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Liming influences growth and nutrient balances in sugar maple (*Acer saccharum)* seedlings on an acidic forest soil

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Abstract

Forests in the northeastern US have been limed to mitigate soil acidification and the acidity of surface waters and to improve soil base cation status. Much of the area considered for liming is within the range of sugar maple (*Acer saccharum),* but there is a poor understanding of how liming influences growth and nutrient balance of this species on sites that are not deficient in Ca. Of particular concern is the balance of K, a nutrient deficient in parts of the range of sugar maple and a deficiency linked with sugar maple decline in vigor. This buried pot study used soil that was low in K availability to test the influence of liming an acidic forest soil on biomass production and nutrient balance in 2-year-old sugar maple seedlings. The influence of surface applied lime and lime incorporated into the soil were compared with a control. Seedlings were planted on May 9 and were harvested on August 30. Plant parts were freeze-dried, weighed and analyzed for N, P, K, Ca, Mg, Al and Fe. In addition to concentrations, nutrient ratios and the diagnosis and recommendation integrated system (DRIS) were used to estimate nutrient balances. Although seedlings were similar in mass and dimensions at the start of the experiment, harvested seedlings were 37% larger in the incorporated treatment and 9% smaller in the surface limed treatment compared to control. Only fine roots showed no difference in mass among treatments. Seedlings from the incorporated treatment had greater foliar Ca ($P = 0.002$), K ($P = 0.004$) and P ($P = 0.004$) than the other treatments. There were no significant differences in foliar Mg, N, Fe or Al concentrations. At the end of the experiment, seedlings from the surface limed treatment contained 11% less K and 3% less P than control seedlings, while seedlings in the incorporated treatment contained 23% more K and 86% more P than in the control. Of the 14 nutrient ratios analyzed, four became more balanced and three became more imbalanced in the incorporated treatment and 10 nutrient ratios became more imbalanced and one ratio improved in the surface limed treatment compared to control. The DRIS indices showed that N was the most closely balanced nutrient relative to other nutrients and K was the most imbalanced nutrient in all treatments. Also, P was quite deficient while Ca, Mg and Fe were overabundant and Al was highly overabundant in all treatments. Surface liming exacerbated K, P and Al imbalances and nutrients remained similarly balanced in seedlings from the control and incorporated seedlings. This study suggested that liming acidic forest soils could intensify nutrient deficiencies, but that over the long term, the availability of highly deficient nutrients could improve.

Keywords: Liming; Sugar maple; Potassium; Phosphorous; Roots

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1. Introduction

Forests have been limed to mitigate soil acidification and the acidity of surface waters and to improve soil base cation status (Smallidge et al., 1993; Driscoll et al., 1996). In the US, much of the forested area considered for liming is within the range of sugar maple (*Acer saccharum*), an important commercial tree species that shows evidence of nutrient deficiency in parts of its range. Although Ca availability is low in some areas (Kolb and McCormick, 1993; Ellsworth and Liu, 1994; Heisey, 1995) and liming may improve growth there, an understanding of how liming influences sugar maple growth and nutrient balance on sites deficient in other nutrients is limited.

Most studies of the influence of liming on sugar maple (Safford, 1974; Carmarean and Watt, 1975; Stone and Christenson, 1975; Ellis, 1979; Lea et al., 1980; Stone, 1980) have shown little or no effect on growth unless lime was combined with other fertilizers (Ouimet and Fortin, 1992; Fyles et al., 1994). The effects of liming on nutrient balance in the species have not been studied. Lea et al. (1980) reported no effects of liming on foliar Ca, K and P concentrations (Lea et al., 1980). Smallidge et al. (1993) observed that striped maple (*Acer pensylvanicum*) and red maple (*Acer rubrum*) responded differently to surface liming, with foliar Ca concentrations increasing in striped maple but not in red maple (Smallidge et al., 1993). In the same study, foliar P levels either did not change (Smallidge, unpublished data) or declined (Raynal, unpublished data). Liming did not influence growth but reduced foliar K concentrations in European beech (*Fagus sylvatica*) (Ljungström and Nihlgård, 1995).

A potential influence of liming is induced nutrient imbalance. A particular concern is the foliar N/K ratios: liming can influence soil K availability (Magdoff and Bartlett, 1980) and the N/K ratio has been linked with declining vigor in sugar maple trees (Bernier et al., 1989) where soil K availability was low (Foster et al., 1992). In addition, nutrient imbalances of sugar maple increased susceptibilities to microbial pathogens (Wargo and Houston, 1974) and drought and frost injury (Gregory and Wargo, 1986; Gregory et al., 1986).

