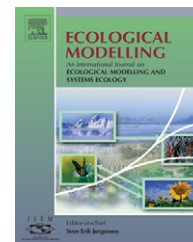


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# Investigating the soil acid–base status in managed boreal forests using the SAFE model

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## ABSTRACT

A dynamic soil chemistry model, SAFE, was applied to boreal stands located in three regions of Quebec (Canada) to investigate the relative contributions of forest harvesting methods (whole-tree and stem-only harvesting), natural disturbances (wildfire and spruce budworm outbreak) and atmospheric deposition on base cation fluxes and the soil acid–base status. Model parameterization was done using measured and published soil and vegetation data, published trends of nutrient dynamics, governmental databases on atmospheric deposition and climate, the reconstruction method MAKEDEP and throughfall equations that we developed for coniferous stands. The model suggested that forest disturbances, both anthropogenic and natural, increased base saturation, and thus base cation availability, to different degrees for periods of one to five decades. However, such disturbances, no matter their interval of return and their intensity, did not appear to be the main driving force of soil chemistry in the long term. On the other hand, simulation results showed that the B horizon at all sites has undergone acidification due to acid atmospheric deposition during the 20th century. Results suggest that atmospheric deposition is the main driver of long-term trends of soil chemistry for the study sites and that the issue of sustainability of soil productivity depends more on air pollution abatement policies than on forest management strategies.

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## 1. Introduction

Biogeochemical cycling in forest ecosystems is partly controlled by internal factors such as stand development and species composition (Alban, 1982; Miller, 1995; Binkley and Giardina, 1998; Bélanger et al., 2004a). Boreal forests of north-eastern Canada are also driven by periodic stand-replacing disturbances such as fires, windstorms, insects and pathogens

that alter nutrient fluxes over various periods of time (e.g. Sprugel, 1984; Yorks et al., 1999; Lamontagne et al., 2000; Hunter, 2001). To those natural influences that have shaped boreal ecosystems functioning for thousands of years, human action in the form of atmospheric pollution and intensive harvesting has been added in the past century.

Many studies have documented the depletion of soil base cation reserves from forest soils of Europe and North America

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over the past several decades, attributed to acidic atmospheric deposition (e.g. Matzner and Murach, 1995; Likens et al., 1996; Driscoll et al., 2001). This depletion reflects the buffering of atmospheric inputs of acidity by dissolution of aluminium (Al) and soil cation exchange reactions; base cations are displaced from exchange sites by hydrogen (H) and Al ions, and readily leached out of the soil profile (Galloway et al., 1983). Declines in forest soil exchangeable base cation pools may also have been worsened by decreased atmospheric inputs of base cations in the last third of the 20th century (Hedin et al., 1994). Base-poor forest ecosystems of the Canadian Shield have been deemed extremely sensitive to acidic deposition and at risk of further base cation depletion if harvested (Watmough et al., 2005; Duchesne and Houle, 2006). Moreover, theoretical geochemical budgets calculated by Paré et al. (2002) for the boreal forest of Quebec showed that clearcutting, especially when done using an intensive method like whole-tree harvesting, can lead to a negative balance of base cations (outputs > inputs) for stands of nutrient-demanding species like balsam fir (*Abies balsamea* (L.) Mill.) and trembling aspen (*Populus tremuloides* Michx.) located on shallow or coarse sandy soils.

On the other hand, Yanai et al. (1999) underlined the difficulty in distinguishing the relative effects of natural forest succession and acidic deposition on base cation cycling, even with extensive long-term field studies. Also, Thiffault et al. (2006) have concluded that stem-only harvesting, when compared with whole-tree harvesting, results in a base cation loading that lasts at least 15–20 years due to the presence of debris left during the logging operations in boreal coniferous stands of Quebec. This loading is however dwarfed when compared with that associated with wildfire (Thiffault et al., in press). Additionally, Bélanger et al. (2003) estimated that even though whole-tree harvesting does represent a loss of soil acid neutralizing capacity (ANC) in black spruce stands of Quebec, this loss is small with respect to the loss of alkalinity associated with atmospheric deposition.

