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Soil and sugar maple response 15 years after dolomitic lime application

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ABSTRACT

Dolomitic lime ($CaMg(CO_3)_2$) was applied in 1994 at rates of 0–50 Mg ha^{-1} to sugar maples (SMs) (*Acer saccharum* Marsh.) in a base-poor and declining northern hardwood stand subjected to a high level of acid deposition in Quebec. The soil chemistry and the SM nutrition, growth, crown vigor, and regeneration status were evaluated 15 years after treatment. The soil chemical properties still responded strongly to lime after 15 years. Similarly, the foliar Ca and Mg concentrations were still higher for treated trees relative to the control trees. After 15 years, the mean crown dieback of trees decreased quadratically with the lime rate, from 39% for the control trees to a value of 1–3% for the lime rates of 5 Mg ha^{-1} and higher. Additionally, the stem basal area increment for the limed trees was nearly double that of the unlimed trees in 2009. The lime application was also beneficial to the SM regeneration. The overall SM seedling density increased with the lime rate, being nearly twice as much in the 50 Mg ha^{-1} (32 seedlings m^{-2}) compared with the controls (16 seedlings m^{-2}). The proportion of the SM seedlings to all of the other species increased quadratically from 22% in controls to more than 55% in the 5–50 Mg ha^{-1} treatments. In contrast, the proportion of competitive species decreased quadratically with the lime rate, including American beech (*Fagus* grandifolia Ehrh.) for which the proportion in the treated plots (24%) was nearly half the proportion observed in the controls (46%). However, increase in stem density of regeneration and canopy closure in response to lime application limit the development of the regeneration which did not benefit in terms of diameter and height. These results show that a single lime addition has long-term beneficial effects on the soil chemistry and the SM nutrition, vigor, growth, and regeneration in base-poor and declining northern hardwood stands. Moreover, the results confirm that liming is an essential tool to restore the SM representation and health in acidic and base-poor soils.

1. Introduction

Numerous studies performed during recent decades have shown that decreasing sugar maple (SM) (*Acer saccharum* Marsh.) vitality remains a major concern in many areas of the northeastern North America, including New York (Hallett et al., 2006), Pennsylvania (Long et al., 1997, 2009, 2011; Horsley et al., 2000, 2002; Bailey et al., 2004), the New England states of New Hampshire and Vermont (Wilmot et al., 1995, 1996; Hallett et al., 2006; Schaberg et al., 2006; Gavin et al., 2008) in the USA as well as Quebec (Duchesne et al., 2002, 2003; Duchesne and Ouimet, 2008; Moore and Ouimet, 2006, 2010; Ouimet et al., 2008) and Ontario (Ryan et al., 1994; McLaughlin, 1998; McLaughlin et al., 2000; Watmough and Dillon, 2003; Tominaga et al., 2008; Watmough, 2010) in Canada.

The SM is established as being very sensitive to soil acidity (Thornton et al., 1986; Ouimet et al., 1996a). In survey plots in Vermont, Wilmot et al. (1995) observed a strong correlation between the soil pH and SM dieback. Other studies have suggested that acid deposition has accelerated the loss of available Ca from the soils with a low acid-buffering capacity in northern hardwood stands (Likens et al., 1998; McLaughlin, 1998; Houle et al., 1997; Sharpe, 2002; Bailey et al., 2005; Long et al., 2009). Duchesne et al. (2002) showed that the appearance of the SM decline phenomenon and associated growth reduction in Quebec can be related, at least in part, to the soil acidification and acid deposition levels.

In this context, it is unsurprising that many studies on SM dieback suggested that base cation deficiency, and particularly Ca deficiency, was a cause of the tree growth reduction and decline (Sharpe and Sunderland, 1995; Wilmot et al., 1995; Long et al., 1997, 2009; Bailey et al., 2004; Schaberg et al., 2006; Huggett et al., 2007; Watmough, 2010). Moreover, a positive growth and vigor response of SM to liming or Ca addition in base-poor northern hardwood stands demonstrated that the Ca deficiency was linked to SM decline in these ecosystems (Wilmot et al., 1996; Moore and Ouimet, 2006, 2010; Juice et al., 2006; Huggett et al., 2007; Ouimet et al., 2008; Long et al., 2011).

Although the short-term (Ouimet and Fortin, 1992; Wilmot et al., 1996; Moore et al., 2000; Juice et al., 2006; Moore and

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Ouimet, 2010) and mid-term (Long et al., 1997; Moore and Ouimet, 2006; Huggett et al., 2007; Ouimet et al., 2008) beneficial effects of fertilization with base cations on SM have been demonstrated, only one study on the long-term effect of this treatment is available (Long et al., 2011: 23 years). Currently, only four advanced trials using Ca (with or without Mg) components are still studied in northeastern North America: the first in Pennsylvania, USA (1988 to present) (Long et al., 2011); the second in Quebec, Canada (1994 to present) (Moore and Ouimet, 2006); the third in New Hampshire, USA (1999 to present) (Juice et al., 2006); and the fourth also in Quebec (2002 to present) (Moore and Ouimet, 2010). However, the liming trial in Quebec represents the only study that has documented the effect of economically operational rates (0.5, 1, 2, 5 Mg ha^{-1}) of a widely available Ca fertilizer on soils and SM. The goal of this study was to help fill this knowledge gap by documenting the long-term (15 years) effect of the 1994 liming experiment (Moore et al., 2000; Moore and Ouimet, 2006) on the soil and the SM nutrition, crown dieback, growth and regeneration in a declining northern hardwood stand situated in acidic and base-poor soils in Quebec, Canada.

