.S. Ross, M.B. Adams, and two anonymous reviewers for helpful reviews of earlier drafts of this manuscript.

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