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DIVISION S-7—FOREST & RANGE SOILS

Influence of Edaphic Factors on Sugar Maple Nutrition and Health on the Allegheny Plateau

S. W. Bailey,* S. B. Horsley, R. P. Long, and R. A. Hallett

ABSTRACT

Sugar maple (*Acer saccharum* Marsh.) decline has been a problem on the Allegheny Plateau for the last two decades. Previous work found that sugar maple is predisposed to decline by poor nutrition and incited to decline by severe insect defoliation. Nutritional diagnoses have been based on foliar chemistry; there is little information on soil attributes that influence susceptibility. We evaluated relationships among soil characteristics, foliar chemistry, and sugar maple decline for 43 stands on the Allegheny Plateau in New York and Pennsylvania using correlation and stepwise regression techniques. Foliar Ca and Mg concentrations correlated with soil exchangeable cations expressed on a concentration or site capital basis. Expression of base cation availability as a saturation value, or in ratio with Al, slightly improved the relationships, suggesting that antagonistic cations are important to sugar maple nutrition. The best predictions of foliar chemistry were made by regressions that considered soil chemistry across the depth of the B horizon, suggesting the importance of looking at more than one depth to assess nutrition. Landscape position and glacial history determined whether weathering products were effectively delivered to the rooting zone, resulting in the observed landscape gradients. All declining stands were on unglaciated upper landscape positions where soils had lower Ca and Mg levels compared with other landscape positions. Declining stands had <2% Ca saturation and <0.5% Mg saturation in the upper B and <4% Ca saturation and <0.6% Mg saturation in the lower B. These thresholds may be useful in predicting susceptibility to sugar maple decline.

The concept of tree decline addresses situations where dieback—the loss of a portion of the crown—or mortality cannot be attributed to a single agent. Manion (1991) defines decline as, "an interaction of interchangeable, specifically ordered abiotic and biotic factors to produce a gradual general deterioration, often ending in death of trees." Several factors, including mineral nutrition, insects, diseases, and climatic factors, may interact to produce the final outcome, and these factors may be different in different situations. Manion (1991) used the terms "predisposing," "inciting" (or "triggering"), and "contributing" to describe the factors involved in tree decline.

Declines of sugar maple have been noted throughout the twentieth century, though the 1957 episode in Florence County, Wisconsin was the first to receive systematic study (Giese et al., 1964; Westing, 1966; Millers et al., 1989). Since then, well-documented sugar maple declines have occurred in Massachusetts in the 1960s (Mader and Thompson, 1969), Ontario in the 1970s (Hendershot and Jones, 1989; Gross, 1991), Quebec, New York, and Vermont in the 1980s (Bernier and Brazeau, 1988a,b,c; Kelley, 1988; Bernier et al., 1989; Hendershot and Jones, 1989; Bauce and Allen, 1992; Cote et al., 1995; Ouimet and Camire, 1995; Wilmot et al., 1995), and Pennsylvania in the 1980s and 1990s (Kolb and McCormick, 1993; Long et al., 1997; Horsley et al., 2000). Stress events such as defoliations, droughts, and extreme weather events (late spring frosts, mid-winter thaw/freeze cycles) have been common themes in all of these declines.

Studies of sugar maple declines have suggested that poor nutrition of base cation elements, including Ca, Mg, and K, was a predisposing factor to decline (Mader and Thompson, 1969; Bernier and Brazeau, 1988a,b,c; Hendershot and Jones, 1989; Adams and Hutchinson, 1992; Kolb and McCormick, 1993; Cote et al., 1995; Wilmot et al., 1995; Long et al., 1997; Horsley et al., 2000). Evidence for this assertion is based primarily on chemical analysis of foliage and surficial (<10 cm) soils from declining and nondeclining stands containing dominant and codominant sugar maple trees. Little research has been conducted on aspects of site quality such as the contribution of deeper soil horizons, the role of physiographic position or history of pedon development in the landscape on sugar maple nutrition or the relationship between soil nutrition and sugar maple health (or growth). Due to its location at the boundary of the Wisconsin glacial advances of 12 000 to 21 000 yr ago on the northern Allegheny Plateau in western Pennsylvania and New York, the most recent decline of sugar maple in Pennsylvania provides an opportunity for insight into these questions.

In the early to mid 1980s, forest land managers in the northwestern and north central Pennsylvania portions of the Allegheny Plateau began to notice unusual levels of crown dieback and mortality of sugar maple in stands on unglaciated sites on upper slopes above about 550 m elevation; stands on lower slopes did not decline (Kolb and McCormick, 1993; Horsley et al., 2000). Affected areas lay just south of the terminal moraine of the Wisconsin glacial incursions. Unglaciated sites typically have highly weathered Ultisols with low base saturation,

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Abbreviations: defsev10, defoliation severity index; PDEADSM, percentage of dead sugar maple basal area.

whereas soils on glaciated portions of the Plateau are typically Inceptisols and may have higher base saturation. There have been few reports of sugar maple decline in stands on glaciated sites in western Pennsylvania and New York (Drohan et al., 1999; Drohan et al., 2002), though declines have been significant in glaciated areas of northeastern Pennsylvania (Hall et al., 1999). The sugar maple decline in Pennsylvania occurred against a background of unusual defoliations and climatic stresses (droughts, killing late spring frosts) (McWilliams et al., 1996; Kolb and McCormick, 1993). Working at four high elevation unglaciated sites in northwestern and north central Pennsylvania, Kolb and McCormick (1993) found that foliar concentrations of Ca and Mg were well below, and Mn was well above, those of presumably healthy trees observed by other researchers and reported in the literature.

Long et al. (1997) confirmed the potential role of Ca, Mg, and Mn in sugar maple decline. In a study beginning in 1985 at four high-elevation (677–716 m), unglaciated sites in north central Pennsylvania near those investigated by Kolb and McCormick (1993), dolomitic limestone was applied to the soil surface at the rate of 22.4 Mg ha $^{-1}$. Liming increased soil pH and exchangeable Ca and Mg in the upper horizons (15 cm), while exchangeable Al and Mn decreased. Increases in levels of Ca and Mg and decreases in Al and Mn were also reflected in sugar maple foliar chemistry. After a lag of 3 to 8 yr, there were statistically significant increases in survival, crown vigor, diameter, and basal area growth, and flower and seed crop production for sugar maple on limed compared with unlimed areas. There was no survival, crown vigor, or diameter and basal area growth response to treatment for American beech (*Fagus grandifolia* Ehrh.) or black cherry (*Prunus serotina* Ehrh.). Foliar N concentrations were similar in limed and unlimed plots, suggesting that potential increased available N due to higher pH, was not a factor in the tree response.

