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Long-term effects of forest liming on mineral soil, organic layer and foliage chemistry: Insights from multiple beech experimental sites in Northern France

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ABSTRACT

Most forest ecosystems grow on acid and nutrient poor soils. In many cases, a slow degradation of forest soil chemical fertility due to increasing external pressures (decreasing atmospheric inputs, intensification of biomass harvesting and silvicultural practices) has been observed and is a growing concern in the international forest community. When the pressure endured by low fertility forest ecosystems is too intense, nutrient losses and ecosystem function losses may occur, forest decline being the ultimate stage of this process. In such cases, forest liming with a carbonate product is a solution to restore soil fertility and reduce soil acidity, globally improve the ecosystem functioning and compensate for nutrient losses caused by biomass harvest and exportation. However, the effects of liming on ecosystem processes and the biogeochemical cycling of nutrients in forest ecosystems are still unclear. We studied the dynamics of magnesium and calcium originating from the dissolution of liming products in the different compartments (organic and mineral soil layers and, aboveground biomass) of five long-term (20 to 40 years) monitoring beech (*Fagus sylvatica* L.) plots located in Northern France from ecosystem magnesium and calcium budgets.

Compared to the control plots, soil exchangeable pools of Mg and Ca in the 0–15 cm mineral soil layer increased during the first decade after liming but these differences rapidly decreased after 20–30 years. The effect of liming on foliar concentrations and tree growth was still observed after 40 years, most probably because the biological cycling of these elements was more dynamic in the limed plots. Liming increased the decomposition rate of the soil organic layer but the pools of Mg and Ca in this layer remained relatively stable over time, probably because Mg and Ca concentrations in foliage and litterfall increased after the liming. Liming effects varied between sites depending on the liming product and amount, and the initial chemical fertility level of the soil. Although liming operations may help improve forest soil fertility, they may also generate nutrient deficiencies and/or imbalances for nutrients that are poorly available in the soil. The planning of liming operations therefore necessitates a thorough soil chemical fertility diagnosis.

1. Introduction

In forest ecosystems, elevated atmospheric inputs of inorganic sulphur and nitrogen may contribute to the acidification of the soil. Sulphate and nitrate inputs, if not immobilized in soils (microorganisms, uptake by plants, retained on soil constituents) are leached below the rooting zone accompanied by cations (including nutrient cations: Ca, Mg and K), which contributes to the degradation of chemical fertility and pH buffer capacity of the soil (Reuss and Johnson, 1986). This leads to an accelerated acidification of the soil (Schulze, 1989; Dambrine et al., 1998) and to tree nutrition disorders (Jonard et al., 2015). High levels of acid deposition in the past have strongly contributed to the degradation of tree mineral nutrition in Europe (Lefèvre, 1997; Dambrine et al., 1998; Dupouey et al., 1998; Poszwa et al., 1998; de Vries et al., 2003; Jandl et al., 2004; Vuorenmaa, 2004; Rogora et al., 2006; Boxman et al., 2008; Pannatier et al., 2011; van der Heijden et al., 2011; Lequy et al., 2013; Jonard et al., 2015) and North America (Johnson et al., 1988; Federer et al., 1989; Hedin and Likens, 1996; Lawrence et al., 1997; Huntington et al., 2000; Bailey et al., 2005; Johnson et al., 2008; Bedison and Johnson, 2010). In those parts of the

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world, emissions and deposition of acidifying agents reached a maximum during the 1970s for sulfur or the 1980s for nitrogen.

Since the 1980s, regulations have led to the reduction of emissions of sulphur and nitrogen air pollutants in Europe and North America. Although S deposition has decreased widely in North America and in Europe, forest soil acidification and forest soil fertility degradation remains a major concern because (i) the reduction of N emissions has been small compared to S (Vuorenmaa et al., 2017) and in many cases, N deposition has remained high (Schöpp et al., 2003; Rogora et al., 2006; Boxman et al., 2008), (ii) decreasing atmospheric deposition rates of Mg and Ca have been observed (Likens et al., 1998) and (iii) the increasing demand for bio-energy and "environmental friendly" materials has led to the intensification of silvicultural practices (*e.g.* shorter rotations and whole-tree harvesting) (Ranger et al., 2011; Achat et al., 2015; Pyttel et al., 2015; Thiffault et al., 2015). Moreover, the accumulation of deposited inorganic N and the mobilization of adsorbed inorganic S pools in the soil accumulated during the period of high SO_4 deposition may pose a threat to ecosystems (van der Heijden et al., 2011). All these pressures may either reinforce the acidification process or delay the natural recovery in anthropogenically acidified forest ecosystems, especially those growing on low chemical fertility soils. Understanding how these pressures impact forest ecosystems and their resilience and how remediation methods may restore degraded soil fertility are major concerns in order to better predict the sustainability of these ecosystems in the context of global change.

Liming may be used to decrease soil acidity, maintain or restore forest soil fertility and improve tree nutrition. In Northern and Central Europe, large-scale terrestrial liming with Ca and Mg carbonates was initiated in the 1980s to mitigate soil and stream acidification caused by acid depositions, and to improve forest nutrition and stream biodiversity. In France, liming is not a common forestry practice and has mainly been carried out in cases of severe soil acidification where tree nutrition and health was threatened. As a consequence, the soils of many forest ecosystems in France have remained acidic and/or acidification has remained an on-going process compared to other regions in Europe where liming was practiced. Many studies dealing with the effects of dolomitic liming on forest ecosystems have been carried out with sometimes contrasting conclusions.