The purpose of this study was to measure the influence of liming an acidic forest soil on biomass production and nutrient balance in sugar maple seedlings. We were interested in both short- and long-term effects of liming and, because surface applied lime dissolves slowly and may take decades to change mineral soil chemistry (Matzner et al., 1985; Nihlgård et al., 1988), a treatment in which lime was incorporated into the soil was used. Following liming, changes in the relative availability of several nutrients were expected. Thus, the relative balances of all the macronutrients were contrasted.

Although a sensitive method of detecting nutrient deficiency is foliage analysis, relative deficiency and abundance among nutrients are not easily ranked using a critical foliar and concentration approach. In addition, due to variability associated with plant age, crown position, seasonal, annual, genetic and site differences, comparisons among studies are difficult to make (Sumner, 1977). Moreover, critical levels of some nutrients change with the concentrations of other nutrients (e.g. N and S) (Turner et al., 1977).

The nutrient ratio approach was developed to overcome some of the limitations of the critical foliar concentration approach. Nutrient ratios are less sensitive to seasonal, annual and crown position variation and more clearly diagnose imbalances of nutrients (Sumner, 1977), however, seasonal differences in optimal ratios have not been adequately determined. A more comprehensive approach to diagnosing nutrient balances, the Diagnosis and Recommendation Integrated System (DRIS) developed by Beaufils (1971), determines relative deficiency or adequacy of each nutrient and has been widely used for many plant species (Walworth and Sumner, 1987). DRIS was the most appropriate approach for this study because the indices are robust with regard to crown position, leaf age and season (Lozano and Huynh, 1989). Further, the method is more appropriate than comparisons of critical concentrations when foliage is sampled in August, as in this study.

We hypothesized that surface liming an acidic forest soil would have little effect on growth and nutrient balance due to the slow dissolution rate

of the lime. In addition, we hypothesized that the incorporation of lime into the soil would have a greater influence on growth and nutrient balance than surface liming, could exacerbate the already low K status of the soil we used, and could relieve the low P status previously documented in adult trees on the site (Foster et al., 1992; Zhang and Mitchell, 1995). We predicted that the high Ca availability after liming could antagonize K uptake (Matzner et al., 1985) and because P was abundant but tightly adsorbed in this acidic soil (Yanai, 1992; Zhang and Mitchell, 1995), higher pH could either increase P availability due to desorption from aluminum compounds or increased mineralization, or decrease P availability by precipitation of calcium phosphates, all possible outcomes of liming acidic soil (Haynes, 1982).

2. Methods

A buried pot field experiment was conducted in a nursery bed at the State University of New York's Lafayette Experiment Station at Syracuse, New York. Soil used in the experiment was collected from the Huntington Wildlife Forest, Newcomb, Essex County, NY (43°59′N, 74°14′W), in the Adirondack Mountains. The soil is a coarse-loamy, mixed frigid Typic Haplorthod in the Becket–Mundal association. The soil is derived from thin (< 1 m depth) glacial till over a gneiss bedrock and is dominated by quartz and feldspar with potassium feldspars and calcium plagioclase.

Soil organic matter concentrations are high (2-21 mol, kg- ^{1}) in the mineral soil (Mitchell et al., 1992) and P in the A horizon is 0.50 mmol P_c kg^{-1} (Zhang and Mitchell, 1995). Foster et al. (1992) reported that the pH of the A horizon was 3.2, exchangeable elements were 0.095 mol, kg^{-1} for Ca, 0.010 mol, kg-' for Mg, 0.005 mol, kg-' for K, 0.002 mol, kg^{-1} for Na and 0.036 mol, kg- ^{1} for Al (Foster et al., 1992). Exchangeable acidity was 0.047 mol, kg^{-1} and cation exchange capacity was 0.255 mol_c kg ^{1}. Base saturation was 44%. The Σ cations was 0.345 mol kg^{-1} for Ca, 0.180 mol kg- ^{1} for Mg, 0.620 mol kg- ^{1} for K, 1.630 mol kg- ^{1} for Na, with an exchangeable acidity of 6.4 kmol, ha- ^{1} and a total acidity of 93 kmol, ha- ^{1}. Mineral soil organic matter was high (2-21 mol_c kg- ^{1}) (Mitchell-et al., 1992). Mineral soil is the major pool of P (Zhang and Mitchell, 1995), but, because it is sorbed on the surfaces of iron and aluminum sesquioxides in acid soils (Yanai, 1992), its bioavailability is low. Foliar K concentrations of sugar maple trees growing on the site were 6.5 mg g^{-1} (Foster et al., 1992), quite low "compared with other reports and in the range of trees undergoing a decline in vigor attributed to K deficiency (Bernier and Brazeau, 1988).

