ECOLOGICAL MODELLING 205 (2007) 410–422

available at www.sciencedirect.com

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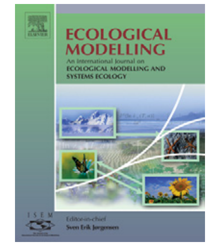

Modeling response of soil productivity to biogeochemical cycling and atmospheric acid deposition in the Hayden Brook watershed (Canada) using the ForNBM model

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ARTICLE INFO

Article history:
Received 7 March 2006
Received in revised form
27 February 2007
Accepted 2 March 2007
Published on line 24 April 2007

Keywords:
Acid deposition
Biogeochemistry
Modeling
Biomass
Soil productivity
Stream nutrient loading

ABSTRACT

A process-based biogeochemistry model, the ForNBM, was calibrated to simulate stream flows, nutrient concentrations and loadings on a monthly time scale using the field data collected from 1973 to 1985 at the Hayden Brook watershed, a natural forested mixed-hardwood watershed, in central New Brunswick, Canada. The model was then used to assess the major biogeochemical processes that influence soil productivity and the sensitivity of soil acidity and nutrient leaching to different scenarios of atmospheric acid deposition in the Hayden Brook watershed.

The results of the model calibration showed that the ForNBM model reproduced the field data well with the Nash–Sutcliffe coefficient of efficiency ranking from 0.63 to 0.99 for the simulations of stream flows, from −0.11 to 0.14 for the stream nutrient concentrations, from 0.03 to 0.63 for the monthly stream nutrient loadings, and from 0.94 to 0.99 for the cumulative stream nutrient loadings.

Field measurements and model predictions indicated that 90% of atmospheric deposited nitrogen (N) was retained in the soils. Atmospheric N deposition may be the most important source of N for the long-term watershed soil N accumulation in the Hayden Brook watershed. Biomass had low nutrient retention rates and high nutrient return rates, which demonstrated that the biogeochemical cycling was fast in the mixed-hardwood forest. The results also showed that annual N supply for biomass uptake was mainly from soil organic matter mineralization, and base cations (Ca^{2+}, Mg^{2+}, and K^{+}) from both soil organic matter mineralization and mineral weathering. Results of sensitivity analysis indicated that the soil pH and base cation leaching were more sensitive to atmospheric acid deposition than N. A 100% increase of current atmospheric acid deposition may cause a 0.6 unit decrease of soil pH, 44%, 39%, and 30% increase of soil Ca^{2+}, Mg^{2+}, and K^{+} leaching, respectively. Long-term soil productivity at the Hayden Brook watershed may also be declined by soil acidity and depletion of base cations due to increased leaching in response to increased atmospheric acid deposition.

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doi:10.1016/j.ecolmodel.2007.03.001

1. Introduction

An important process of biogeochemistry cycling is the nutrient transfer from terrestrial to aquatic ecosystems through stream nutrient loading. This transfer impacts both terrestrial and aquatic ecosystems (Howarth et al., 2002; Van Breemen et al., 2002). For terrestrial ecosystems, nutrient losses to streams through surface runoff, lateral flow and soil leaching may reduce soil nutrient availability for plant uptake. Over the long-term, excessive soil nutrient losses through stream loading may deplete soil nutrients and result in the decline of soil productivity. For aquatic ecosystems such as lakes and reservoirs, increased nutrient loading from soils may cause eutrophy and result in taste and odour problems, toxic algal blooms, fish kills and deteriorated water quality.

Traditionally, field experiments are conducted by measuring stream water yield and sampling water for chemical analysis to determine stream nutrient concentrations and loadings and their associated impacts on the productivities of both terrestrial and aquatic ecosystems (Meng et al., 1995; Jewett et al., 1996; Krause, 1982; Powell, 1981, 1884). Although field experiments can collect useful data for scientific research and watershed management, some ecological processes remain unknown, such as mineral soil weathering, as those processes are slow and difficult to measure. Thus, process-based models that link terrestrial and aquatic ecosystem processes are needed to (1) fill the data gaps for those ecological processes with difficulty to measure, (2) understand the relationships of stream nutrient concentrations and loadings with other ecological processes, and (3) analyze how the responses of terrestrial and aquatic ecosystems to different scenarios of ecosystem disturbance, atmospheric acid deposition, and climate change.

