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Response of northern hardwoods to experimental soil acidification and alkalinisation after 20 years

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A B S T R A C T

We resampled a research trial 20 years after applying acidifying or liming compounds (−16 to +16 kmol (+) ha^{-1} of acid-neutralizing capacity [ANC]) in a northern hardwood stand. Although soil properties showed no statistical changes after this period, foliar calcium (Ca) concentrations of sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britt.) and American beech (*Fagus grandifolia* Ehrh.) were still related to the treatment ANC. The three species showed distinct growth responses to treatments. Over the two decades following treatment, basal area increment (BAI) of sugar maple increased by 138% in limed plots compared with controls, while it decreased by 25% in acidified plots. The BAI of yellow birch in limed plots increased mainly during the second decade, while in acidified plots, it remained comparable to that of the controls. As for American beech, the BAI increased by 133% over two decades in acidified plots, but not significantly in limed plots. Results support the hypothesis that liming improves the foliar calcium status of these hardwood species, and that acid input: (1) leads to long-term nutritional imbalance for calcium that could explain, at least in part, the positive growth response of sugar maple and yellow birch to liming, and (2) contributes to slow the growth of sugar maple relative to that of American beech in northern hardwood stands located on acid soils in northeastern North America.

1. Introduction

The species composition of many northern hardwood stands on acid soils in northeastern North America has changed in the last 20 years. Sugar maple (*Acer saccharum* Marsh.) has decreased in favor of other tree species, especially American beech (*Fagus grandifolia* Ehrh.) (Duchesne et al., 2005; Bedison et al., 2007; Duchesne and Ouimet, 2008; Sullivan et al., 2013; Bishop et al., 2015; Pontius et al., 2016). The maple decline is generally related to nutrient stress linked to the poor base status of soils (Bal et al., 2015). Despite a 78% reduction in atmospheric SO_2 emissions and a 46% reduction in NO_x emissions in the United States over the last 25 years (Environment Canada, 2014), evidence of increasing soil acidity and of calcium loss has been reported in northeastern North America (Bailey et al., 2005; Courchesne et al., 2005; Miller and Watmough, 2009). Recent resampling of forest soils in the northeastern US and eastern Canada showed that the forest floor base saturation has begun to increase in relation to the reduction of SO_4 deposition (Lawrence et al., 2015). Nonetheless, restoration of available Ca in the soil has not yet been observed (Hazlett et al., 2011). The loss of available Ca from naturally base-poor soils has had deleterious effects on northern hardwood forest ecosystems, causing a decrease in sugar maple growth at the regional scale (Bal et al., 2015) and shifting the relative performance of seedlings and saplings to favor American beech over sugar maple (Duchesne and Ouimet, 2009; Battles et al., 2014). Meanwhile, reversal of soil acidification has improved both the growth and crown vigor of sugar maple trees relative to those of American beech (Huggett et al., 2007; Duchesne et al., 2013; Marlow and Peart, 2014).

In 2009, we revisited an acidification/alkalinisation experiment that was 20 years old at the time, to observe the long-term effects of two soil treatments (acidification and alkalinisation) on soil chemical properties, foliar nutrient status, and growth of the three main tree species forming northern hardwood stands in eastern Canada: sugar maple, yellow birch (*Betula alleghaniensis* Britt.), and American beech. The 10-year results had indicated that soil Ca saturation, foliar Ca concentrations, and growth rate of sugar maple (the only sampled tree species at the time) decreased in response to the acidifying treatment, and increased in response to the alkalinizing treatments at the Duchesnay site (Ouimet et al., 2008). We wanted to verify whether the addition of acidic compounds to a base-poor soil continued to cause soil base cation

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depletion and acidification after 20 years, and whether it predisposed trees to long-term nutrient stress and growth decline. By contrast, adding base compounds could improve tree mineral nutrition and growth in the longer term. We also wanted to test the hypothesis that sugar maple was more sensitive to acid or base addition than yellow birch and American beech.

2. Material and methods

Since the material and methods were detailed in length in a previous paper (Ouimet et al., 2008), only a brief summary of the experiment is recalled here.

2.1. Experimental site

Of the two original experimental sites, only the one at Duchesnay remained suitable for remeasurement in 2009. The site is located in the Lower Laurentians range, approximately 50 km northwest of Québec City (Quebec, Canada): lat. 46°57′ N, long. 71°40′ W; altitude: 285 m asl; mean ann. prec.: 1300 mm; mean ann. temp.: 2.5 °C. The uneven-aged stand is dominated by sugar maple, yellow birch, and American beech. A similar but untreated long-term forest monitoring plot (site no. 301, 0.5 ha) located near the soil treatment experiment was used as an untreated control to estimate the state and change in stand characteristics over the years (Table 1). The forest floor is of mor-moder type. The poor, very stony, moderately mounded, moderately well-drained, loamy-sandy soil was a Podzol derived from glacial till, according to the regional Archean gneissic lithology. It belongs to the Sainte-Agathe soil series (Raymond et al., 1976), the most widely distributed soil series mapped in Quebec, which spreads throughout the Lower Laurentians range. One year prior to treatment applications (1989), effective soil base saturation (BS) of the forest floor and of the first 15 cm of the mineral B horizon were 58.0% and 2.8%, respectively.