The forest floor (0 horizon) was collected from an $\approx$ 10 x 10 m area; then a tractor powered backhoe was used to collect the top 20 cm of A horizon soil. Rocks and roots were removed and the soil was thoroughly mixed during a two step sieving process employing 5 and 1 cm mesh sieves. This sieved soil was transported to Syracuse, NY, in plastic pots.

The Shoemaker, McLean and Pratt (SMP) method was used to calculate the amount of $CaCO_3$ required to raise the soil pH to 6.5, according to McLean (1982). This involved adding a buffered solution of p-nitrophenol, potassium chromate, calcium chloride dihydrate and calcium acetate and triethanolamine adjusted to pH 7 using sodium hydroxide. The lime requirement of 25 t ha^{-1} was the amount needed to raise the soil pH from 3.2 to 6.5 in the 9-1 pots of soil, an optimal soil pH for sugar maple. Lime was donated by Pfizer Chemical Company and was .95-97% $CaCO_3$, 2% acid insoluble matter and 0.5–1% $MgCO_3$. Average particle size was 4 μm, with $>$ 99% of the material $<$ 15 μm.

Each of 120 plastic pots (9-l) was amended in one of three ways. The 40 control pots were filled with thoroughly re-mixed soil, topped with a 3 cm depth of leaf litter, then one 2-year-old sugar maple seedling was planted in each pot. The 40 'incorporated' treatment pots were prepared by thoroughly mixing lime (equivalent of 25 t $CaCO_3$ ha- ^{1}) into the soil, adding a 3 cm layer of litter to the soil surface and planting seedlings. Surface limed pots were prepared the same way as the control but lime (25 t $CaCO_3$ ha- ^{1}) was sprinkled over the litter covering the soil surface after the seedlings were planted. Pots were buried to their

rims to maintain natural soil temperatures, positioned randomly 1 m apart in four equally spaced 30-m long rows.

Two-year-old sugar maple seedlings of unknown genetic stock were purchased from a commercial nursery in April 1988. The most uniformly sized 150 of the 300 purchased seedlings were selected and stored in the dark at 4°C until May 9, 1988 when 120 randomly chosen seedlings were planted, one per pot. Between unpacking and planting, seedlings were immersed in cold water to their root collars to ensure maximum hydration of root cells. Before planting, the root crown diameter (d), stem length (h) and root length of each seedling were measured. In addition, the root collar diameter and root and stem lengths of the remaining 30 of the 150 seedlings were also measured, dried at 70°C to a constant mass and weighed.

Seedling dimensions and weights of the 30 seedlings were used to estimate the mass of the planted seedlings. Scatterplots were produced of the original mass plotted against d^2, d^2h and double log transformation of each. Untransformed relationships were used, unless the variance was heteroscedastic. Then, transformations that homogenized variance were used. Confidence intervals (95%) were plotted to determine outliers and if only one outlier was found in any data set, the outlier was discarded before the regressions were re-run. Otherwise, all values were used in the regressions, For transformed variables, the bias was corrected using the Baskerville method (Baskerville, 1972). The equations were then used to estimate the original mass of planted seedlings from their pre-planting dimensions.

Soil moisture was monitored with tensiometers and maintained at -10 kPa using a drip irrigation system. Pots were weeded and insect defoliation minimized by manual removal of weeds and insects. In addition, deer were restricted from the plot with an electric fence modified for the restriction of deer from seedling plots (Burke et al., 1992).

Thirty randomly chosen seedlings were harvested from each treatment on August 30, 1988. Soil from each plot was sieved to collect all roots from the previously root-free soil medium. Harvested plants were cleaned, then separated into leaves, stems (material above root collar present at the start of the experiment), new shoots (material above the terminal bud scar minus leaves), coarse roots and fine roots ($\leq$ 2 mm in diameter). Roots were washed in tap water to remove soil and organic matter, but roots were never allowed to soak in the water. No effort was made to quantify mycorrhizal infection. All tissues were freeze-dried, after which the tissues were weighed and ground in a Wiley mill to pass through a 20 mesh screen. Yield was determined for each seedling as the difference between final mass and estimated mass of each plant part.

For each treatment, 30 samples of new shoots, stems, fine roots and coarse roots were analyzed for N using Kjeldahl digestion, P was determined colorimetrically using an acidified solution containing vanadate and molybdate and Ca, Mg and K were determined using atomic absorption spectroscopy at the State University of New York (SUNY) Soil Laboratory in Syracuse according to procedures of Bickelhaupt et al. (1983). In addition, 10 foliar samples for each treatment were produced by bulking each three of the original 30 samples. Nitrogen was measured using Kjeldahl digestion and P was determined colorimetrically at the SUNY laboratory. Foliar Ca, Mg, K, Al and Fe were determined using atomic absorption spectroscopy by Waters Laboratory at Camilla, GA. Blind duplicates and standard foliage material were included to insure quality control.

