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ORIGINAL ARTICLE

Modelling changes in forest soil chemistry in the oldest spruce stands in the Potok Dupniański Catchment in Southern Poland using ForSAFE model

Stanisław Małek[1] ✉, *Salim Belyazid*[2], *Harald Sverdrup*[3]

[1] University of Agriculture in Krakow, Faculty of Forestry, Department of Forest Ecology, al. 29 Listopada 46, 31-425 Kraków, phone: +4812 6625077, e-mail: rlmalek@cyf-kr.edu.pl

[2] Belyazid Consulting and Communication AB, Stationsvägen 13, 51734, Bollebygd, Sweden

[3] Lund University, Department of Chemical Engineering, P.O. Box 124, 221 00 Lund, Sweden

Abstract

The dynamic forest ecosystem model ForSAFE was applied to the oldest spruce forest stand in a forested catchment – the Potok Dupniański (southern Poland), to study changes in forest soil chemistry and possible recovery from acidification following changes in atmospheric deposition. The simulation shows a considerable historical acidification. The model uses data from intensive monitoring of a plot established in 1999 in a spruce stand which was planted in 1880. Observations showed that stand soil was depleted of base cations. Percent base saturation measured in 1999 was between 5–8% in different soil layers. Notwithstanding large emission reductions in the region, forest ecosystems in the Potok Dupniański still suffer from very high loads of acidifying input. Soil recovery depends on future emission, and especially on base cation and nitrogen deposition. While higher base cation deposition will promote recovery, continual elevated nitrogen deposition in the future may delay recovery owing to its interference in the biogeochemical cycle (e.g. by increasing base cation uptake from the soil).

Key words

soil chemistry, soil acidification, base saturation, ForSAFE model, spruce stands, southern Poland

Introduction

Cycling of elements in Norway spruce (*Picea abies* Karst.) stands affected by industrial emissions is much as a subject of active research (Małek and Astel 2008). Conforming to the Convention on Long-Range Transboundary Air Pollution and subsequent agreements (UN/ECE 2005), different forest ecosystems respond differently to the reduction in acidifying deposition. Forest soils respond very slowly or not at all (Małek et al. 2005; Martinson et al. 2005a,b).

The Potok Dupniański catchment is particularly heavily polluted compared to other places in the region, and average S-SO_4^{2-}, N-NO_3^- and N-NH_4^+ in bulk precipitation in the period of 1999–2003 were 14 kg/ha, 9 kg/h and 12 kg/ha, respectively (Małek and Astel 2008; Małek 2010). The latest protocol within the UN-ECE-LRTAP Convention – the Gothenburg Protocol

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suggested a cut of S emissions in 2010 by 63% as compared to 1990 (UNECE 1999). Observations in the Potok Dupniański showed that the present base saturation is below 10% (Małek 2009).

Dynamic soil chemistry models are used to predict impacts of future emission and forest practices on soil and water quality. Most commonly used dynamic soil chemistry models are: MAGIC (Cosby et al. 2001), SMART (de Vries et al. 1994), VSD (Posch et al. 2003) and SAFE (Warfvinge et al. 1993). In this paper we model future soil chemistry at a spruce forest site in the Potok Dupniański using the dynamic model ForSAFE (Wallman et al. 2005, 2006). The study investigates forest soil response to changes in atmospheric deposition. The model output is compared to time series observations from 1999–2003 with a scenario in which we assume that present day base cation deposition will remain constant until 2100. The aim of the present study was to find out the result of emission control protocols on forest soils as well as to provide forest and emission management policies for information on development of soil chemistry in the oldest Norway spruce stands at the Potok Dupniański – the most damaged when compared with the stands of other age classes (Małek 2009, 2010).

MATERIAL AND METHODS

Site description

The Potok Dupniański catchment of the area of 1.6787 km^2 is located in southern Poland in the Silesian Beskid (latitude 49°35’, longitude 18°50’). The catchment area is covered by spruce stands at different development stages, which grow on the Istebna sandstone on dystric cambisols. This region of Polish part of the Carpathian Mountains is affected by air pollution (Bytnerowicz et al. 2002; Małek et al. 2005; Małek and Astel 2008; Małek 2010).

