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Combined effect of atmospheric nitrogen deposition and climate change on temperate forest soil biogeochemistry: A modeling approach

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ABSTRACT

Atmospheric N deposition is known to severely impact forest ecosystem functioning by influencing soil biogeochemistry and nutrient balance, and consequently tree growth and overall forest health and biodiversity. Moreover, because climate greatly influences soil processes, climate change and atmospheric N deposition must both be taken into account when analysing the evolution of forest ecosystem status over time.

Dynamic biogeochemical models have been developed to test different climate and atmospheric N deposition scenarios and their potential interactions in the long term. In this study, the ForSAFE model was used to predict the combined effect of atmospheric N deposition and climate change on two temperate forest ecosystems in France dominated by oak and spruce, and more precisely on forest soil biogeochemistry, from today to 2100. After a calibration step and following a careful statistical validation process, two atmospheric N deposition scenarios were tested: the current legislation in Europe (CLE) and the maximum feasible reduction (MFR) scenarios. They were combined with three climate scenarios: current climate scenario, worst-case climate scenario (A2) and best-case climate scenario (B1). The changes in base saturation and inorganic N concentration in the soil solution were compared across all scenario combinations, with the aim of forecasting the state of acidification, eutrophication and forest ecosystem recovery up to the year 2100.

Simulations highlighted that climate had a stronger impact on soil base saturation, whereas atmospheric deposition had a comparative effect or a higher effect than climate on N concentration in the soil solution. Although deposition remains the main factor determining the evolution of N concentration in soil solution, increased temperature had a significant effect. Results also highlighted the necessity of considering the joint effect of both climate and atmospheric N deposition on soil biogeochemistry.

1. Introduction

Anthropogenic activities have contributed significantly to an increase in nitrogen and sulfur emissions since the end of the 1800s, leading to the acidification and eutrophication of ecosystems (Galloway et al., 2003 De Vries et al., 2007; De Schrijver et al., 2008). Atmospheric deposition is known to have a severe impact on forest ecosystem functioning by influencing soil biogeochemistry and nutrients balance, and consequently tree growth and

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overall forest health and biodiversity (Probst et al., 1995; Belyazid et al., 2006; Jonard et al., 2012).

Owing to the transboundary nature of atmospheric pollution, the United Nations Convention on Long-Range Transboundary Air Pollution (LRTAP) was established involving all European countries (UNECE, 2005). In this context, a common effort was made to reduce atmospheric emissions from the 1980s, keeping in mind that the Earth's soil can be considered a public good that is always at risk from the use of short-term and highly profitable technology typical of our century (Perc et al., 2013). As a result, atmospheric sulfur emissions have decreased by almost 80% in France, and the same trend has been observed in measured atmospheric deposition (Pascaud, 2013). Nevertheless the decrease was less obvious for nitrogen, with deposition reductions of around 35% and 5% for NO_x and NH_y respectively (CITEPA, 2010), due especially to the multitude and diversity of nitrogen sources (Galloway et al., 2008). Moreover, the nitrogen cycle is more complex than that of sulfur as nitrogen interacts with all ecosystem compartments, e.g., soil, plants and micro-organisms, and through various chemical forms (Galloway et al., 2003). For these reasons, atmospheric nitrogen emissions, deposition and effects on ecosystems have become an area of great interest in research in recent decades (Bobbink et al., 2010; Van Dobben and de Vries, 2010).

The noticeable impact of nitrogen on terrestrial ecosystems, and particularly on forests, is well documented in literature. Many experiments have been designed to study the impact of various nitrogen concentrations on soil biogeochemistry and vegetation composition. Results highlight significant variations in the nitrogen cycle as a consequence of higher nitrogen inputs, ranging from mineralisation and nitrification (Aber et al., 1995) to changes in species richness (Stevens et al., 2004), composition (Krupa, 2003; De Vries et al., 2007; Bobbink et al., 2010) or relative abundance (Gilliam, 2006). Moreover, leaching of nitrogen from soils involves a concomitant leaching of base cations (Dambrine et al., 1995), further threatening plant nutrient balances. One way of appreciating overall nitrogen equilibrium in the soil is to consider the balance between nitrogen inputs into the ecosystem and nitrogen immobilisation and uptake (UNECE, 2004), where nitrogen leaching occurs when inputs are greater than immobilisation and uptake. Therefore, nitrogen concentration in soil solution is often considered a key sensitive parameter for assessing the impact of atmospheric deposition on a given ecosystem.