Analysis of variance (ANOVA) was utilized to determine significant differences among treatments. A completely randomized design with a fixed effects model was used for the ANOVA. For each variable, homogeneity of variance among treatments was tested with Bartlett's test (Sokal and Rohlf, 1981). When there was heteroscedasticity, the data were transformed to obtain homogeneity of variance. For all variables showing treatment effects, means were compared using Tukey's honestly significantly different test when sample sizes were equal. When the design was imbalanced due to missing data or insufficient material for analysis, Sheffe's test (Kirk, 1982) was used. Analyses of biomass and yield were conducted using SYSTAT (Wilkinson, 1988) and

all Sheffe's tests and tests on foliar nutrients were conducted using SAS (SAS Institute, 1985).

Foliar nutrient concentrations were compared with published 'critical levels' (Bernier et al., 1989; Côté et al., 1993) to determine nutrient deficiencies. In addition, nutrient ratios were compared with published reports of optimum (Lozano and Huynh, 1989) and imbalanced values (Bernier and Brazeau, 1988) and relative nutrient balances were determined using the DRIS. This method minimizes effects of aging, season and crown position and, through the use of nutrient ratios, expands the usefulness and accuracy of foliar diagnoses (Walworth and Sumner, 1987).

The DRIS method allows nutrient ratios to be expressed in a meaningful way using nutrient balance indices. The indices are averages of the deviations of ratios of given nutrients relative to other nutrients from their ideal ratios. The ideal nutrient ratios, called 'norms', were developed for sugar maple by Lozano and Huynh (1989) from an Ontario population of sugar maple (Lozano and Huynh, 1989). The norms used were from upper crown position in that study, however, identical diagnoses resulted from all crown positions (Lozano and Huynh, 1989). Only nutrient ratios significant at the 5% level in separation of tree vigor were used, with norms and indices for N composed of N/K, N/Al and Ca/N ratios; P norms and indices of Ca/P, P/Fe and Al/P; K norms and indices of N/K, Ca/K, Mg/K and Fe/K; Ca norms and indices of Ca/N, Ca/P, Ca/K, Mg/Ca; Mg norms and indices of Mg/K, Mg/Ca, Mg/Fe and Mg/Al; and Fe norms and indices of P/Fe, Mg/Fe, Fe/N and Fe/K.

To produce the DRIS indices, functions were calculated to compare norm values with values derived from our experimental samples. One of two formulae was used, depending on whether the norm ratio was larger or smaller than the sample ratio. When the norm ratio for nutrients a and *b* ***(a/b)*** were larger than the sample ratio for those nutrients (A/B), the following equation was used to calculate the function for that ratio pair:

$$f(A/B) = \left(\frac{A/B}{a/b} - 1\right)\frac{1000}{\mathrm{CV}}$$

where CV is the coefficient of variation associated with the norm (from Lozano and Huynh, 1989). When a/b was smaller than ***A/B,*** the following equation was used:

$$f(A/B) = \left(1 - \frac{a/b}{A/B}\right)\frac{1000}{\mathrm{CV}}$$

The DRIS index for each nutrient consisted of the average of all functions for that nutrient.

When the nutrient indexed was in the numerator, functional values were added and when the nutrient was in the denominator, those functional values were subtracted. For example, the Ca index was calculated as:

$$\mathrm{Ca}_{\mathrm{index}} = \frac{[f(\mathrm{Ca/N}) + f(\mathrm{Ca/P}) + f(\mathrm{Ca/K}) - f(\mathrm{Mg/Ca})]}{4}.$$

Thus, these indices were scaled with zero indicating perfect balance. The magnitude of overabundance for any nutrient was indicated by positive index values and the magnitude of deficiency was indicated by negative index values. This method allowed easy diagnoses of nutrient deficiencies and overabundances and rankings of the most deficient to most abundant foliar nutrient relative to nutritional requirements. DRIS was calculated and graphed using Microsoft EXCEL 5.0 (Microsoft@ Corporation, 1993).

3. Results

Seedlings were similar in size among treatments at the start of the experiment. Stem and root lengths were 47.5(±1.9) and 28.4(±1.6) cm for the control, 46.7(±2.3) and 27.2(±1.0) cm for the surface and 42.6(±1.6) and 29.4(±1.4) cm for the incorporated treatments. In addition, there were no differences in estimated initial seedling biomass among treatment, with mean total seedling weights of 4.1, 4.3 and 4.7 g for control, surface and incorporated treatments, respectively.