The instruments for measuring water volumes, meteorological parameters in spruce stands and open areas as well as outflow from the catchment were installed within the catchment in 1998 with the use of ICP Forest Manual (1998) method. Detailed characteristics of the catchment and installed equipment were presented in Małek and Astel (2008) and Małek (2010). The spruce stand observed was established after clear-cutting beech and spruce stands in the year 1880.

Model description

ForSAFE is a mechanistic model of forest ecosystems dynamics with limited empirical dependencies (Wallman et al. 2005, 2006). ForSAFE was designed for the purpose of simulating dynamic responses of forest ecosystems to environmental changes (Wallman et. al. 2005; Akselsson et al. 2010; Belyazid et al. 2011). The model brings together the three basic material and energy flow cycles: the biological cycle, the biochemical cycle and the geochemical cycle (Kimmins 1997). The ForSAFE model (fig. 1) integrates the biogeochemical cycles of water, carbon and selected nutrients in a forest ecosystem.

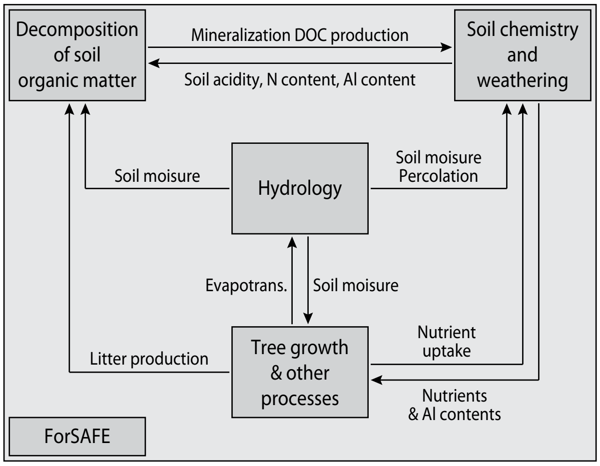

Fig. 1. ForSAFE is made up of four main central modules, to which the VEG module is annexed (ground vegetation was not present in this spruce stand and were omitted in presented studies) – adapted from Belyazid et al. 2006 with slightly modification

Photosynthesis is simulated by availability of light and ambient temperature, and scaled based on moisture and nutrients availability in the soil. Photosynthates are allocated to three tree compartments, namely wood, foliage and roots (Aber et al. 1992). Soil processes as regards balances of weathering, cation exchange, precipitation, mineralization and material mass are modelled according to the SAFE model (Alveteg et al. 1995). As stated by Belyazid and Moldan (2009), the release of carbon and nutrients from litter as well as the recalcitration of soil organic matter are modelled according to the principles developed in the DECOMP model (Wallman et al. 2006). Litter produced by the forest growth module is sorted into four pools of increasing resistance to decomposition, and decomposition rate of each of these pools is controlled by soil moisture and temperature, soil solution acidity and nitrogen content in soil. As a final point, the PULSE model for soil hydrology (Lindström and Gardelin 1992) is incorporated into ForSAFE to simulate the vertical flow of moisture in soil, simultaneously driving percolation and leaching of chemical elements (Belyazid and Moldan 2009).

Data acquisition

Deposition

Time series of throughfall and bulk deposition of SO_4^{2-}, NO_3^-, NH_4^+, Ca^{2+}, K^+, Mg^{2+}, Cl^- and Na^+ were measured at the site in the years 1999–2003. Set-up of the plot and number of samplers as well as collection frequency was described by Małek and Astel (2008) and Małek (2010). The average throughfall deposition in the period of 1999–2003 was used and scaled to historical and future deposition trends (Małek et al. 2005). The trends for SO_2, NO_x and ammonia used were described by Schöpp et al (2003) and these assumed full implementation of the UNECE LRTAP Gothenburg Protocol by the year 2010. Base cation trends were taken from Sverdrup et al. (1996). Apart from anthropogenic depositions given by the trends, dry deposition calculated by MAKEDEP (Alveteg et al. 1998) varies with canopy volume. The resulting depositions of sulphate, nitrate, ammonia and base cations were shown in Małek et al. (2005).