Liming operations are expected to enhance the biological activity of the soil and thus enhance organic matter decomposition (Marschner and Wilczynski, 1991; Geissen and Brümmer, 1999; Vuorenmaa et al., 2017). However, some studies have reported no liming effect (Baath et al., 1980; Smolander et al., 1996) or a decreased decomposition rate after liming (McCay et al., 2013). Soil biological activity and community may be affected by liming (Balland-Bolou-Bi and Poszwa, 2012; Clivot et al., 2012; Lepleux et al., 2013; Moore et al., 2013), or not (Lepleux et al., 2013; Moore, 2014). Liming operations are also expected to improve tree nutrition and growth. Contrastingly in an experimental site in Pennsylvania, 23 years after a dolomitic liming, Long et al. (2011) showed both negative and positive effects of liming on tree growth depending on the tree species. Findings on topsoil fertility and tree nutrition reach a better consensus with generally positive effects of liming at short (Huettl, 1989; Wilmot et al., 1996; Burke and Raynal, 1998; Meiwes et al., 2002; Moore and Ouimet, 2014) and long term (Bakker, 1998; Moore et al., 2012; Forey et al., 2015; Long et al., 2015). Despite these studies, the long-term dynamics and impacts of liming on the biogeochemical cycling of forest ecosystems is still poorly understood and few studies dealing with the long term effects of liming have focused simultaneously on the different ecosystem compartments (mineral soil, soil organic layer, tree). Many questions regarding the dosage and the duration of liming effects, the fate and the residence time of applied elements in the soil plant system remain to be addressed.

The objectives of the present study focusing on five permanent beech (*Fagus sylvatica* L.) plots in Northern France are to (i) characterize and understand the long-term dynamics of Mg and Ca released from liming products in the mineral soil profile, the organic layer and the aboveground biomass and (ii) define and quantify the ecosystem response (fertility, acidification, tree nutrition) to liming. For this, we used the data from a network of monitored limed/fertilized forest plots in France.

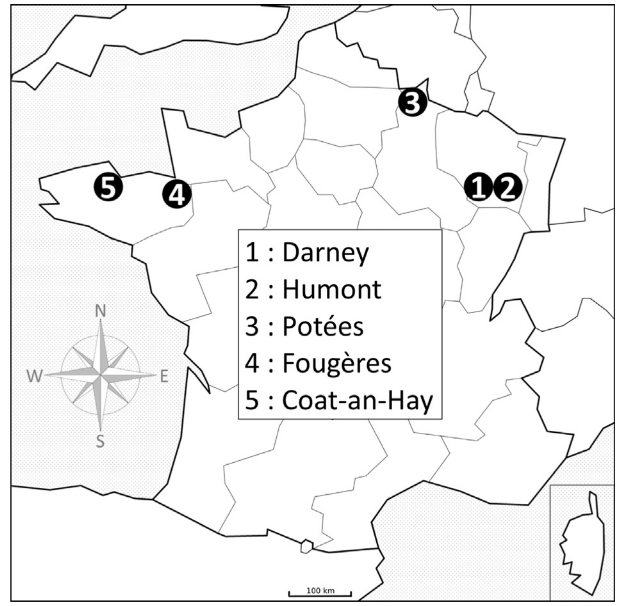

Fig. 1. Localization of the experimental sites.

2. Material and methods

2.1. Study sites

Five experimental liming sites in pure beech stands and located in the northern part of France were selected for the present study: Humont, Coat-an-Hay, Potées, Darney and Fougères. The sites were selected to cover a wide range of soil and climatic conditions. The Coat-an-Hay and Fougères sites are located in Brittany (oceanic climate). The Darney and Humont sites are located in the Vosges Mountains (semi-continental climate). The Potées site is located in the Ardennes (semi-continental climate) (Fig. 1). Site elevation ranges from 185 m (Fougères) to 570 m (Humont). The average annual precipitation calculated over the 1995–2016 period was close to 1000 mm for all sites except for Humont which was ca 1600 mm. Precipitation was evenly distributed throughout the year for all sites. The forest stand at each site is mainly composed of European beech (*Fagus sylvatica* L.) but differ in tree age: at the time of liming tree age ranged from 9 to 97 years (Table 1). European beech stands at the Potées and Coat-an-Hay sites were both plantations. All sites are situated within state-owned forests and are managed (thinnings) following the local forest management plan. Forest inventory data was available for the Potées, Darney and Fougères sites (Table 2).

Bedrock at the five sites varies from sandstone in the Vosges Mountains, shale in the Ardennes, to granodiorite (Fougères) and gneiss (Coat-an-Hay) in Brittany. The soil at the different sites is acidic and nutrient poor and soil types are similar between sites: Dystric Cambisols or Luvic Cambisols (WRB FAO). However, the physical and chemical properties of the soil vary between sites. At the time of the liming operation, the soil water pH (pH_{water}) values ranged from 3.8 (Fougères) to 5 (Coat-an-Hay) in topsoil (0–5 cm) and from 4 (Darney) to 5 (Coat-an-Hay) in the deeper soil layer (45–60 cm). The cationic exchange capacity (CEC) was below 10 cmolc kg^{-1} for all sites. The base saturation (BS) of the soil cationic exchange capacity was the lowest at both the sites in the Vosges Mountains (Humont and Darney) (BS $<$ 10%) in all the profile, intermediate at Fougères and Potées (BS