Growth was greatest in the incorporated treatment > control > surface liming (Table 1). Harvested seedlings in the incorporated treatment were on average 37% larger than control seedlings and seedlings in the surface limed treatment were

9% smaller than control seedlings. Foliage, stem biomass, stem yield and large root biomass (but not yield) were greater in the incorporated than the surface limed treatment (P = 0.05). Similarly, new stem mass was not significantly (P = 0.07) greater in the incorporated than either other treatment. There were no significant treatment effects for fine root biomass.

Seedlings from the incorporated treatment had significantly greater foliar Ca (P = 0.002), K (P = 0.004) and P (P = 0.004) concentrations than in the other two treatments. Liming had no significant effect on foliar concentrations of Mg, N, Fe or Al.

Compared to control seedlings, Ca concentrations in fine roots were greater in the surface limed (P = 0.003) and incorporated treatments (P = 0.001) (Table 2), with greater concentrations in the incorporated treatment (P = 0.01). There were no significant differences in Ca concentration for new shoots, stems, nor coarse roots. Liming had little effect on Mg concentrations in non-foliar tissue. Incorporation of lime into the soil reduced K concentrations relative to the control in stems (P = 0.04) and fine roots (P = 0.05).

The only treatment effect for N was in coarse roots, where N concentrations were greater in the incorporated treatment than the control (P = 0.004) and were not significantly greater in the surface liming treatment (P = 0.06). P concentrations in coarse roots were greater in the incorporated treatment than control or surface limed treatment (P = 0.05), were not significantly greater for new shoots (P = 0.06) and stems (P = 0.08), and were not different for fine roots (P = 0.54). There were no differences between the control and surface application treatment for any tissue P concentration ($P \geq 0.43$).

Due to differences in biomass and tissue nutrient concentrations among treatments, total nutrient contents also varied among treatments. For example, there was 11% less K sequestered in seedling tissue from the surface application treatment compared to the control and 23% more sequestered in seedlings from the incorporated treatment. Similarly, there was 3% less P in seedling tissue in the surface application treatment compared to the control, but 86% more in the seedlings in the incorporated treatment. Mainly, these differences were due to more growth in the incorporated treatment, although concentrations were higher for some nutrients in that treatment.

In general, incorporating lime into the soil did not change foliar nutrient ratios (7 of 14) but four ratios were improved based on the Lozano and Huynh (1989) optimum values (Table 3). Only three ratios showed greater imbalance in the incorporated lime treatment. In contrast, most (10) of the nutrient ratios were made more imbalanced in the surface liming treatment while only one ratio improved.

DRIS index values showed that N was the nutrient most closely balanced relative to other nutrients and K was the most imbalanced. Also, P was deficient, while Al was highly overabundant. Ca, Mg and Fe were slightly overabundant in all treatments (Fig. 1). It was clear that surface liming exacerbated K, P and Al imbalances and nutrients were similarly balanced in seedlings from the control and incorporated treatments.

Table 1
The mean final mass (g ± SE.) and yield (± SE.) of seedling tissues in the three treatments

Tissue	Control	Surface	Incorporated
Biomass (g)			
Leaves	2.74 (0.26)^{ab}	2.44 (0.22)^{b}	3.66 (0.47)
New stem	0.33 (0.05)	0.34 (0.03)	0.69 (0.15)
Stem	5.98 (0.56)^{ab}	5.27 (0.60)^{b}	7.80 (0.84)
Large roots	5.16 (0.60)^{ab}	4.80 (0.52)^{b}	7.36 (0.94)^{ab}
Fine roots	2.55 (0.28)	2.38 (0.27)	3.41 (0.43)
Total mass	16.7	15.2	22.9
Yield			
Stem	1.70 (0.24)^{ab}	1.40 (0.23)^{b}	2.32 (0.29)
Large roots	2.22 (0.32)	1.92 (0.31)	2.55 (0.36)
Fine roots	12.60 (1.24)	11.34 (1.44)	14.00 (1.72)

Means with columns followed by the same letter are not significantly different ($P \leq 0.05$).
Yield is (final mass-estimated original mass)/original mass; ***n = 30.***

4. Discussion

Treatment effects were not biased by initial seedling size because seedlings were similar in size

Table 2
Nutrient concentrations (mg g^{-1} ± SE.) and content (mg) of nutrients in seedling tissues