The dramatic species-specific effects of lime on sugar maple in Pennsylvania prompted further investigation to determine the distribution of Ca, Mg, Al, and Mn in the landscape (Horsley et al., 2000). In 1995 and 1996, 43 stands were located along topographic gradients at 19 sites on glaciated and unglaciated portions of the Allegheny Plateau in northwestern and north central Pennsylvania and southwestern New York. Sites were selected to represent the range of sugar maple health conditions across a greater than 18 000 km^2 portion of the Allegheny Plateau. Sites were stratified by glaciation and topographic position and represent the range of soils and geology in the region. Health of dominant and codominant sugar maple trees, foliar chemistry, defoliation and management history, and stand characteristics were evaluated in each stand. Using the percentage of dead sugar maple basal area as the measure of health, the most important factors associated with sugar maple health were foliar concentration of Mg and Mn and defoliation history. Declining stands had less than ~700 mg kg $^{-1}$ Mg, greater than ~2000 mg kg $^{-1}$ Mn, and two or more moderate to heavy defoliations in the 10 yr preceding health evaluation. All moderately to severely declining stands were located on the upper slopes of unglaciated sites in summit, shoulder, or upper backslope physiographic positions. The lowest foliar Mg, highest foliar Mn, and the highest number and severity of defoliations were associated with these physiographic positions. Stands on glaciated sites and the lower slopes of unglaciated sites were not declining.

Detailed knowledge of variation in soil nutrient content with genetic horizon, glaciation, topographic position, geology, elevation, and the effects of these parameters on sugar maple health is lacking. In this paper, we use the topographic gradient study discussed above to investigate the role that soil factors play in sugar maple nutrition and health. Specifically, we address the questions: (1) What is the relationship between foliar Ca and Mg concentrations in sugar maple and soil parameters and what does this imply about what part of the soil, and what aspects of soil quality are important to sugar maple nutrition? (2) How is soil quality related to sugar maple health? and (3) Are specific landscape conditions associated with poor nutrition of sugar maple? Soil quality parameters considered here include available cations, expressed several different ways, pH, organic matter content, particle-size class, rock fragment content, solum thickness, depth to root restriction, and drainage as represented by depth to redoximorphic features.

MATERIALS AND METHODS

Site Selection and Foliage Sampling

Study stands were established at 19 sites across the Allegheny Plateau from Chautauqua County, New York in the west to Tioga County, Pennsylvania in the east (Fig. 1). Study stands (n = 43) span a wide range of soil parent materials and geologic influences found on the Allegheny Plateau (Table 1). Bedrock consisted of a number of clastic sedimentary formations, dominated by sandstone, with variable amounts of shale, siltstone, conglomerate, and minor amounts of coal. Soil parent materials included Late Wisconsinan till and unglaciated residuum and colluvium. Bedrock formations were determined by locating the study stands on published maps (Rickard and Fisher, 1970; Berg and Dodge, 1981). Soil classification was determined for sampled pedons following Soil Survey Staff (1996).

At each site, two or three stands were sampled along the local elevational distribution of sugar maple (Horsley et al., 2000). Within each stand, five dominant or codominant sugar maples, presumed healthy by lack of symptoms of crown dieback, were selected for foliage sampling. Only presumably healthy trees were sampled so that effects due to site nutritional quality could be distinguished from those due to poor tree health (Kolb and McCormick, 1993; Long et al., 1997). Foliage chemistry was used as a bioassay of site nutritional quality because of its ability to integrate horizontal and vertical differences in soil nutrition within stands (Armson, 1973; Leaf, 1973; Morrison, 1985). A midcrown sample of 25 healthy sun leaves was obtained from each tree during the last 2 wk of August by shooting small branches from the periphery of the crown with a shotgun. Foliar chemistry was determined at the University of Minnesota Research Analytical Laboratory. For

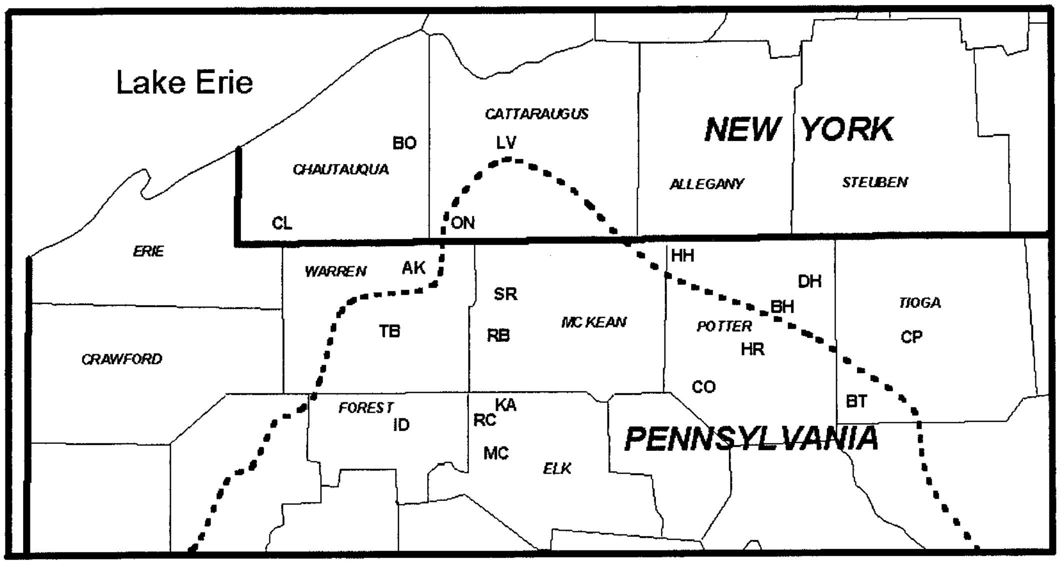

Fig. 1. Location of study sites in northwestern Pennsylvania and southwestern New York. The broken line represents the southern extent of Pleistocene glaciation. Study sites: AK, Akeley; BH, Baldwin Hollow; BO, Boutwell Hill; BT, Brooks Trail; CL, Clymer; CO; Costello; CP, Colton Point; DH, Dodge Hollow; HH, Hemlock Hollow; HR, Hardwood Ridge Trail; ID, Indian Doctor; KA, Kane Experimental Forest; LV, Little Valley; MC, Mill Creek; ON, Onoville; RB, Red Bridge; RC, Russell City; SR, Sugar Run; TB, Tanbark Trail.

details on foliage sample processing and analytical methods, see Horsley et al. (2000).

Stand Health Evaluation and Defoliation History

The trees sampled for foliage formed the locus for establishing three 400-m^2 plots for determination of forest composition and health (Horsley et al., 2000). All standing live or dead trees ≥10 cm diameter at a height of 1.4 m (diameter at breast height, DBH) were evaluated using protocols developed by the North American Maple Project (NAMP) (Cooke et al., 1996). Previous findings indicated that the percentage of dead sugar maple basal area (PDEADSM) was the best discriminator between nondeclining and declining stands. Nondeclining stands were those with 0 to 11 PDEADSM, while moderately to severely declining stands ranged from 21 to 56 PDEADSM (Horsley et al., 2000).

