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Soil properties and maple–beech regeneration a decade after liming in a northern hardwood stand

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ABSTRACT

Soil properties, regeneration, sugar maple (SM, *Acer saccharum* Marsh.) crown dieback, and light interception were evaluated following dolomitic lime application ($CaMg(CO_3)_2$; 0, 2, 5, 10 and 20 t ha^{-1}) in a base-poor and declining northern hardwood stand of Quebec (Canada). Ten years after liming, soil pH, cation exchange capacity and base saturation increased with the lime rate. Meanwhile, concentrations of exchangeable K, Na, and acidity (0–20 cm) decreased. Concentrations and content of total carbon, organic matter, and total N decreased in the top sampled soil layer, mainly for the highest lime rate. Mean crown dieback of SM ranked from 0 to 3.4% among lime treatments, while it ranked 18.4% for the unlimed controls. Light interception by the canopy responded with an opposite pattern to crown dieback, with higher interception in lime treatments and lower in control. Proportion and diameter of SM regeneration stems increased with lime rate while proportion of American beech (AB, *Fagus grandifolia* Ehrh.) regeneration stems decreased in the understory. Height and stem diameter of the three taller regeneration stems (mainly AB) in each plot were inversely correlated with lime rate. Overall, the results suggest that the increase in soil fertility following liming had a beneficial effect on SM regeneration within 10 years, even if light availability was lower under treated SM than under control, and had an overall negative impact on AB regeneration.

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1. Introduction

Sugar maple (SM; *Acer saccharum* Marsh.) has a broad distribution in North America, and thrives throughout the northeastern United States and southeastern regions of Canada. Many studies in the Northeast have demonstrated the importance of calcium (Ca) for SM vitality (Heisey, 1995; Ouimet and Camiré, 1995; Wilmot et al., 1995, 1996; Sharpe et al., 1999; Horsley et al., 2000, 2002; Moore et al., 2000; Duchesne et al., 2002; Moore and Ouimet, 2006). Calcium, the fifth most abundant element in trees, is an important component for wood formation and maintenance of cell wall (e.g. Lawrence et al., 1995). This nutrient also plays a role in fine-root growth of SM (Adams and Hutchinson, 1992). Moreover, some studies suggest better photosynthetic rates for SM with increasing Ca availability (Ellsworth and Liu, 1994; Wilmot et al., 1996). In recent decades, however, acid deposition increased leaching losses from soil of base cations, particularly Ca, above the replenishment rate by chemical weathering and atmospheric depositions, causing a reduction in the availability of mineral nutrients in some non-calcareous soils (Bailey et al., 2005; Houle et al., 1997; Likens et al., 1998; Ouimet et al., 2001, 2006; Watmough and Dillon, 2003).

Although other hypotheses were developed to explain the failure of SM regeneration and the large increase of pole-size American beech (AB; *Fagus grandifolia* Ehrh.) trees observed in northeastern North America in last decades, such as the indirect effect of beech bark disease (Hane et al., 2003), recent studies suggest that acid deposition and subsequent depletion of base cations and acidification of soils, combined with SM dieback in some areas, are another likely explanation to this phenomenon (Jenkins, 1997; Duchesne et al., 2005). Moreover, the absence of AB growth response to liming noted in the Long et al. (1997) study, contrary to SM, suggests that AB is not highly sensitive to the acid–base status of soils. This reasoning seriously questions the sustainability of SM in Ca-deficient and declining northern hardwood stands, and suggests that the importance of AB in many regions could increase at the expense of SM if no intervention is taken regarding Ca deficiency. It has been demonstrated that soil exchangeable Ca depletion and its influence on seedling dynamics could lead to substantial decreases in SM

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canopy dominance within a single forest generation (<125 years, Kobe et al., 2002).

To restore soil Ca status and SM tree health, Ca addition has been tested in Ca-poor northern hardwood soils (Wilmot et al., 1996; Long et al., 1997; Moore et al., 2000; Moore and Ouimet, 2006; Juice et al., 2006). Although beneficial effects of Ca treatment on SM trees were demonstrated in these studies, only a few of them have evaluated the effect of this treatment on SM regeneration (Long et al., 1999; Kobe et al., 2002; Juice et al., 2006; Bigelow and Canham, 2007). In Pennsylvania, Long et al. (1999) observed that SM seedling survival was higher (70%) in limed (22.4 t ha^{-1}) compared with unlimed plots (32%), 5 years after treatment. In New Hampshire, Kobe et al. (2002) observed a 52% increase in relative diameter growth of SM seedlings in Ca-amended plots (100 kg Ca ha^{-1}) compared to controls, after 2 years. In the same area, Juice et al. (2006) also reported a much higher survivorship of SM seedlings on Ca-treated (36.6%) than on a control watershed (10.2%), 5 years after treatment.

Given the importance of regeneration for future forest composition and structure, we evaluated the mid-term (11 years) effect of liming on regeneration in a Ca-poor northern hardwood stand. We hypothesized that liming changed soil properties and that these changes caused a beneficial effect on SM regeneration abundance and growth, but no effect on AB regeneration.