	Concentration (mg g^{-1})			Content (mg)		
	Control	Surface	Incorporated	Control	Surface	Incorporated
Calcium						
Leaves	19.1 (4.6)"	21.6 (0.8)	26.1 (1.8)"	52.3	53.2	95.5
New shoot	16.8 (1.9)	17.8 (1.0)	15.1 (1.0)	5.5	6.0	10.4
Stem	9.6 (0.7)	9.2 (6.1)	8.9 (0.5)	57.4	48.5	69.4
Coarse roots	7.2 (0.5)	8.0 (0.6)	8.3 (0.5)	37.2	38.4	61.1
Fine roots	7.0 (0.3)[a]	8.6 (0.5)[b]	10.5 (0.4)	17.8	20.6	34.1
Total				170.2	166.7	270.5
Magnesium						
Leaves	2.5 (0.1)	2.7 (1.6)	2.9 (0.1)	6.9	6.5	10.8
New shoot	1.5 (0.1)	1.5 (0.1)	1.3 (1.2)	0.5	0.5	0.9
Stem	0.8 (0.1)	0.7 (0.1)	0.9 (01)	4.8	3.7	7.0
Coarse roots	1.4 (0.1)	1.3 (0.1)	1.4 (0.1)	7.2	6.2	10.4
Fine roots	3.0 (0.2)	2.7 (0.1)	2.5 (0.2)	7.6	6.4	8.5
Total				27.0	23.3	37.6
Potassium						
Leaves	4.9 (0.4)[b]	4.5 (0.4)[b]	6.2 (0.6)	13.4	11.0	22.5
New shoot	4.0 (0.1)	3.4 (0.3)	3.4 (0.2)	1.3	1.1	62.3
Stem	6.9 (0.4)	6.6 (0.4)[ab]	6.1 (0.4)[b]	41.3	34.8	47.6
Coarse roots	6.5 (0.4)	6.7 (0.2)	6.1 (0.4)	33.5	32.2	44.9
Fine roots	9.7 (0.4)[a]	8.9 (0.6)[ab]	8.2 (0.3)[b]	24.7	21.4	28.0
Total				114.2	100.5	145.3
Phosphorus						
Leaves	1.4 (0.1)"	1.4 (0.1)	2.0 (0.2)[b]	3.9	3.3	7.4
New shoot	0.9 (0.0)	0.9 (0.0)	1.0 (0.0)	0.3	0.3	0.7
Stem	0.5 (0.0)	0.5 (0.0)	0.7 (0.0)	3.0	2.6	5.5
Coarse roots	0.6 (0.1)"	0.6 (0.0)	0.9 (0.1)[b]	3.1	2.9	6.6
Fine roots	1.0 (0.0)	1.2 (0.1)	1.1 (0.1)	2.6	2.8	3.7
Total				12.9	12.0	23.9
Nitrogen						
Leaves	22.2 (1.0)	23.1 (0.9)	24.2 (1.0)	60.8	56.1	88.6
New shoot	8.6 (2.8)	9.7 (0.4)	9.5 (0.3)	2.8	3.3	6.6
Stem	5.7 (0.1)	6.1 (0.5)	6.0 (0.4)	37.1	32.1	4.7
Coarse roots	6.1 (0.5)"	8.8 (0.7)[ab]	10.2 (1.0)[b]	31.4	42.2	75.5
Fine roots	13.2 (0.8)	13.8 (0.6)	15.0 (0.8)	29.4	32.8	51.2
Total				158.5	166.5	226.8
Aluminum						
Leaves	0.12 (0.01)	0.14 (0.02)	0.14 (0.02)	0.33	0.34	0.51
Iron						
Leaves	0.09 (0.01)	0.11 (0.01)	0.13 (0.02)	0.25	0.27	0.48

at the beginning of the experiment. Furthermore, it was unlikely that the original nutrient status of planted seedlings influenced the results of this experiment because there was substantial growth in all treatments (354–474% of initial mass), thus any differences in original nutrient status would have been diluted.

An impressive divergence in growth response occurred between the liming treatments: surface liming depressed (not significantly) growth while

Table 3
Foliar nutrient ratios from seedlings planted May 9 and harvested August 30, compared with optimum ratios

Nutrient ratio	Optimum ratio[a]	Treatment		
		Control	Surface limed	Incorporated lime
N/K	1.8	4.5	5.1	3.9
N/Al	390.8	185.0	165.0	172.8
P/Fe	24.7	15.6	12.7	15.4
K/Al	226.1	40.5	32.1	44.3
Ca/N	0.6	0.9	0.9	1.1
Ca/P	6.1	13.6	15.4	11.6
Ca/K	1.1	3.9	4.8	4.2
Mg/K	0.1	0.5	0.6	0.5
Mg/Ca	0.1	0.1	0.1	0.1
Mg/Fe	19.4	27.8	24.5	22.3
Mg/Al	49.5	20.8	19.3	20.7
Fe/N	0.004	0.004	0.004	0.005
Fe/K	0.008	0.018	0.024	0.021
Al/P	0.03	0.08	0.10	0.07

[a] From Lozano and Huynh (1989).

incorporating lime into the soil improved growth. These results corroborate previous studies of sugar maple in which there was little influence of surface liming on tree growth (Smallidge et al., 1993). The lack of treatment effects in previous field liming studies could have been due to other factors including a much lower amount of applied lime. In this study, a relatively large quantity was needed to neutralize the soil (to pH 6.5 in the incorporated treatment), an amount more than twice that used in the experimental watershed liming study (Driscoll et al., 1996) and recommended for mineral soils by Brady (1984).