Soil data

Detailed soil data and methods applied in their determination were presented in Małek et. al. (2005) and Małek (2009). In order to calculate weathering, the SAFE model requires data on soil mineralogy in every layer. Soil mineralogy was determined based on total elemental analysis as described in Warfvinge and Sverdrup (1995). The surface area was calculated from texture according to Warfvinge and Sverdrup (1995). The determination of sulphate adsorption parameters by a series of batch experiments on samples collected at the site is described in Martinson and Alveteg (2004).

Soil solution data

Soil solution data from the Istebna site were used to validate the performance of the ForSAFE model in which base cations can be treated separately, not lumped together as Bc^{2+} (Wallman et al. 2005). Percolating soil solution was sampled each month during the 1999–2003 period by 4 soil lysimeters at the depth of 20 cm by isolated gravity technique (Malek 2010).

Vegetation

The MAKEDEP model simulates nutrient uptake and cycling. The model uses information on the standing biomass in different compartments and the nutrient contents of each compartment at the site. The total content of elements Na, K, Ca, Mg in the plant material was determined with the Atomic Absorption Spectrophotometer Varian AA-20 after wet mineralization in HNO_3 and $HClO_4$ solution at a ratio 1 : 4. Nitrogen was determined with LECO CNS 2000 analyzer. Adaptive nutrient data was used in the SAFE model, which implied that base cation uptake distribution in the defined rooting-zone in spruce stands would be limited when the concentration was low and directed to a soil layer with more available base cations (Martinson and Alveteg 2004).

RESULTS AND DISCUSSION

Comparison of measured and modelled (for base saturation only) soil chemical indicators showed that: chloride (indicates the accuracy of soil moisture simulation); sulphate adsorption; Na (indicates a rate of weathering); base cations and nitrates were reasonably modelled and in the range of measurements. Large seasonal variations in NO_3^- concentrations (fig. 2) are due to the lack of uptake by ground vegetation in the early spring (before trees start nutrient uptake).

For simplicity, all fluxes are printed once every 10 years, meaning that we don't see yearly variations. This is to avoid too much noise in the graphs, since we are more interested in trends. There is for example a peak in leaching in 1881 after the clearcut which does not appear in 10-year averages.

Modelled base saturation at 20 cm depth (mineral soil accessible to tree roots) is presented in fig. 3. The vertical line in 1880 shows the year of clear-cutting. Tree branches and needles are believed to be left behind at the site after the clearcut. Decomposition of and nutrient release from clearcut debris gave a decrease in percent base saturation (BS) by releasing base cations into the soil solution and dropped dramatically due to acid deposition, and will very slowly recover over the next 100 years. Base saturation will still remain under 20% limit even by the year 2100 which is confirmed by data obtained by Małek et al. (2005) and Mill (2007). The same process was observed in the Ore Mountains (Oulehle et al. 2007) .

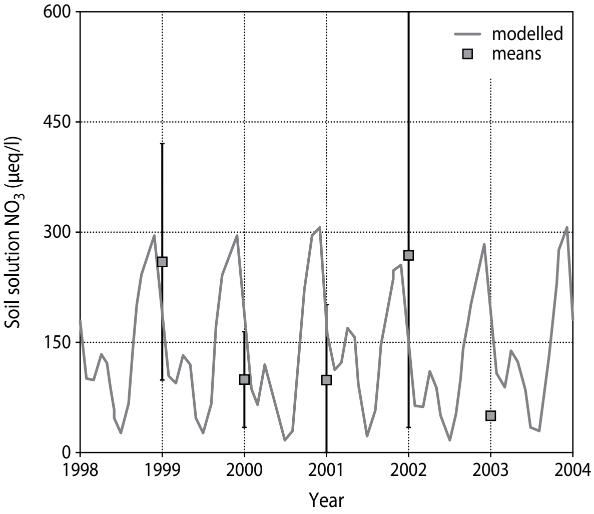

Fig. 2. Modelled (1998–2004) and measured – meas (1999–2003) content of NO_3^- at 20 cm depth within 1999–2004 years

