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Liming effect on radial growth depends on time since application and on climate in Norway spruce stands

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ABSTRACT

During the 1980s and 1990s, liming was largely used as a tool to protect or restore forest stands located on acid soils from further acidification due to atmospheric deposition. Whereas impacts on soil properties and tree nutrition are well documented, little is known about the long-term temporal impact of liming on radial growth, and on the effect of climate on this response.

We therefore analysed time series of radial increment on 128 dominant trees from spruce liming trials located in the Belgian (Gouvy, 1995–2008) and French (La Croix-Scaille, 1981–2008) Ardennes; these stands were limed at *ca* 40–45 years old. The growth gain associated with liming (GGL, %) was defined by the ratio of the difference in Mean Individual Basal Area Increment between treatments (BAINC limed–BAINC control) corrected for initial differences, to BAINC of the control trees. The effect of climate on GGL was assessed by computing the difference between precipitation (P) and evapotranspiration (PET) over three reference periods of the current growing year (March–June, July–September, March–September).

Liming resulted in a two stage growth response pattern. In the first stage (4–8 years after treatment), GGL increased up to a maximum value of 29% in Gouvy and 54% in La Croix-Scaille. In a second stage, GGL decreased linearly with time from application while remaining >0. In La Croix-Scaille, the residuals around this tendency (Y) were positively and linearly related to the difference (P–PET; X) during the current vegetation period ($Y = 0.0037X - 0.68$; $R^2 = 0.36$, $P = 0.0029$), suggesting tree response to liming depended on water availability. Compared to the control, liming increased the expected growth response that is described by the linear trend, without considering the variation due to climate.

1. Introduction

Following the widespread spruce decline that occurred on acid soils in the 1970s and 1980s, liming with $CaCO_3$ with or without additional Mg as $CaMg(CO_3)_2$ (dolomite), MgO and/or $MgSO_4{\cdot}7H_2O$ (kieserite) has been recommended as a tool to mitigate or prevent the effects of the so-called acid rain and heavy atmospheric N deposition in Central and Western Europe (Huettl, 1989; Ulrich, 1986).

Reanalysis of old and new liming trials, as well as results from controlled laboratory experiments, showed that these treatments improved the soil chemical properties, with most effects restricted to the topsoil (Formánek and Vranová, 2002; Matzner et al., 1985; Misson et al., 2001; Ponette et al., 1997; Ponette et al., 1996; Schaaf and Hüttl, 2006).

Increase in pH, cation exchange capacity and base saturation were expected to benefit tree vitality and growth. As long as Mg deficiency was not associated with severe foliar losses, crown condition of damaged trees could be more or less rapidly improved depending on the type and solubility of the fertilizer-liming treatment (Zoettl et al., 1989). By contrast, quite different responses were observed regarding tree and stand growth (Huettl and Hunter, 1992). Several reasons have been postulated to explain the lack of any growth responses or even the decrease in tree growth following liming, such as the existence of some other major growth constraint, induced deficiency or inappropriate liming rate (Huettl and Zoettl, 1993). While these factors do certainly have some influence, most studies completely disregarded the impacts time issues could have in explaining these contrasting responses. In particular, time of treatment application relative to stand age or to other disturbance, as well as time of measurement including time from application and integration period have often been overlooked in previous studies. Documentation of these effects would need detailed time series of tree increments, based on periodic measurements or, better, on destructive core samples.

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On the other hand, long-term tree response to liming is also of major importance to document how this treatment could possibly interact with other disturbances. This is of particular importance in the context of climate change. In the future, forest ecosystems could be more regularly impacted by extreme weather events (Klein Tank and Können, 2003; Lindner et al., 2010; Schär et al., 2004). For instance, some climatic models predict an increase in the frequency and mainly in the duration of drought periods (Burke et al., 2006; Hanson and Weltzin, 2000; Overpeck et al., 1990). A drought event like the one in Europe in 2003 is currently exceptional in term of intensity but it is expected to become the norm by the end of the century (Beniston and Diaz, 2004). The relative response of limed *vs.* unlimed stands to drought needs to be documented, especially in a context of high nitrogen deposition and chemically poor soils as in the Ardennes. In those conditions, high nitrogen inputs are expected to increase drought susceptibility of trees by reducing fine root density (Spiecker, 1990/1991), and were shown to induce nutrient unbalance (e.g. Nys, 1990; Zoettl et al., 1989). If lime application is generally expected to improve tree nutrition (e.g. Zoettl et al., 1989), its effects on drought sensitivity is controversial. Some authors postulated that improvement of chemical soil conditions would lead to increased Spruce rooting depth, leading to decreased sensitivity to drought, but contrasting patterns of fine root growth, biomass, and/or distribution were reported from liming field studies. In particular, several researchers reported shallower rooting systems and/or reduced fine root biomass in limed stands (Helmisaari and Hallbäcken, 1999; Kreutzer, 1995; Nowotny et al., 1998), which would increase sensitivity to drought.