2. Materials and methods

2.1. Site description

The Lake Clair Watershed (46′57″, 71′40″, 285 m a.s.l.) is located approximately 50 km northwest of Quebec City, QC. The forest stand is uneven-aged and dominated by SM in association with AB and yellow birch (*Betula alleghaniensis* Britt.), with basal areas of 17.3, 7.3, and 4.0 m^2 ha^{-1}, respectively (2006 survey). Dominant and codominant SM trees are between 85 and 130 years old with an average height and diameter at breast height (DBH) of 20.2 m and 27.6 cm, respectively. Dendrochronological analysis revealed that basal area increment of dominant and co-dominant SM trees followed a negative trend over the last 40 years which is a strong indicator of a true tree growth decline (Duchesne et al., 2002, 2003). Forest inventory data revealed a 20% decrease of SM while AB increased by 128% in terms of basal area over the last 20 years. No sign of beech bark disease has been reported in this area. The soil is a well-drained Typic Haplorthod (Soil Survey Staff, 1998) or Orthic Ferro-Humic Podzol (Canada Soil Survey Committee, 1998) with a moder humus. Forest floor and soil pH in this area ranged from 2.8 to 3.7 and from 3.3 to 4.5, respectively (Houle et al., 1997, 2002; Moore, unpublished data). The site has been receiving atmospheric acid deposition in the order of 15 kg S ha^{-1} yr^{-1} and more since the 1970s and is being depleted in Ca (Houle et al., 1997). No earthworms were observed in this soil. Additional information on site and stand characteristics are provided in Houle et al. (1997, 1999).

2.2. Experimental setup

In 1994, powdered and pelletized dolomitic lime was applied on forest soils in an experimental forest section located at the border of the Lake Clair Watershed. This liming experiment was established to determine the nutrient, vigor and growth response of SM to amendments (Moore et al., 2000; Moore and Ouimet, 2006). Briefly, 98 SM, spaced by at least 15 m one from the other, were selected and randomly distributed among eight $CaMg(CO_3)_2$ treatments (0, 0.5, 1, 2, 5, 10, 20, 50 t ha^{-1}). The 1 t lime ha^{-1} rate corresponded approximately to the current total exchangeable Ca in the soil (200 kg ha^{-1}, Houle et al., 1997). Dolomitic lime was applied evenly within a 5-m radius around each tree in the last week of August 1994, after cutting and removing the entire understory over the same radius to reduce variability of understory abundance and to ensure uniform spreading of lime. No other tree stem was in the 5-m radius around SM trees. For the purpose of the present study, five trees were randomly selected from the 0, 2, 5, 10 and 20 t ha^{-1} treatments, for a total of 25 trees.

2.3. Regeneration sampling

Two inventory types were carried out in this study. First, in August 2005, regeneration stems were numbered and their diameter (at 15 mm from the surface of the forest floor) and height were measured in four circular sub-plots of 0.20 m^2 (radius 25 cm) located on cardinal points at 2.5 m from the center of the stem, for a total of 0.80 m^2 per plot, representing 1% of the plot area. Systematic sub-plots distribution for sampling an entire plot, as made in our study, is often considered more important than sample size (Cochran, 1977). Also, the surface sampling area was comparable to other published surveys on the subject (Long et al., 1999: 1.8%; Juice et al., 2006: 0.07%). The portion of sub-plot occupied by rocks or woody debris was visually estimated and subtracted from the total plot area. Second, height and stem DBH at 15 cm from the surface of the forest floor of the three taller regeneration stems were measured in each 5-m radius plot. Some observations made along the 11-year study confirmed that probably most of the taller regeneration stems of AB were sprouts. However, while it is likely that the lower regeneration stems of SM were mostly germinants, the origin of the taller regeneration stems of SM and the rest of AB regeneration was not determined.

2.4. Soil sampling and analysis

Ten years after liming, soils were sampled at two different locations around each tree. The first soil surface samples (0–12 cm) were extracted using a 261 cm^3 volumetric hammer soil sampler. Care was taken not to compact the soil during sampling. This first sample contained the forest floor (7–10 cm in thickness), a small eluviated horizon when present, and the top of the first B horizon. Volumetric sampling was carried out for this layer to ascertain whether soil organic C accumulated or not, because it was observed that organic C concentrations increased in the top soil layers with the lower liming rates 5 years after treatment (Houle et al., 2002). The mineral soil at 12–20 and 20–40 cm depth was qualitatively sampled separately using an auger. Samples of the same depth were pooled for each tree, air dried, weighed, and sieved to 2 mm before chemical analysis. Soil pH was measured using a soil-to-water ratio of 1:2.5. Exchangeable cations (K, Ca, Mg, Na, Al, Fe, and Mn) were extracted with an unbuffered NH_4Cl (1 M, 12 h) solution, and measured with an inductively coupled plasma emission spectrophotometer (Thermo Jarrell Ash ICAP-9000). Exchangeable hydrogen ions were directly measured in the extracts using a pH probe. Exchangeable acidity was estimated by calculating the sum of extracted H, Al, Fe, and Mn, assuming complete ion hydrolysis. Subsamples were ground to 0.5 mm for analysis of total carbon (dry combustion), organic matter (loss on ignition) and nitrogen (Kjeldahl) (Page et al., 1982).

2.5. Crown dieback and light measurements

In August 2004, crown dieback of SM trees was visually estimated (Moore and Ouimet, 2006). The percentage of light interception by the canopy, measured in August 2006, was also used as an index of crown defoliation and transparency, and to describe the resulting light environment under each tree. Above-canopy photosynthetic photon flux density 400–700 nm (PPFD) was measured with a point quantum sensor (Li-190, LICOR,

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