Long-term impacts of acid deposition on terrestrial and aquatic ecosystems have been considered an important environmental problem (Sogn and Abrahamsen, 1997). Analysis of how terrestrial and aquatic ecosystems respond to different scenarios of atmospheric acid deposition has been conducted in the United States (Meixner et al., 2004; Sogn and Abrahamsen, 1997; Johnson et al., 1993) and in Europe (de Vries et al., 1995; Kauppi et al., 1986) by using process-based ecosystem models. However, research on how Canadian soil and surface water ecosystems respond to changing climate conditions and acid deposition is limited. Recently, a process-based biogeochemistry model, the ForNBM, has been developed based on the ecological properties of Canadian forest ecosystems (Zhu et al., 2003a) and used to simulate the impacts of forest harvesting on soil productivity (Zhu et al., 2003b, 2004) and stream nutrient loading (Zhu et al., 2005). This provides a tool for us to assess the impacts of changing atmospheric acid deposition and climate conditions on Canadian forest soil and surface water ecosystems. The objectives of this study were to (1) calibrate the ForNBM model for the Hayden Brook watershed, a natural forested mixed-hardwood watershed in central New Brunswick, Canada; (2) determine seasonal patterns of stream nutrient concentrations and loadings and their relationships with biomass growth and climate conditions; (3) determine annual nutrient flux and retention rates in and between biomass, soil, and streams; (4) analyze the impact of different atmospheric acid deposition scenarios on soil acidity and productivity.

2. Methods

2.1. Site description

The Hayden Brook watershed is located in central New Brunswick (46°18′N latitude and 67°02′W longitude) and spans 660 ha (Jewett et al., 1996) (Fig. 1). According to the Köeppen climatic classification, the watershed falls in the Df region, a cold snow-forest climate with no dry season.

According to weather station data recorded from 1973 to 1985, the average annual air temperature was 3.5 °C, with January average at −14.50 °C and July average at 21.13 °C. Mean annual precipitation was 1322 mm, including 440 mm as snow (Lutgens and Tarbuck, 1986).

Forest cover consisted essentially of hardwoods, mixed-hardwoods and softwoods. The hardwoods tended to dominate at high elevations, while mixed woods were found on the slopes, and softwoods found in the valleys. The main species were red spruce (*Picea rubens* Sarg.), balsam fir (*Abies balsamea* (L.) Mill.), red maple (*Acer rubrum* L.), sugar maple (*Acer saccharum* March), striped maple (*Acer pensylvanicum* L.), beech (*Fagus grandifolia* Ehrh), yellow birch (*Betula papyrifera* Marsh), eastern hemlock (*Tsuga canadensis* Carr.), and eastern white cedar (*Thuja occidentalis* L.) (Powell, 1981, 1884).

The soil consists of Orthic Humo-Ferric (O.HFP), Ferro-Humic Podzols (O.FHP), and Gleyed Sombric Brunisols (GL.SB) on gently (2.50%) to strongly sloping (10.42%) terrain. They cover approximately 73% of the area and sustain the most productive softwood and hardwood stands of the watershed. The textures are silt to sandy loam with a depth of at least 50 cm. Gleyed Ferro-Humic Podzols (GL.FHP) occupy approximately 3% of the basin on the gently sloping areas in the upper portion of the basin. Other soils cover 24% of this area. These include Orthic Humic Gleysols (O.HG), Orthic Gleysols (O.G), and Rego Gleysols (R.G) found next to streams (Fig. 1; Krause, 1982).

2.2. Experiment and data collection

The Hayden Brook watershed research was a cooperative project of the University of New Brunswick, Environment Canada, the Province of New Brunswick, and St. Anne Nackawic Pulp and Paper Co. Ltd. The experiment was carried out from 1973 to 1985.

A weather station was set up at Headquarters in 1971 and had been in operation from 1971 to 1989 to record air temperature and precipitation quantity and intensity (Fig. 1). Air temperatures were recorded continuously with hygrothermographes located in a Stevenson screen. There were 11 standard AES (Atmospheric Environment Service, Canada) type B rain gauges with 8 in. in diameter throughout the watershed. Precipitation accumulation was measured on a 15 min basis by a shielded Fischer and Porter Recording precipitation gauge in the Headquarters. Three 250 ml precipitation samples were taken for each precipitation event