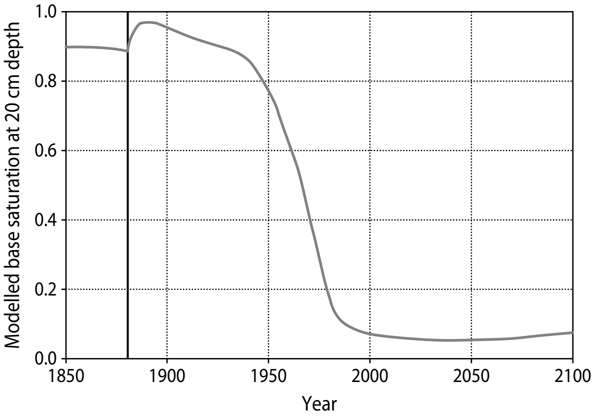

Fig. 3. Modelled base saturation at 20 cm depth within 1850–2100 years (1=100%)

Modelled base cation uptake (net uptake; this is the difference between gross uptake and base cation losses by litterfall) is presented in fig. 4 – it will slightly increase in the future sustained by the elevated nitrogen deposition. Net base cation uptake will be around 30% higher at the forest rotation same stage (stand age) as compared to before 1900. The drop in uptake in 1880 corresponded to low demand due to clear-cutting. Leaching increased substantially after acid deposition increase, then levels of a sulphur deposition decreased in the early 2000s (Małek and Astel 2008; Małek 2010).

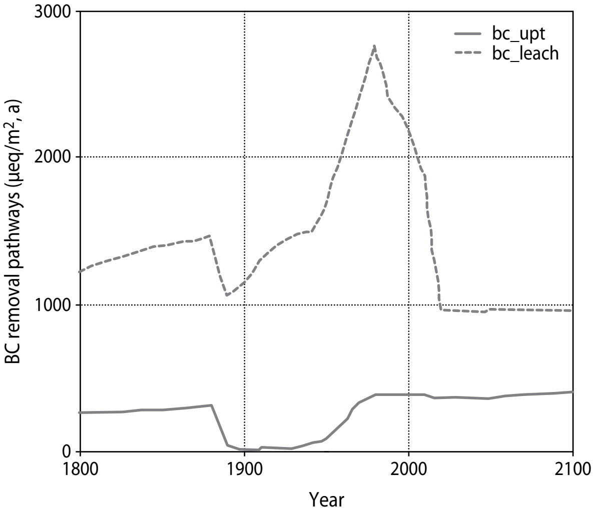

Fig. 4. Base cation leaching (bc_leach) and uptake (bc_upt) at 20 cm depth within 1800–2100 years

The increase of net uptake is caused by enhanced tree growth as a result of augmented nitrogen deposition. After clear-cutting, there is observed low net uptake and high base cation leaching attributable to low base cation uptake by young trees and a high degree of soil mineralization resulting from the clearcut residue. At this point, mineralization may be higher than uptake, resulting in negative net base cation uptake and considerable base cation leaching. The importance of net uptake in base cation removal from soil increases, shifting the principal cause of base cation depletion from leaching to uptake. This shift implies that, in the future, forest management will have a greater effect on soil base cation content than before and that high nitrogen deposition will contribute to depletion of soil base cations as it was observed on Swedish sites (Belyazid et al. 2006).

Due to the effect of artificial spruce monoculture on base cation nutrient budgets we have to consider using broad-leaved species in new forest generation so as to maintain forest in this site.

CONCLUSIONS

1. The results of the ForSAFE model show that soil acidification has occurred in the Potok Dupniański catchment, however temporary signs of recovery, although small, can be seen.
2. Atmospheric deposition of N and S can contribute to acidification of soils directly by changing soil chemistry and indirectly – by base cation uptake. Following the reduction in deposition (after the 1980s), soil under the oldest spruce stands continue to become acidified mainly as a result of removal of base cations through uptake by trees and harvesting.
3. Uptake of base cations is accelerated by higher availability of nitrogen from atmospheric deposition. This suggests that for forest soils to be able to sustain continuous forest rotations in the future, there are required further reductions in nitrogen emission or else spruce monoculture should be turned into mixed broad-leaved forest.
4. Soil recovery depends on future emission, and especially on base cation and nitrogen deposition. While higher base cation deposition will promote soil recovery, continual elevated nitrogen deposition in the future may delay recovery owing to its interference in the biogeochemical cycle (e.g. by increasing base cation uptake from soil).

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