There is little information on the long term effects of liming, however, Ljungstriim and Nihlgard (1995) found no significant effect of liming on growth of European beech seedlings 5 years after liming (Ljungstriim and Nihlgard, 1995). Even finely ground limestone, such as that used in this experiment, has slow dissolution rates under a forest canopy. Concentrated lime in the forest floor could influence soil respiration, mineralization rates and abundances of bacteria and other organisms (Smallidge et al., 1993) that in turn can influence nutrient availabilities. Lime addition probably caused abrupt changes in soil pH down the profile, however, pH was not measured. If the incorporated lime treatment accurately simulated the soil conditions to be expected years or decades after surface liming, it appears that sugar maple growth and nutrient balance initially could be adversely affected but eventually could be improved.

The increase in foliar Ca concentrations was expected and is a typical but sometimes temporary effect following liming studies, e.g. (Ouimet and Fortin, 1992; Fyles et al., 1994). Relative to other cations, Ca was highly available in this soil (Foster et al., 1992), so it was not surprising that luxury consumption occurred in all treatments. In this study, the effects of added lime were not confused with that of added Mg because Mg levels in the lime were negligible ($\leq$ 1%). Because foliar Mg concentrations increased (but not significantly) with liming, it was concluded that Ca antagonism with Mg for uptake was not important in this study. Foliar Al concentrations were at the threshold of critical phytotoxicity levels, 0.14 mg g^{-1} for young sugar maple seedlings to 0.34 mg g^{-1} for mature trees (Thornton et al., 1986) and were not significantly higher in the liming treatments compared to the control.

In general, nutrient concentrations were above the critical values provided by Côté et al. (1993)

for sugar maple. The exception was K for which concentrations were below the critical level of 6 mg g^{-1} in the control and surface limed treatments, but not in the incorporated lime treatment. Bernier and Brazeau (1988) proposed 5.5 mg g^{-1} as a foliar concentration threshold below which sugar maple decline was expected (Bernier and Brazeau, 1988). However, it was possible that some retranslocation of K from foliage occurred before harvest: Bernier and Brazeau measured a 6-25% reduction in K concentrations during August in adult sugar maple trees.

Based on comparisons of the perennial and foliar tissues, retranslocation of K appeared to be more advanced in the control and surface limed seedlings than in the incorporated treatment. K concentrations in perennial tissues were higher and foliar concentrations were lower in the control and surface limed treatments compared to the incorporated lime treatment. These results are similar to those of an earlier study in which the more nutrient rich and vigorous sugar maple seedlings had delayed retranslocation of carbohydrates from foliage compared to nutrient poor seedlings (Burke et al., 1992).

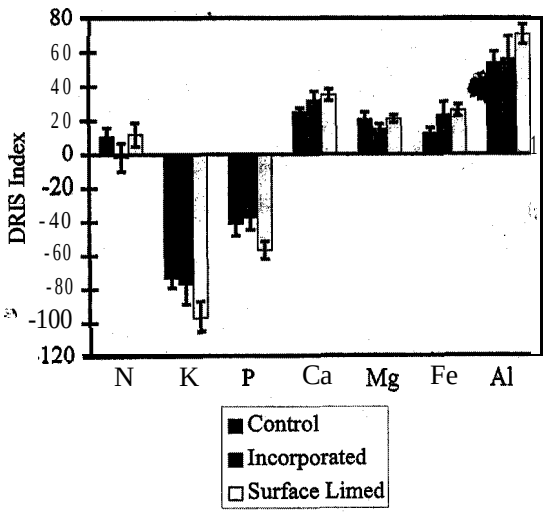

Fig. 1. DRIS indices (mean ± S.E.) for foliage in the control (black) incorporated lime (gray) and surface limed (white) treatments (n = 10). Indices for each element were scaled, with zero indicating perfect balance for that nutrient relative to other nutrients. The magnitude of overabundance for elements was indicated by positive index values and the magnitude of deficiency was indicated by negative index values. DRIS indices for N were calculated using N/K, N/Al, Ca/N and Fe/N ratios. Indices for P used Fe/P, Al/P and Ca/P ratios. Indices for K used N/K, Ca/K, Mg/K, Fe/K and K/Al. Indices for Mg used Mg/K, Mg/Ca, Mg. Fe and Mg/Al ratios. Indices for Ca used Ca/N, Ca/P, Ca/K and Mg/Ca ratios. Indices for Fe used P/Fe, Mg/Fe, Fe/N and Fe/K ratios.