Defoliation incidence and severity were determined for each stand for the most recent 10-yr period from 1987 to 1996 (Horsley et al., 2000). A geographic information system (GIS) comprised of annual layers of digitized sketch maps was queried to determine the timing, agent, and severity of defoliation (light: <30%; moderate: 30–60%; or heavy: >60%). In addition, local land managers were consulted to supplement or confirm information from the GIS database. A defoliation severity index (defsev10) was calculated by summing the number of defoliations documented for the preceding 10-yr period; each year with a defoliation event was weighted according to severity as 1 = light, 2 = moderate, or 3 = heavy.

Physiography

Local physiography was classified for each stand using a system similar to that used by the North American Maple Project (Cooke et al., 1996). Summit and shoulder physiographic positions were grouped together (physiography = 1) and represented sites with the least moisture and nutrient retention. Stands on upper backslopes (physiography = 2) were the next most susceptible to deficiencies in moisture or nutrient retention, followed by middle backslope stands (physiography = 3), and lower backslope stands (physiography = 4). A fifth category represented sites with the most moisture and nutrient retention (physiography = 5) and included stands on foot- or toeslopes, benches, or any topographic position with concave microtopography.

Soil Description and Sampling

County soil surveys and reconnaissance observations were used to locate one representative sampling pit per stand. Pedons were described using the protocols of the Soil Survey Staff (1993) to a depth of at least 130 cm, unless bedrock was encountered at a shallower depth. Root density for each horizon was determined by estimating root density classes as many (>100), common (10–100), or few (1–10) fine (<2 mm diam.) root tips per square decimeter. Rock fragment content of each horizon, expressed as the volume percentage of rocks (2 mm–25 cm diameter), was estimated by comparison of the pit face to the percentage area charts, and by examination of horizon samples removed for analysis. Depth to a root-restricting layer was measured as the distance from the soil surface to a fragipan, densipan, bedrock, or to the base of the pit (130 cm), in the absence of any of the above. Depth to redoximorphic features was recorded as the depth from the soil surface to the shallowest observed redoximorphic features. Solum thickness was calculated as the distance from the top of the Oa or A horizon to the shallowest of either the top of the C horizon, bedrock, or 130 cm, if a C or R horizon was not encountered at that depth.

Soil samples for chemical analysis were collected by genetic horizon, air-dried, and screened to remove particles >2 mm. Samples were analyzed for pH in 0.01 *M* $CaCl_2$ (Robarge and Fernandez, 1987). Organic content was estimated by loss-on-ignition (Robarge and Fernandez, 1987). Exchangeable cations (Ca, Mg, Na, and K) were determined in 1 *M* NH_4Cl extracts (Blume et al., 1990). Exchangeable Al and acidity were determined in 1 *M* KCl extracts. Exchangeable acidity was determined by potentionmetric titration (Thomas, 1982). Concentrations of all cations in soil extracts were measured with direct-coupled plasma spectrophotometry. Effective cation-exchange capacity was determined as the sum of exchangeable Ca, Mg, Na, K, and acidity. Effective base saturation was determined as the sum of exchangeable Ca, Mg, Na, and K

Table 1. Site characteristics of study stands.

Site	Stand	Physiography	Parent material	Bedrock formation	Particle-size class	Pedon classification
AK	1	shoulder	residuum	Venango	loamy skeletal	Lithic Dystrochrept
AK	3	bench	colluvium	Chadakoin	fine-loamy	Aeric Fragiaquept
BH	1	upper backslope	glacial till	Huntley Mountain	loamy skeletal	Typic Haplorthod
BH	3	footslope	glacial till	Huntley Mountain	fine-loamy	Aeric Epiaquept
BO	1	bench	glacial till	Venango	fine-loamy	Aquic Fragiboralf
BO	3	bench	glacial till	Venango	coarse loamy	Aquic Fragiorthod
BT	1	summit	colluvium	Catskill	fine-loamy	Ultic Fragiorthod
BT	3	middle backslope	colluvium	Catskill	fine-loamy	Ultic Hapludalf
CL	1	upper backslope	glacial till	Chadakoin	coarse-loamy	Aeric Epiaquept
CL	2	bench	glacial till	Chadakoin	coarse-loamy	Aquic Dystrochrept
CL	3	footslope	glacial till	Chadakoin	coarse-loamy	Aeric Epiaquept
CO	1	shoulder	colluvium	Huntley Mountain	fine-loamy	Ultic Haplorthod
CO	3	middle backslope	colluvium	Huntley Mountain	fine-loamy	Typic Hapludult
CP	1	shoulder	glacial till	Catskill	coarse loamy	Typic Dystrochrept
CP	3	lower backslope	glacial till	Catskill	coarse loamy	Typic Dystrochrept
DH	1	upper backslope	glacial till	Huntley Mountain	coarse-loamy	Typic Dystrochrept
DH	2	middle backslope	glacial till	Catskill	coarse-loamy	Typic Dystrochrept
DH	3	lower backslope	glacial till	Catskill	coarse-loamy	Typic Dystrochrept
HH	1	upper backslope	glacial till	Huntley Mountain	coarse loamy	Typic Dystrochrept
HH	3	footslope	glacial till	Catskill	loamy skeletal	Aeric Epiaquept
HR	1†	summit	residuum	Huntley Mountain	fine-loamy	Aquic Hapludult
HR	2	bench	colluvium	Huntley Mountain	loamy-skeletal	Typic Glossoboralf
HR	3	footslope	colluvium	Catskill	fine-loamy	Oxyaquic Glossoboralf
ID	1	summit	colluvium	Pottsville	fine-loamy	Aquic Fragiudult
ID	3	footslope	colluvium	Shenango/Cuyahoga	fine-loamy	Aquic Fragiudult
KA	1†	summit	residuum	Allegheny	fine-loamy	Typic Hapludult
KA	2†	shoulder	residuum	Allegheny	fine-loamy	Aquic Fragiudult
KA	3	bench	residuum	Allegheny	fine-loamy	Aquic Fragiudult
LV	1	middle backslope	glacial till	Venango	coarse loamy	Aquic Fragiboralf
LV	3	lower backslope	glacial till	Chadakoin	coarse loamy	Aquic Fragiorthod
MC	1†	shoulder	residuum	Pottsville	fine-loamy	Typic Hapludult
MC	3	lower backslope	colluvium	Shenango/Oswayo	fine-loamy	Oxyaquic Fragiudalf
ON	1	upper backslope	colluvium	Venango	fine-loamy	Aquic Fragiboralf
ON	3	footslope	colluvium	Chadakoin	fine-loamy	Aquic Fragiudalf
RB	1†	summit	residuum	Pottsville	fine-loamy	Typic Hapludult
RB	2†	upper backslope	colluvium	Pottsville	fine-loamy	Aquic Hapludult
RB	3	footslope	residuum	Shenango/Oswayo	fine-loamy	Oxyaquic Fragiudalf
RC	1	summit	colluvium	Pottsville	fine loamy	Aquic Fragiudult
RC	3	footslope	colluvium	Shenango/Oswayo	fine loamy	Oxyaquic Fragiudalf
SR	1	upper backslope	colluvium	Shenango/Oswayo	loamy skeletal	Typic Fragiboralf
SR	3	lower backslope	colluvium	Shenango/Oswayo	fine-loamy	Typic Fragiboralf
TB	1	middle backslope	colluvium	Corry/Riceville	fine loamy	Aquic Fragiudult
TB	3	lower backslope	colluvium	Venango	fine-loamy	Aquic Fragiudalf