Field experimental studies obviously depend on ecosystem characteristics such as soil pH. It has been shown, for example, that the nitrogen mineralisation rate increases with nitrogen atmospheric deposition and that the more acidic the soil, the faster the processes (Falkengren-Grerup and Diekmann, 2003).

Nevertheless, field experiments dealing with the impact of atmospheric N deposition do not enable predictions to be made for the long term. Therefore in order to model and predict the impact of atmospheric N deposition on forest ecosystems, and more particularly on soil biogeochemistry, a modeling approach is required. Historically, models developed for this purpose have been based on the ecosystem mass balance which, using nitrogen inputs and outputs through a given ecosystem, reflects the atmospheric N deposition that the ecosystem can tolerate before showing harmful changes (Hettelingh et al., 2001; Spranger et al., 2008). However, this modeling approach is steady state, i.e., it relies on the ecosystem having a sustainable state. Dynamic biogeochemical models have been developed to include time trends and changes (see De Vries et al., 2010 for an overview of the existing models). This is particularly important for testing different scenarios of atmospheric N deposition that, by definition, change over time.

Moreover, the impact of atmospheric N deposition must be considered in the today's context of climate change (Wamelink et al., 2009; Belyazid et al., 2011a De Vries and Posch, 2011). Indeed, soil biogeochemistry is directly and strongly affected by climate since climate influences soil temperature and moisture conditions, which themselves are a major driver of the decomposition of soil organic matter and consequently of soil nitrogen availability (Rustad et al., 2001; Ge et al., 2010; Butler et al., 2012; Guntinas et al., 2012). Therefore the expected temperature increase due to future climate change could also affect soil nitrogen processes.

Atmospheric N pollution and climate change impacts on ecosystems are traditionally considered separately, whereas they have a combined effect (Van Harmelen et al., 2002; Swart, 2004; Bytnerowicz et al., 2007; Serengil et al., 2011). To model and predict forest ecosystem trends effectively over time, climate change and atmospheric N deposition must both be taken into account.

In this context, this study aimed to use a modeling approach to predict the combined effect of atmospheric N deposition and climate change on temperate forest ecosystems in France, and more precisely on forest soil biogeochemistry, from the present day to 2100. Modeling tests were computed to determine the relative importance of climate and atmospheric N deposition on the N cycle and base saturation in the soil, both of which are of considerable importance for tree growth and forest stand development. To achieve these objectives, the integrated biogeochemical model ForSAFE (Wallman et al., 2005; Belyazid, 2006) was calibrated and validated for French forests, and used to simulate the future development of two forest sites in France dominated by oak and spruce.

2. Material and methods

2.1. Modeling tool: ForSAFE

2.1.1. Description

The ForSAFE biogeochemical model has been used in a number of European countries (Belyazid et al., 2006; Moncoulon et al., 2007; Belyazid et al., 2011b) and has regularly been improved as a matter of common concern. ForSAFE builds on the merger and then the improvement of the PnET forest growth model (Aber and Federer, 1992; Aber et al., 1997) and the SAFE soil geochemistry model (Warfvinge et al., 1993). It is a dynamic and process-based model at forest-stand scale.

ForSAFE includes four submodels related to: (1) soil hydrology, (2) soil chemistry and weathering, (3) soil organic matter decomposition and (4) photosynthesis and tree growth (Wallman et al., 2005; Belyazid, 2006).

ForSAFE simulates the temporal changes of a forest ecosystem, depending on soil characteristics, climate, atmospheric deposition and forest stand characteristics. Model outputs include the allocation of the major elements (C, N, Mg, Ca, K) in the three tree compartments (leaves, wood and roots), the uptake of these elements for tree growth, the fluxes (i.e., light and rainfall intercepted by trees and thus reaching the ground), the nitrogen and base cation content in foliage, the base cation weathering rate, the soil organic carbon and nitrogen content in the forest soil and deadwood, the soil solution characteristics (pH, concentration of major elements) for each soil layer, the tree biomass by compartment, the leaf area index and net photosynthesis, and finally soil moisture, potential and real evapotranspiration and percolation.

2.1.2. Calibration

The main calibration was performed on the characteristics of the dominant tree species of the forest stand under consideration (Wallman et al., 2005). The PnET model was used in ForSAFE partly because of the full set of parameters existing for different tree