Foliar nutrient concentrations showed that surface liming exacerbated the K deficiency and incorporating lime alleviated the deficiency, but the use of foliar nutrient concentrations to diagnose nutrient imbalance has been criticized. Concentrations can vary with plant and leaf age, crown position and there are seasonal differences (Walworth and Sumner, 1987): some nutrients accumulate during the growing season (Ca, Mg, Fe), while others decline (K, P and N) (Bernier and Brazeau, 1988). Although not a nutrient, Al concentrations in sugar maple foliage also declined during the growing season (Bernier and Brazeau, 1988).

Foliar nutrient ratios are preferred over nutrient concentrations in diagnosing nutrient status because nutrient ratios remain more constant (Walworth and Sumner, 1987) and some have been closely correlated with plant vigor. For example, the N/K ratio was correlated with decline in the vigor of sugar maple trees. Values of 3.4 or higher in July and 4.0 or higher in August indicated declining trees, ratios of circa 3.0 or less in both July and August indicated healthy trees (Bernier and Brazeau, 1988) and a ratio of 1.8 was optimum for growth (Lozano and Huynh, 1989). Seedlings from all our treatments were highly N/K imbalanced: control and surface limed seedlings had unusually high values and although still in the range where low vigor was expected, foliar ratios were lower in the incorporated treatment.

Comparisons of other nutrient ratios reveal additional nutrient imbalances. Relative to the optimum ratios, K was highly imbalanced with Ca, Mg and Al in all treatments. In addition, P was low relative to Ca and Fe and Mg was low relative to Fe. In contrast, Mg was in perfect balance with Ca in all treatments.

Nutrient ratios, although more useful than actual concentrations, also have limitations. In

young plants, ratios can be variable because concentrations can change rapidly (Walworth and Sumner, 1987). In addition, if more than one nutrient is deficient, it can be difficult to rank relative deficiencies. Major strengths of the DRIS analysis are that the assessment is highly sensitive to nutrient imbalances and leaf age and season have no effect on the DRIS nutrient diagnoses (Walworth and Sumner, 1987). In fact, the results of another DRIS analysis for sugar maple showed similar results were obtained regardless of crown position or date of sampling (Lozano and Huynh, 1989). Another strength of the DRIS analysis is that results are easily interpreted: in this study the ranking of nutrients in terms of limiting growth was K deficiency > P deficiency and Ca overabundance > Mg > N = Fe. Incorporating lime into the soil reduced the slight overabundance of N to almost perfect balance with other nutrients, probably due to an increase in the availability of other limiting nutrients that improved growth and diluted foliar N. Although surface liming did not influence the relative abundance of N, Ca, Mg or Fe, it intensified the relative deficiencies of K and P substantially more than foliar concentrations would indicate.

Our hypothesis that liming would reduce K uptake (based on Matzner et al., 1985) was supported only ,in the surface limed treatment. K appeared to be more plant available in soil of the incorporated lime treatment compared to the control. Similarly, P uptake was lower in the surface liming treatment and higher in the incorporated lime treatment. It was not determined whether greater P uptake was due to desorption of P from aluminum compounds in the soil or increased mineralization of organic matter. Reduced P uptake in the surface liming treatment could have been due to precipitation of calcium phosphates. Enhanced P desorption, greater P mineralization and greater precipitation of P are all possible outcomes of liming acidic soils (Haynes, 1982).

Obviously, the results of this study can not be fully extrapolated to mature forest stands because seedlings are physiologically different from adults trees (Kramer and Kozlowski, 1979). In addition, the experimental conditions of this experiment differed from field conditions: irrigation of the seedlings eliminated any possible interaction effects between nutrient balances and drought stress and herbivory and light limitation were eliminated. Although the outcome for field grown seedlings could have differed, these results from a controlled experiment 'showed liming sugar maple seedlings on an acidic soil could, in the short term, intensify nutrient deficiencies. Of particular concern is the influence of surface liming on the K status of the seedlings because this nutrient deficiency is associated with increased susceptibility to frost injury, drought and pathogens in sugar maple. In addition, these results suggest long-term effects of liming may be quite different from and more desirable than the short-term effects commonly reported.

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