† Stands defined as unhealthy by Horsley et al. (2000).

divided by effective cation-exchange capacity. Exchangeable Ca and Mg were expressed three ways—(i) on an oven-dry mass basis (e.g., cmol$_c$ kg^{-1}), (ii) as a saturation value, calculated as exchangeable Ca or Mg divided by effective cation-exchange capacity and expressed as a percentage, and (iii) in a molar ratio with exchangeable Al, an ion that has been shown to interfere with uptake of Ca and Mg by tree roots (Smith and Shortle, 1988; Cronan and Grigal, 1995). Site nutrient capital (kg ha^{-1}) was estimated by exchangeable Ca and Mg concentrations, horizon thickness, volumetric coarse fragment content, and typical values of bulk density reported in county soil surveys. Nutrient capitals were calculated for different portions of the soil including (i) for the Oa plus A horizon, (ii) for the solum (Oa through B horizons), and for the portions of the pedon with (iii) many roots, (iv) many or common roots, and (v) many, common, or few roots, as defined above in the soil description and sampling section.

Statistical Analysis

The relationships between soil and foliage chemistry were evaluated using parameters measured at the horizon and pedon level. To simplify analyses, and allow for comparison between pedons with differing horizon sequences, three indicator horizons were chosen for statistical analysis—the A or Oa horizon (generally only one or the other was present in a given pedon, depending on organic matter content) to characterize surficial, organic-rich horizons with the highest root density, the uppermost subdivision of the B horizon (generally a Bhs or Bw$_1$), and the lowermost subdivision of the B (generally a Bw, Bt, or BC). The E horizon was not considered as it was not present in all pedons, and invariably had relatively low cation-exchange capacity and base saturation. Statistical analyses were conducted in SAS ver. 8 (SAS Institute, 2001). Logarithmic transformations were used to linearize soil variables, which typically spanned several orders of magnitude. Pearson correlation analysis with uncorrected probabilities was used to examine relationships between foliar Ca and Mg and soil parameters. Soil parameters with p values < 0.10 were considered in a stepwise linear regression analysis to develop models predicting foliar nutrient concentration and sugar maple mortality from soil variables. Backward selection was used with a probability of F-to-enter/remove limit equal to 0.05. Mallow's Cp was evaluated to determine relative effects of covariance on each model.

RESULTS

Study stands were located on all physiographic positions from summit to footslope, on soils that ranged from moderately deep to very deep, well drained to poorly drained, and included soils of four orders (Inceptisols, Spodosols, Alfisols, and Ultisols; Table 1). Particle-size classes included fine loamy, coarse loamy, and loamy skeletal. All stands defined as unhealthy by Hor-

Table 2. Correlation of foliar chemistry with soil horizon parameters. Values shown are Pearson correlation coefficients with uncorrected probabilities in parentheses.

Relationship	Oa/A	Upper B	Lower B
Foliar Ca vs.			
exchangeable Ca, $cmol_c$ kg^{-1}†	0.404 (0.007)	0.676 (<0.001)	0.651 (<0.001)
Ca saturation, %†	0.425 (0.004)	0.755 (<0.001)	0.660 (<0.001)
Ca/Al molar ratio†	0.446 (0.003)	0.738 (<0.001)	0.616 (<0.001)
base saturation, %†	0.375 (0.013)	0.691 (<0.001)	0.586 (<0.001)
cation exchange capacity, $cmol_c$ kg^{-1}	0.090 (0.565)	−0.160 (0.307)	0.128 (0.414)
organic matter, %	−0.295 (0.055)	−0.235 (0.129)	−0.035 (0.822)
pH	0.794 (<0.001)	0.532 (<0.001)	0.454 (0.002)
rock fragments, % by vol.	0.627 (<0.001)	0.584 (<0.001)	0.474 (0.001)
Foliar Mg vs.			
exchangeable Mg, $cmol_c$ kg^{-1}†	0.387 (0.010)	0.757 (<0.001)	0.667 (<0.001)
Mg saturation, %†	0.466 (0.002)	0.748 (<0.001)	0.672 (<0.001)
Mg/Al molar ratio†	0.408 (0.007)	0.748 (<0.001)	0.612 (<0.001)
base saturation, %†	0.273 (0.076)	0.653 (<0.001)	0.615 (<0.001)
cation exchange capacity, $cmol_c$ kg^{-1}	0.027 (0.865)	−0.059 (0.707)	0.139 (0.375)
organic matter, %	−0.307 (0.046)	−0.212 (0.173)	0.005 (0.972)
pH	0.684 (<0.001)	0.521 (<0.001)	0.443 (0.003)
rock fragments, % by vol.	0.346 (0.023)	0.304 (0.048)	0.305 (0.047)

† Log_{10} transformation.

sley et al. (2000) were on unglaciated Ultisols with a fine-loamy particle-size class (Table 1).

Foliar Ca and Mg were correlated with many variables measured on the soil horizon level (Table 2) and the stand level (Table 3). Expressions of cation nutrient availability on a mass basis, as a saturation value, and in ratio with Al all showed significant correlation ($p < 0.01$) with foliage in all three indicator horizons (Table 2). Correlation coefficients were slightly higher in the upper B compared with lower B horizons, and much lower in the Oa/A horizons. In most cases, the nutrient saturation expression yielded slightly higher correlation coefficients compared with expression on a mass or Al ratio basis (Table 2). Base saturation, which was dominated by Ca and Mg due to low concentrations of exchangeable Na and K, also showed significant correlations with foliage values, although the correlation coefficients were lower than for single-nutrient soil parameters.