2.2. Experimental setup

Of the eight fertilizer treatments applied as a single dose in a randomized complete block design in 1990 (Ouimet et al., 2008), only three were revisited in 2009: (1) the control (acid neutralizing capacity [ANC] = 0), (2) the most acidifying treatment, consisting of 285 kg ha^{-1} of elemental sulphur (256 kg S ha^{-1}; ANC = −16 kmol ha^{-1}), and (3) the most alkalinizing treatment, consisting of 800 kg ha^{-1} of lime ($CaCO_3$; 320 kg Ca ha^{-1}; ANC = 16 kmol ha^{-1}). The rate of application had been adjusted so the ANC of the compounds would represent about 20, 0, or −20 times the amount of acidity brought by the annual atmospheric S + N wet deposition in southern Quebec in the early 1990s. We selected only those extreme soil ANC treatments since we wanted to study their impacts on the three main northern hardwood tree species (sugar maple, yellow birch, and American beech). The site comprised two blocks, for a total of two replications by treatment. Each block was divided into eight rectangular plots measuring 20 m × 40 m, separated by a 5 m buffer. Fertilizers were applied manually in each block at the end of May 1990. Treatments were allocated randomly among plots.

2.3. Sampling and laboratory analyses

In addition to sugar maple, yellow birch and American beech are co-occurring tree species in these blocks. In each block, care was taken to select three trees of each species that were free of major trunk defects and of important dieback. Diameter at breast height of these subject trees ranged from 12 to 70 cm (average ± SE: 28.1 ± 1.6 cm).

In July 2009, two increment cores were taken on each subject tree to measure basal area increment (BAI). At the same time, foliage was sampled from the upper third of the crown of each subject tree. After this, the forest floor was sampled by bulk volumetric sampling, and the first 15 cm of the mineral B horizons was sampled by augering, at four random spots in each block.

Cores were dried, glued to a wooden holder, and sanded according to standard procedure (Stokes and Smiley, 1968). After detection and identification of ring boundaries under binocular magnification, the last 40 annual rings were measured to the nearest 0.001 mm with the WinDendro Image Analysis System for tree-ring measurement (Regent Instruments Inc.). Ring width values were converted to BAI using R's *dpl* package (Bunn, 2008), version 1.6.2.

The collected leaves were first dried at 65 °C, then ground to 250 μm. Their total N (Kjeldahl) concentrations were determined by colorimetry (Lachat Quickchem 8000) following digestion with concentrated H_2SO_4–H_2O_2–Se at 380 °C (Parkinson and Allen, 1975). Phosphorus, K, Ca, and Mg concentrations were measured in the digests by inductively coupled plasma atomic emission spectrometry (ICP-AES, Thermo Jarrell-Ash Model 61E). Standard reference materials used were always within 5% of the reference values.

Replicate soil samples were pooled for each horizon and block, air dried, and passed through a 2 mm sieve prior to chemical analyses. They were analysed for pH in a 0.01 M $CaCl_2$ solution. Exchangeable cations (K, Ca, Mg, and Al) were extracted with a solution of unbuffered NH_4Cl (1 M) for 12 h, and measured by ICP-AES. Exchangeable acidity (H + Al) was determined by summing the net H^+ (extract H^+ measured by pH probe) and Al concentrations of the extract. The effective cation exchange capacity (CEC) was computed as the sum of exchangeable base cations and exchangeable acidity. Base saturation (BS) was calculated as the proportion of CEC accounted for by base cations. Subsamples were ground to 0.5 mm for total analysis. Organic matter content was determined by loss-on-ignition (Nelson and Sommers, 1982); total

Table 1
Forest composition (merchantable stems with diameter at breast height [DBH] > 9 cm) in the untreated long-term forest monitoring plot no. 301, located in the Duchesnay Experimental Forest near the soil treatment experiment.

Year	Density (nb. stems ha^{-1})				Average stem DBH (cm)				Stem basal area (m^2 ha^{-1})			
	SM	YB	AB	Total	SM	YB	AB	Total	SM	YB	AB	Total
1986	310	44	34	388	27.3	24.6	28.4	24.6	21.4	3.0	2.6	27.0
1989	300	42	36	378	27.5	26.0	27.8	26.0	21.2	3.0	2.8	27.0
1996	284	44	46	374	28.3	24.1	25.4	24.1	20.6	2.4	3.2	26.2
2001	246	50	84	380	28.9	23.1	17.9	23.1	18.8	2.6	3.0	24.4
2006	210	88	170	468	30.1	19.2	14.4	19.2	17.2	3.4	3.6	24.2
2011	188	120	246	554	30.2	19.2	14.0	19.2	15.6	4.8	5.0	25.4

Note: SM: sugar maple; YB: yellow birch; AB: American beech.