2. Materials and methods

2.1. Site description

The experimental stand (46°57′N, 71°40′W) is located in the Duchesnay Experimental Forest, approximately 50 km northwest of Quebec City (Quebec). The elevation varies between 270 and 390 m. The average slope is approximately 10%. The mean annual temperature and annual precipitation (1960–1990) are 3.4 °C and 1300 mm, respectively. The vegetation is dominated by SM in addition to yellow birch (*Betula alleghaniensis* Britt.) and American beech (AB) (*Fagus grandifolia* Ehrh.). According to the *Canadian System of Soil Classification* (Canada Soil Survey Committee, 1998), the soil is classified as a stony, sandy loam Orthic Ferro-Humic Podzol. The humus is of moder type, and the surface deposit is a very acidic and stony glacial till derived from the granitic gneiss bedrock of the Canadian Shield.

2.2. Stand conditions and disturbance history

The Lake Clair Watershed, located near the experimental liming site, is among the catchments in northeastern North America where acid deposition continue to acidify soils, with relatively high net soil Ca losses (Watmough et al., 2005). Over the 15-year period of the study (1994–2009), the atmospheric NO_3^-, NH_4^+, SO_4^{2-}, and H^+ loads in bulk deposition were estimated at 22, 5, 23 and 0.5 kg ha^{-1} yr^{-1}, respectively. During this period, neither severe insect defoliation nor frost or ice damage was observed in this area. However, relatively short drought episodes occurred during the summers of 1995 and 2002 but without lasting growth reductions. The last forest cutting in the experimental area was a thinning, which occurred in the 1940s.

The foliar Ca concentrations for unlimed SM in the liming experiment were among the lowest in northeastern North America (cf. Moore and Ouimet, 2010). The low availability of Ca in this ecosystem is probably attributable to the combination of high levels of acid deposition, significant Ca leaching, and relatively low Ca replenishment through mineral weathering in the soil (Houle et al., 1997; Ouimet and Duchesne, 2005).

The dieback rates of selected trees in 1994 (before liming) were low (<7%, Fig. 3). These low rates can be explained by the selective choice of SM trees among the healthiest available to maximize the long-term monitoring for this liming experiment.

2.3. Experimental design

In the stand, 98 SM trees were selected, numbered and treated randomly in the fall of 1994 (14 replicates for controls and 12 for the seven other treatments; see below). Their diameter in 1994 was 30.9 ± 5.6 cm (mean ± SE; range = 20.0–44.0 cm). The dolomitic lime ($CaMg(CO_3)_2$) of agricultural grade, containing 22% of Ca and 12% of Mg, was applied manually within a 5-m radius of each tree during the last week of August 1994, after cutting and removing the entire understory throughout the same radius to reduce the variability of understory abundance and to ensure the uniform spreading of lime. No other tree stem was within the 5-m radius around the SM trees. A total of 8 lime rates were applied (0, 0.5, 1, 2, 5, 10, 20 and 50 Mg ha^{-1}). Additional details on the experimental design can be found in Moore et al. (2000).

Foliage sampling was performed in mid-July before the treatment (1994) and in mid-August for the years following the treatment (1995–1998, 2002, 2004, and 2009). The foliar nutrient concentrations were used to evaluate the nutrient status.

In October 2009, the soil around each tree was sampled in duplicate with a bi-partite auger (Eijkelkamp model 05.02). The forest floor was separated from the first 10 cm of mineral soil. The samples were pooled for each horizon and tree, air-dried, and passed through a 2-mm sieve prior to physico-chemical analyses.

Two increment cores were taken from each tree after the growing season in October 2009 to measure the tree radial growth. The annual ring width measurements were performed using the Win-Dendro version 6.1D software (Régent Instruments Inc., 2009) and validated with the signature rings. The ring width values were converted to basal area increments (BAIs) using the following equation:

$$BAI_t(cm^2) = \pi(R_t^2 - R_{t-1}^2)$$

where R is the tree radius (cm), and t is the year of tree-ring formation.

The dieback was evaluated from 1994 to 1998 and in 2002, 2004, and 2009 by estimating the percentage of the missing crown foliage (5% class intervals) from the careful visual inspection by the same two experienced observers. The crown assessment was performed the same day as the foliage sampling.

Two inventory types were made in summer 2009 to evaluate the regeneration response to liming. First, the 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 each tree; the total area was 0.80 m^2 per plot, representing 1% of the total plot area. Second, the species, height and stem diameter at 15 cm from the forest floor surface for the ten taller regeneration stems were measured in each 5-m radius plot.

2.4. Chemical analyses

The soil pH was measured with water using a soil:solution ratio of 1:2.5 (w:w). The organic matter content was determined by loss-on-ignition (Nelson and Sommers, 1982) and organic C by dry combustion (LECO). Exchangeable cations (Ca, Mg, K, Na, Al, Mn, Fe) were extracted with an unbuffered NH_4Cl (1 M, 12 h) solution and measured by inductively-coupled plasma emission spectrophotometry (ICP). The exchangeable acidity was evaluated by summing the H^+ (measured by pH probe), Al, Mn, and Fe concentrations of the extracts. The effective cation exchange capacity (CEC) was computed as the sum of exchangeable base cations and acidity. The concentrations are reported on a dry-weight basis.