No significant relationships were found between foliar chemistry and effective cation-exchange capacity (Table 2). Organic matter content showed weak negative relationships with foliar chemistry, which were significant only for foliar Mg vs. the Oa/A horizon. Soil pH was correlated with both foliar Ca and Mg in all three horizons, with higher correlation coefficients for Ca compared with Mg and decreasing coefficients with depth. Significant correlations were found between rock fragment content and foliar Ca and Mg in all horizons, with the best relationships for Ca compared with Mg, and in the Oa/A compared with the B horizons.

There was a negative relationship between foliar Mg ($p = 0.013$) and defsev10 (Table 3). A similar inverse relationship between foliar Ca and defoliation severity index is suggested by the data, but was not significant ($p = 0.115$). Depth to a root restrictive layer was also negatively related to foliar nutrient concentrations. Relationships between foliar chemistry and depth to redoximorphic features and solum thickness were not significant. Soil nutrient capital was significantly correlated with foliar Ca and Mg ($p < 0.001$) with the higher correlation coefficients generally shown by soil capital summations, which included larger portions of the pedon. The highest correlation coefficients for both nutrients were seen with soil capital summed for the portion of the pedon with many and common roots ($r = 0.680$, 0.683 for Ca and Mg, respectively).

While these northern hardwood stands are found on a fairly narrow range of soil particle-size class (Table 1), the textural variation present did not account for variation in sugar maple foliar chemistry. Analysis of variance did not indicate a difference in foliar Ca or Mg between loamy skeletal and coarse loamy particle-size classes ($p = 0.597$ and 0.325, respectively), or between fine loamy and coarse loamy particle-size classes ($p = 0.295$, 0.836). Stands with soils in the fine-loamy particle-size class had significantly lower foliar Ca and Mg than stands on loamy skeletal soils ($p = 0.036$, 0.041).

Step-wise multiple regression analysis was conducted to further evaluate the relationship between foliar Ca and Mg and soil parameters. All parameters with a p-value < 0.10 in a regression with foliar base cations (Tables 2 and 3) were included in an initial regression equation. To minimize problems with covariance, separate equations were developed with nutrient supply calculated as exchangeable nutrient on a mass basis, versus a saturation value or in ratio with Al. The best model for predicting foliar Ca (in terms of having the highest r^2 and lowest Cp) was a three-parameter model that included one parameter from each of the indicator horizons (Table 4). The best model for predicting foliar Mg

Table 3. Correlation of foliar chemistry with site parameters. Values shown are Pearson correlation coefficients with uncorrected probabilities shown in parentheses.

Property	Foliar Ca	Foliar Mg
defsev10	−0.244 (0.115)	−0.377 (0.013)
depth to root restriction, cm	−0.348 (0.022)	−0.419 (0.005)
depth to redoximorphic features, cm	0.049 (0.755)	−0.167 (0.284)
solum thickness, cm	−0.163 (0.298)	−0.126 (0.420)
forest floor capital, kg ha^{-1}†	0.558 (<0.001)	0.601 (<0.001)
solum capital, kg ha^{-1}†	0.645 (<0.001)	0.624 (<0.001)
capital with many roots, kg ha^{-1}†	0.644 (<0.001)	0.637 (<0.001)
capital with common roots, kg ha^{-1}†	0.680 (<0.001)	0.683 (<0.001)
capital with few roots, kg ha^{-1}†	0.680 (<0.001)	0.661 (<0.001)

† Log_{10} transformation.

Table 4. Regression models predicting foliar nutrient levels from soil variables. Coefficients are in parentheses.

Dependent variable	Parameter 1	Parameter 2	Parameter 3	Multiple r^2	Cp
Foliar Ca	rock fragments Oa/A (104)	Ca/Al upper B (1954)	Ca/Al lower B (980)	0.757	2.3
Foliar Ca	rock fragments Oa/A (94)	Ca saturation upper B (2441)	Ca saturation lower B (1391)	0.755	5.5
Foliar Ca	rock fragments Oa/A (77)	pH Oa/A (2974)	exchangeable Ca lower B (1271)	0.748	5.1
Foliar Mg	depth to restriction (−3.2)	pH Oa/A (240)	exchangeable Mg lower B (331)	0.686	−0.2
Foliar Mg	depth to restriction (−3.2)	Mg saturation upper B (361)	Mg saturation lower B (123)	0.676	0.0
Foliar Mg	depth to restriction (−4.2)	Mg/Al upper B (386)		0.625	0.5

was also a three-parameter model, but included one site variable and one variable from each of the Oa/A and lower B horizons. The second best model for both Ca and Mg was a three-parameter equation of similar form for each element, including cation-saturation values from the upper and lower B horizons. The third parameter was rock fragment content in the Oa/A in the case of Ca and depth to root restrictive layer for Mg (Table 4).

A backward-elimination step-wise regression was conducted to evaluate the relationship between site quality and health, expressed as mortality percentage of sugar maple basal area. As with the foliar regression, all parameters with significant correlations ($p < 0.10$) were considered. The saturation expression of nutrient availability was chosen to represent soil Ca and Mg due to its performance in predicting both foliar Ca and Mg. The resulting equation ($r^2 = 0.779$; $p < 0.0001$) included depth to root restriction (coefficient = 0.154), organic content Oa/A (−0.191), and Ca and Mg saturation in the Oa/A (17.462 and −23.672, respectively), upper B (−58.991 and 54.921) and lower B (16.591 and −21.843). Parameters removed by the stepwise procedure included defsev10, pH, and rock fragment content in all three indicator horizons.

Although statistical testing with ANOVA was not deemed useful due to the small number of stands in some site types, an examination of soil chemical trends by glacial history and landscape position suggests broad trends in site quality (Table 5). Chemistry of the Oa/A horizon was similar across all site types. Exchangeable base cation levels were much lower in the upper and lower B horizons at unglaciated summits and shoulders compared with other sites. For example, mean exchangeable Ca and Mg in the upper B were <50% of the next lowest mean—the summit/shoulder of glaciated sites (Table 5). Similarly, in the lower B horizon, exchangeable Ca and Mg were 14 and 28%, respectively, of the next lowest mean– glaciated upper backslopes. Generally, the lowest concentrations of base cations were in the upper B, with the highest concentrations either in the Oa/A or the lower B. The clearest differences in site quality were shown by site capital means, summed for the portion of the pedon from the Oa to the top of the C horizon. Calcium and Mg site capital were lowest for unglaciated summits and shoulders while lower back slopes and enriched sites of both glaciated and unglaciated sites had the highest mean capitals.

Table 5. Mean soil chemical values by glacial history and physiographic position. Standard deviation is shown in parentheses.