Clearly, there is a need to quantify base cation fluxes, sources and sinks in the boreal forest so that we can assess the contributions of the various drivers of soil base cation availability and soil acidification. By doing so, the best mitigation/prevention strategies could be adopted, either at the forest management level or at the pollutant emissions control level.

Long-term field data of fluxes and changes in pools may be the best way of assessing the relative importance of ecosystem processes to long-term ecosystem changes (Johnson and Todd, 1990). However, ecosystem simulation represents an interesting proxy in the absence of such studies (Wei et al., 2003). Dynamic modelling provides an opportunity to increase our knowledge of the interactions between biological, edaphic and chemical components of the forest system while addressing the issue of time scale in ecosystem response (Kros and Warfvinge, 1995). The soil chemistry model SAFE (Soil Acidification in Forested Ecosystems) has been developed to provide a basic understanding of the main fluxes of ions in boreal ecosystems, the processes involved and the links between them (Warfvinge et al., 1993). In this paper, we present the results of a modelling exercise aimed at calibrating SAFE in order to theoretically explore the relative contribution of harvesting methods (stem-only harvesting: SOH and whole-tree

harvesting: WTH), natural disturbances and atmospheric pollution to the long-term dynamic pattern of the soil acid-base status for various boreal coniferous stands of Quebec. Different scenarios were used in this exercise, involving three sites with contrasting soil and vegetation characteristics. For one of these sites, a range of scenarios was also simulated to explore the influence of harvested species, growth rates, mineralization rates and canopy structure on soil chemistry.

## 2. Materials and methods

### 2.1. Model description

SAFE is a dynamic, multi-layer, process-oriented soil model that calculates soil water chemistry, cation exchange reactions and weathering rates from physical and chemical soil data coupled with a schematic description of atmospheric deposition as well as nutrient uptake and cycling.

SAFE includes mathematical descriptions of weathering of soil minerals, cation exchange reactions, leaching and adsorption of dissolved chemical components, and solution equilibrium reactions. SAFE also includes the following fluxes, specified as time-series files: (1) atmospheric deposition of Ca, Mg, K, Na, NO<sub>3</sub>, NH<sub>4</sub>, SO<sub>4</sub> and Cl; (2) litterfall of Ca, Mg, K and N; (3) canopy exchange of Ca, Mg, K and N; (4) plant net uptake of Ca, Mg, K and N; (5) net mineralization of Ca, Mg, K, S and N. Each soil horizon is assumed to be physically and chemically homogeneous. The processes interact only via the soil solution. Some processes not included in the model are sulphate adsorption and the organic complexation of metals such as Al. Also, dissolved organic matter is not modelled by the rate of mineralization of organic matter but rather specified as input data.

Changes in soil acidity are expressed as acid neutralizing capacity (ANC), which is modelled by calculating the mass balance of the various processes contributing or consuming acidity. The buffering of the liquid phase is controlled by the carbonate equilibrium reactions, the dissolution-precipitation reactions of a solid gibbsite phase which produce various charged Al-OH complexes, and the acid-base reactions of a monovalent organic acid (RH):

$$[\text{ANC}] = [\text{OH}^-] + [\text{R}^-] + [\text{HCO}_3^-] + 2[\text{CO}_3^{2-}] - [\text{H}^+] - 3[\text{Al}^{3+}] \\ - 2[\text{Al}(\text{OH})^{2+}] - [\text{Al}(\text{OH})_2^+]$$

Calcium, Mg and K are lumped together into one divalent base cation component (BC). The Gapon principle is used for controlling cation exchange reactions. The rate of exchange is limited by mass transfer of BC, and is proportional to the difference in BC concentration between the exchange complex and the soil solution (Warfvinge et al., 1993). The relationship between Al and H is constrained by gibbsite equilibrium and thus cation exchange in SAFE is an exchange reaction between BC and acidity. Many studies (e.g. Mulder et al., 1989) have shown that Al solubility is controlled by solid-phase organic Al complexes rather than some forms of Al hydroxides. It should thus be noted that the primary reason for using the apparent gibbsite solubility is that reasonable titration curves can be derived with this model and easily implemented in simula-

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