In this context, the specific objectives of this study were (i) to analyse the long-term temporal pattern of the liming effect on Norway spruce trees using individual basal area increment (BAINC) as an indicator of tree vitality, and (ii) to evaluate the influence of climate conditions on Spruce response to liming. For this, we analysed time series of radial increment on 128 dominant trees from two well-documented long-term trials selected among a wider set of spruce liming trials (Jonard et al., 2010; Misson et al., 2001; Nys, 1989; Renaud et al., 2009) spread over the Belgian (Gouvy, 1995–2008) and French (La Croix-Scaille, 1981–2008) Ardennes; these stands were all limed at *ca* 40–45 years old.

2. Materials and methods

2.1. Study area and site description

Sampling was carried out in two liming trials installed in Norway spruce stands in the Ardennes. These two sites were chosen among various liming trials located in Belgium (Wallonia) and France, based on two criteria (i) availability of soil, stand and climate data, and (ii) controlled statistical design, avoiding any possible confounding effect.

The Belgian site is located near Gouvy (50°14′N, 5°59′E) at the northeast limit of the Belgian Ardennes while the French site is located at La Croix-Scaille (49°55′N, 4°50′E), in the north of French Ardennes. The average altitude is 510 m and 480 m, the mean annual temperature is 8.0 °C and 7.5 °C and the average annual precipitation is about 1000 mm and 1300 mm (1971–2008 period) at Gouvy and La Croix-Scaille, respectively. Both sites are located on highlands and on acid brown soils (Dystric Cambisol, FAO classification) representative of the forest soils of Belgian Ardennes (Delecour and Weissen, 1977; Genot et al., 2009). At both sites, the soils are acidic (pH H_2O < 4.5) and the soil exchange complex is largely dominated by exchangeable Al (Table 1). Both forests consist of even-aged pure spruce stands that were planted between 1948 and 1950 at Gouvy and in 1937 at La Croix-Scaille. Major stand characteristics of the control plots are shown in Table 2.

2.2. Liming treatments

Liming was applied in winter 1994–1995 at Gouvy and in autumn 1980 at La Croix-Scaille; the stands were respectively 45 and 43 years old. At each study site, the treatments, including the control, were applied using a randomised block design with four plots by treatment (Gouvy: 45 × 45 m, La Croix-Scaille: 50 × 50 m). The amount and the composition of the liming products are presented in Table 3.

2.3. Sampling procedure and ring-width measurements

Tree sampling was carried out in autumn 2008. At both sites and for each treatment, the sampled trees were selected from past inventory data, among the 250 largest trees per hectare in 2000 at Gouvy and in 1981 at La Croix-Scaille. This selection criterion was used as these individuals are expected to constitute the final stand (Dagnelie et al., 1988). Mean circumference (±confidence intervals

Table 2
Mean dendrometric characteristics of control plots in 2000 at Gouvy and in 1981 at La Croix-Scaille (standard deviation between brackets). Lime was applied in 1995 in Gouvy and in 1980 in La Croix-Scaille.

Site	Age (year)	N[a] (ha^{-1})	C_{130}[b] (cm)	Basal area ($m^2\ ha^{-1}$)
Gouvy	51	641 (57)	88 (5)	39.5 (1.6)
La Croix-Scaille	44	688 (47)	84 (3)	38.3 (3.8)

[a] Number of trees per hectare.
[b] Girth at breast height (arithmetic mean).

Table 1
Selected soil properties of the control plots at both sites (measured in 1997 at Gouvy and in 1979 at La Croix-Scaille).

	pH H_2O	N[a] ($mg\ g^{-1}$)	Exchangeable cations[b] ($cmol_+\ kg^{-1}$)					Base saturation[c] (%)	Stock of exchangeable cations ($kg\ ha^{-1}$)	
			Ca	Mg	K	Mn	Al		Ca	Mg
Gouvy										
0–10 cm	4.1	5.1	0.25	0.17	0.13	0.09	6.59	8	32.1	21.8
10–20 cm	4.3	3.0	0.06	0.05	0.05	0.05	2.48	6	10.0	8.3
20–40 cm	4.3	1.8	0.09	0.04	0.04	0.04	1.66	9	36.1	16.1
Croix-Scaille										
0–5 cm	3.4	4.5	0.80	0.19	0.31	0.04	6.77	16	68.1	16.2
5–15 cm	4.2	1.9	0.15	0.03	0.15	0.06	5.98	5	27.1	5.4
15–30 cm	4.3	1.2	0.08	0.02	0.15	0.03	3.43	7	21.6	5,4
30–50 cm	4.4	0.1	0.09	0.02	0.10	0.02	2.56	8	30.7	6,8

[a] Kjeldahl method (Duchaufour, 1970).
[b] Gouvy: barium chloride extraction (Hendershot and Duquette, 1986); La Croix-Scaille: ammonium acetate extraction (Duchaufour, 1970).
[c] $\{(Ca + Mg + K)/(Ca + Mg + K + Mn + Al)\} \times 100$.