Property	Summit or shoulder	Upper back	Mid-back	Lower back	Bench
			Glaciated sites		
number of stands	2	4	2	3	7
exchangeable Ca Oa/A, $cmol_c\ kg^{-1}$	18.5 (5.3)	10.5 (5.9)	8.4 (4.3)	14.4 (5.4)	8.5 (3.2)
exchangeable Ca upper B, $cmol_c\ kg^{-1}$	0.68 (0.04)	2.5 (1.4)	2.8 (0.7)	0.83 (0.05)	1.7 (0.8)
exchangeable Ca lower B, $cmol_c\ kg^{-1}$	1.70 (0.92)	1.1 (0.5)	3.7 (1.8)	1.2 (0.9)	3.1 (1.2)
Ca site capital, $kg\ ha^{-1}$	1200 (540)	1100 (520)	1400 (180)	1700 (950)	3200 (1600)
exchangeable Mg Oa/A, $cmol_c\ kg^{-1}$	1.8 (0.3)	0.93 (0.41)	2.1 (1.4)	2.1 (0.7)	1.4 (0.6)
exchangeable Mg upper B, $cmol_c\ kg^{-1}$	0.12 (0.01)	0.27 (0.10)	0.64 (0.34)	0.16 (0.05)	0.45 (0.27)
exchangeable Mg lower B, $cmol_c\ kg^{-1}$	0.45 (0.30)	0.28 (0.12)	0.76 (0.35)	0.57 (0.51)	1.4 (0.8)
Mg site capital, $kg\ ha^{-1}$	190 (97)	130 (55)	270 (9)	600 (460)	1300 (970)
Ca/Al molar ratio Oa/A	18.7 (7.0)	26 (23)	16 (16)	15 (13)	9.1 (6.6)
Ca/Al molar ratio upper B	0.14 (0.04)	1.0 (0.7)	0.42 (0.23)	0.08 (0.02)	0.41 (0.28)
Ca/Al molar ratio lower B	0.47 (0.66)	0.4 (0.3)	3.5 (3.0)	0.32 (0.26)	7.6 (4.1)
pH Oa/A	4.1 (0.2)	3.6 (0.4)	3.7 (0.1)	3.2 (0.1)	3.6 (0.2)
pH upper B	3.9 (0.2)	3.9 (0.3)	3.8 (0.2)	3.5 (0.2)	3.9 (0.1)
pH lower B	4.0 (0.4)	4.0 (0.1)	4.3 (0.4)	3.9 (0.1)	4.4 (0.2)
			Unglaciated sites		
number of stands	9	3	3	3	7
exchangeable Ca Oa/A, $cmol_c\ kg^{-1}$	5.5 (1.6)	4.8 (1.9)	9.5 (1.7)	5.7 (3.6)	4.4 (0.6)
exchangeable Ca upper B, $cmol_c kg^{-1}$	0.28 (0.11)	0.73 (0.38)	2.2 (1.2)	1.6 (0.8)	1.3 (0.5)
exchangeable Ca lower B, $cmol_c kg^{-1}$	0.16 (0.05)	1.4 (0.7)	1.5 (0.9)	5.8 (2.3)	2.9 (1.2)
Ca site capital, $kg\ ha^{-1}$	360 (110)	1100 (410)	1700 (750)	4700 (1500)	3100 (1200)
exchangeable Mg Oa/A, $cmol_c\ kg^{-1}$	0.76 (0.22)	1.0 (0.3)	1.5 (0.3)	1.1 (0.6)	0.82 (0.08)
exchangeable Mg upper B, $cmol_c\ kg^{-1}$	0.058 (0.017)	0.24 (0.11)	0.41 (0.18)	0.42 (0.22)	0.34 (0.13)
exchangeable Mg lower B, $cmol_c\ kg^{-1}$	0.078 (0.047)	2.1 (1.6)	0.31 (0.17)	2.0 (0.4)	1.2 (0.5)
Mg site capital, $kg\ ha^{-1}$	110 (52)	760 (400)	330 (130)	1600 (450)	1100 (460)
Ca/Al molar ratio Oa/A	1.8 (0.9)	2.6 (2.1)	1.5 (0.2)	1.5 (1.2)	7.8 (7.0)
Ca/Al molar ratio upper B	0.031 (0.010)	0.089 (0.044)	0.6 (0.5)	0.33 (0.24)	0.52 (0.36)
Ca/Al molar ratio lower B	0.027 (0.008)	0.49 (0.33)	0.6 (0.5)	23 (12)	11 (6.5)
pH Oa/A	3.1 (0.1)	3.5 (0.1)	3.4 (0.2)	3.8 (0.3)	3.8 (0.2)
pH upper B	3.6 (0.1)	3.8 (0.1)	3.8 (0.3)	4.1 (0.2)	4.0 (0.1)
pH lower B	3.9 (0.1)	3.9 (0.2)	4.2 (0.2)	4.8 (0.2)	4.3 (0.2)

DISCUSSION

Significant correlation of many soil parameters with foliar Ca and Mg confirms the utility of foliar analyses in addressing site quality and base cation nutrition for sugar maple. The B horizon provided the best indicators of foliar chemistry, suggesting the importance of this portion of the pedon in sugar maple nutrition. The best models for predicting foliar chemistry include expressions of soil chemistry in both the upper and lower B horizon (Table 4), suggesting that the best picture of sugar maple nutrition is gained by looking at a range of horizons rather than focusing on one specific indicator horizon.

The relatively poor relationship between foliar chemistry and the chemistry of the Oa/A horizon was surprising given that high density of fine roots we observed in this portion of the pedon. A possible interpretation for this finding is that spatial variability of this part of the pedon is most extreme as it is the portion of the soil most affected by disturbances such as tree throw and animal activity, including burrowing by small mammals and macroinvertebrates. A more extensive sampling program may have yielded better relationships between the uppermost horizons and foliar chemistry. Using the approach taken here of sampling the perimeter of a single large pit, evaluation of the B horizon appears to be an economical and efficient method for accessing base cation supply for sugar maple. More costly quantitative sampling and/or extensive replication may be needed to better detect relationships with the Oa/A horizon.

Rock fragment content of all three horizons was positively correlated with foliar Ca and Mg levels, suggesting the importance of coarse fragments to nutrient supply. Although standard soils laboratory procedures involve testing only the portion of samples that passes a 2 mm screen, a procedure inherited from methodology originally developed for relatively stone-free agricultural soils, there is evidence that coarse fragments may contain important nutrient pools in some forest soils. Ugolini et al. (1996) found that the coarse fragments in forest soils formed in sandstone intercalated with siltstone, similar to the geologic origin of soils on the Allegheny Plateau, contained from 20 to 55% of the effective cation-exchange capacity in the B and BC horizons. Observations of coarse fragments from our excavations show that many are quite porous, with small pits indicating primary porosity, as well as secondary porosity due to dissolution of mineral clasts or fossils. Secondary calcite observed on the underside of ledges at some sites suggest that active calcite weathering may be occurring in some of the largest coarse fragments although smaller pieces of rock fragment exhibited weathering alterations throughout freshly broken sections.

Given the good relationship between soil and foliar nutrient concentrations, it is not surprising that like foliar chemistry, soil chemistry is a good predictor of which stands were susceptible to decline. Horsley et al. (2000) reported that unhealthy stands were those with both low foliar base cation nutrient concentrations and a history of more severe insect defoliation. Foliar Mg was a better predictor of decline than foliar Ca, with no stands misclassified if unhealthy stands were predicted by foliar Mg concentrations <700 mg kg^{-1} and two or more moderate to severe insect defoliations in the preceding 10-yr period (defsev10 $\geq$ 4). In contrast, stands with foliar Mg concentrations >700 mg kg^{-1} remained healthy regardless of defoliation history.

Figure 2 shows the relationship between soil Ca and Mg saturation values, defoliation severity index and sugar maple mortality for each of the three indicator horizons examined. No clear threshold relationship is evident for the Oa/A horizon, with declining stands spanning much of the range in Ca and Mg saturation seen in nondeclining stands. The upper B horizon shows the best threshold relations. Stands with an upper B horizon Ca saturation $<2\%$ or Mg saturation $<0.5\%$ and two or more moderate to severe insect defoliations in the preceding 10-yr period (defsev10 $\geq$ 4) had high sugar maple mortality. In contrast, stands with less defoliation stress (defsev10 $<$ 4) and base cation levels below these thresholds stayed healthy. Similarly, stands with base cation levels above these thresholds remained healthy regardless of defoliation history. The one exception to this pattern was stand RC-1, which appeared healthy although it had upper B horizon Ca and Mg levels below the proposed threshold and defsev10 = 6. Upon further investigation, it was discovered that this stand had been thinned before study, which likely removed some unhealthy trees, thus lowering the standing dead basal area (Horsley et al., 2000).

The lower B horizon also shows an apparent threshold relationship between base cation levels and sugar maple mortality, at 4% Ca saturation and 0.6% Mg saturation. Again, stand RC-1 appears healthy, but is below the proposed soil threshold, probably as a result of thinning unhealthy trees. A second stand (Cl-2) is just below the threshold (3.7% Ca saturation; 0.5% Mg saturation) but remained healthy despite a severe defoliation history (defsev10 = 6). No known site history explains this anomaly, suggesting that the lower B horizon may be a slightly less reliable indicator of health risk compared with the upper B horizon. We suggest that in practice, the most reliable diagnosis of a nutrient problem on a site might be had if both upper and lower B horizon samples yielded concentrations above or below the proposed thresholds.

The variation in site quality across the Plateau might be explained by a model that considers the location of weathering reactions and the effect of landscape position on delivery of weathering products to the rooting zone. Mineralogy of unglaciated soils is dominated by primary minerals such as quartz and muscovite, which are highly resistant to weathering and devoid of Ca and Mg, and secondary minerals, the products of advanced weathering, such as kaolinite and illite, which are stable in the soil environment. Weatherable minerals are confined to lower portions of the regolith well below the rooting zone, or within underlying bedrock. Thus, the delivery of weathering products, such as Ca or Mg ions, to the rooting zone is limited to portions of the landscape

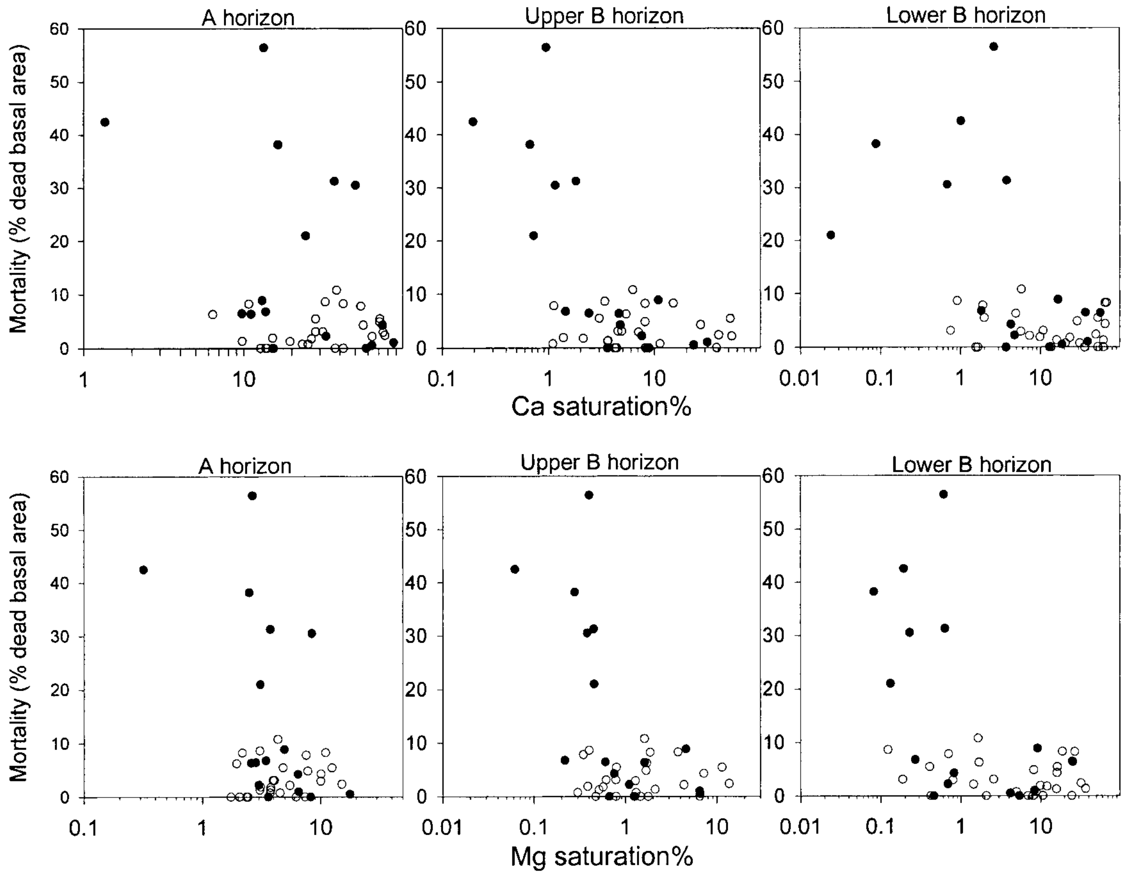

Fig. 2. Exchangeable Ca and Mg (expressed as a percentage of saturation value) in the Oa/A, upper B and lower B horizons vs. sugar maple mortality (percentage of standing dead basal area). Open circles represent stands where defsev10 was less than four; filled circles are stands where defsev10 was four or higher. Note the x-axes are on a log scale.

where water flowpaths bring ions released from bedrock or deeper regolith to the solum where roots are active (Fig. 3a). Locations where water that has percolated into the bedrock is forced laterally into the regolith by a stratum of lower permeability may be expressed as hillslope seeps. On other portions of the landscape, particularly unglaciated summits, shoulders, and upper backslopes, base cation nutrient inputs are dominated by atmospheric inputs; nutrient conservation by efficient biological cycling is particularly important on these sites, increasing the importance of the upper soil horizons in maintaining site fertility.

In contrast, on glaciated portions of the Plateau, much of the weathered regolith was removed by glacial erosion. Soils are developed in glacial till (Fig. 3b), incorporating relatively unweathered material freshly exposed by glacial erosion. Thus, weathering reactions occur within the rooting zone, creating less contrast in base cation levels by landscape position. However, even on glaciated sites weathering in the rooting zone may be limited where glacial till is largely derived from bedrock units with few weatherable minerals, such as quartzose sandstone.

The role of base cation depletion and acid deposition in contributing to sugar maple decline remains difficult to quantify. Acid deposition has been shown to reduce exchangeable base cations in soil based on theoretical grounds (Reuss, 1983) and in laboratory studies (Lawrence et al., 1999). Long-term depletion of exchange pools has been documented by retrospective studies (Shortle and Bondietti, 1992; Lawrence et al., 1997; Markewitz et al., 1998) and is consistent with watershed mass balance studies (Bailey et al., 1996; Likens et al., 1998). In the present study, the base cation-poor sites where sugar maple decline has occurred are located in landscape positions and on bedrock formations and soil parent materials (Table 1) that one would expect to have the lowest nutrient levels, based on lack of weatherable minerals in the rooting zone and lack of hydrologic pathways to deliver weathering products from deeper sources. Given the available evidence, it is reasonable to hypothesize that nutrient depletion due to acid deposition has increased the portion of the landscape with nutrient values below a critical threshold for maintenance of sugar maple health in a stressful environment. However, in light of the great variety of site quality due to landscape position, mineralogy and soil development, the extent that acid deposition has contributed to sugar maple decline remains unquantified.

Analysis of early land survey records shows that the greatest abundance of sugar maple in the presettlement forest of the unglaciated Allegheny Plateau was on better drained, coarser textured, sandstone-derived soils of plateau tops and summits with thick deposits of "non-

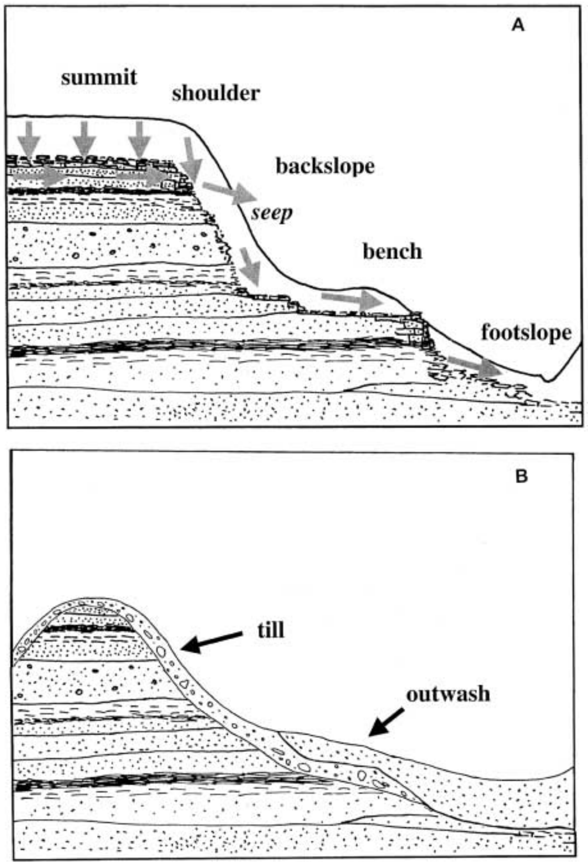

Fig. 3. Schematic cross sections of (a) unglaciated and (b) glaciated portions of the Allegheny Plateau. Patterned areas represent interbedded sandstone, siltstone, and shale bedrock. Soils on the unglaciated portion are developed in relatively thick, weathered residuum, colluvium, and alluvium shown as the unpatterned area above the bedrock. Arrows suggest general directions of water flow in unglaciated soils and bedrock. Soils on the glaciated portion are developed in relatively unweathered glacial till and outwash.

rubbly sandy loam to silt loam soils" (Goodlett, 1954; Whitney, 1990). The fact that sugar maple historically occupied these portions of the landscape that have proven susceptible to decline suggests that either nutrition has declined relative to presettlement levels, perhaps as a result of acid-deposition induced leaching, or that the recent stress environment, in terms of the frequency and severity of defoliation, drought, or untimely frost events, has become more severe.

CONCLUSIONS

Soil characterization and chemical analysis support earlier findings that sugar maple decline on the Allegheny Plateau is characterized by an interaction of poor nutrition of Ca and Mg and repeated insect defoliation. Correlation analysis and linear regression suggest that measurement of exchangeable cations in the upper and lower B horizons, estimates of volumetric rock fragment content and depth to a root restrictive layer can provide a good indication of availability of Ca and Mg for sugar maple, as expressed in foliar analyses. The exchangeable cation levels in the upper and lower B horizons may also be useful as predictors of stands susceptible to decline. Stands with soil values below the proposed thresholds might be considered susceptible to decline in the event of other stressors, such as repeated insect defoliation. Knowledge of susceptible stands might be used by managers to evaluate the risk of sugar maple culture on marginal sites, or alternatively, of the possible benefits of insect suppression or fertilization to sugar maple health (Horsley et al., 2002).

These findings suggest several areas where knowledge of forest nutrient cycling is limited, affecting our ability to access spatial patterns and mechanisms responsible for variations in site quality. The strong positive relationships between coarse fragment content and soil base cation content suggest that coarse fragments may be much more important in nutrient supply in some forest soils than commonly accepted. The high concentrations of exchangeable base cations in the lower B horizons, particularly at lower landscape positions, often in the presence of seeps, suggests the importance of deep seepage as a base cation source in some stands. Lateral flowpaths might provide a mechanism for bringing nutrients released by weathering reactions in the C horizon or bedrock into the rooting zone where they are available for plant uptake.

Finally, the use of soil nutrient thresholds to measure the potential implications of soil quality for tree health may be a useful tool that deserves further development. It would be important to determine whether similar thresholds describe the occurrence of decline in other regions, or whether there is a relationship between the value of the soil threshold for health and the severity of stressors, such as defoliation.

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