

## Application of the Nutrient Cycling Model NuCM to a Forest Monitoring Site Exposed to Acidic Precipitation in China\*<sup>1</sup>

ZHU Jian-Hua<sup>1</sup>, YU Peng-Tao<sup>1</sup>, T. A. SOGN<sup>2</sup>, WANG Yan-Hui<sup>1,\*2</sup> and J. MULDER<sup>2</sup>

<sup>1</sup>*Research Institute of Forest Ecology and Environment, Chinese Academy of Forestry, and the Key Laboratory of Forest Ecology and Environment of the Chinese State Forestry Administration, Beijing 100091 (China). E-mail: zhucool@caf.ac.cn*

<sup>2</sup>*Department of Plant and Environmental Sciences, Agricultural University of Norway, P.O. Box 5003, N-1430 Aas (Norway)*

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### ABSTRACT

The nutrient cycling model NuCM is one of the most detailed models for simulating processes that influence nutrient cycling in forest ecosystems. A field study was conducted at Tieshanping, a Masson pine (*Pinus massoniana* Lamb.) forest site, in Chongqing, China, to monitor the impacts of acidic precipitation on nutrient cycling. NuCM simulations were compared with observed data from the study site. The model produced an approximate fit with the observed data. It simulated the mean annual soil solution concentrations in the two simulation years, whereas it sometimes failed to reproduce seasonal variation. Even though some of the parameters required by model running were measured in the field, some others were still highly uncertain and the uncertainties were analyzed. Some of the uncertain parameters necessary for model running should be measured and calibrated to produce a better fit between modeled results and field data.

*Key Words:* acid rain, forest soil, nutrient cycling model, simulation

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### INTRODUCTION

Soil acidification because of acid rain in northern Europe has been blamed for causing indirect forest damage (Matzner and Murach, 1995). Increased soil acidification by acid rain is most likely taking place in southern China (Larssen and Carmichael, 2000; Larssen *et al.*, 2006). Since the beginning of the 1990s, China has become the third largest acid rain region in the world (Liu *et al.*, 2003). This ongoing soil acidification is a clear sign of a future threat to forest ecosystems in this region. Various biogeochemical processes may influence the forest health in the acid region, and the interactions among these processes are numerous, complex, and difficult to predict. The prevailing knowledge about the damage of acid deposition to forest trees in China is influenced by the researches in Europe on the one hand, and based on some observations and research in China on the other hand. From the 1980s, China has carried out several national research projects to study acid rain and its damage to forest ecosystems. A nation-wide forest monitoring system, including more than 230 thousand field study sites, has been established, but the damage on account of acid deposition is still not well understood (Feng, 2000). The need for studying and predicting the effects of various perturbations on forests, coupled with the great improvements in computing power and budget cuts in recent years, has led to an increased use of simulation modeling. In 2001, a comprehensive acid rain monitoring network was established in China by the Sino-Norwegian multidisciplinary Integrated Monitoring Program on Acidification of Chinese

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\*<sup>2</sup>Corresponding author. E-mail: wangyh@caf.ac.cn.

Terrestrial Systems (IMPACTS) project (Tang *et al.*, 2001). There are five IMPACTS monitoring sites which are all located within the acid rain control zone (Hao *et al.*, 2001) in southern China. As a part of the study by IMPACTS, the nutrient cycling model NuCM was applied in China for the first time.

The nutrient cycling model NuCM, developed during the Integrated Forest Study (IFS) in the USA (Liu *et al.*, 1991), is one of the most detailed models simulating processes in forest ecosystems, and has been applied to several forest ecosystems (ponderosa pine, red spruce, beech, eastern deciduous, loblolly pine, slash pine, Scots pine, and Norway spruce) in Europe and North America, to simulate the effects of changing atmospheric deposition, harvesting, species change, precipitation quantity, increased temperature, elevated CO<sub>2</sub>, liming, *etc.* (Liu *et al.*, 1991; Johnson *et al.*, 2000a, b). According to some research results (Johnson *et al.*, 1995; Sogn *et al.*, 1995; Sogn and Abrahamsen, 1997; Johnson *et al.*, 1998, 2000a, b), NuCM was able to simulate a lot of observed changes fairly well, by adjusting some key parameters. It has been concluded that NuCM is more successful in matching decadal-scale changes in nutrient pools and soils and less successful in capturing intra-annual variation in soil solution chemistry. However, the model has provided valuable insights into nutrient cycling in forest ecosystems, including the potential for short-term soil change and the great importance of nutrient translocation in N cycling. Nevertheless, the research results from Europe and North America can not be directly used to explain the problems occurring in the Chinese forest ecosystems, usually because of different atmospheric, hydrologic, vegetation, soil chemical, and rate limited and equilibrium processes. It is necessary to develop research on some details of these processes in the Chinese forest ecosystems.

In this study, NuCM simulations were compared with observed data from one of the IMPACTS monitoring sites and NuCM was calibrated to reproduce soil water data from the monitoring site. The objective of this study was to contribute to a clearer understanding of the uncertainties in the model predictions and thereby to improve the model.

## MATERIALS AND METHODS

### *Site description*

Tieshanping (TSP) (29° 38' N and 104° 41' E), one of the IMPACTS monitoring sites, is a Masson pine (*Pinus massoniana* Lamb.) forest located on a sandstone ridge, 25 km outside the metropolitan Chongqing City. The TSP small watershed has an area of about 16 hectares and the elevation ranges from 450 to 500 m. TSP has a subtropical, humid climate with little frost and snow, but with frequent fog all year round. Long-term (1971–2000) mean annual temperature is 18.2 °C, and mean annual precipitation is 1105 mm. Collection of precipitation, throughfall, and soil water samples has been undertaken at TSP since 1995. Volume weighted average pH value in precipitation is about 4.1. This site received the highest total amounts of both wet and dry S and N among the five IMPACTS monitoring sites, which have been estimated at 16 and 4.0 g m<sup>-2</sup> year<sup>-1</sup> (Vogt *et al.*, 2006). The soil of the site is silty loam to loam (pH 3.5 to 3.8) developed on sandstone, with the bulk density increasing from 1.25 g cm<sup>-3</sup> in the A horizon to 1.34 g cm<sup>-3</sup> in the B horizon and the base saturation ranging from 4.5% to 26.9%. Residues of primary minerals include quartz and K-feldspar. Secondary minerals are dominated by kaolinite, but small amounts of smectite and illite are also present. The forest stand at TSP is predominated by Masson pine. Trees were planted in the 1960s. Ten macro-plots with a size of 30 m × 30 m were established in 2000, of which four plots were for more intensive monitoring (Plots B, C, K, and L). For further details see Vogt *et al.* (2001, 2006) and Larssen *et al.* (2004).

### *Data collection*

Ceramic cup lysimeters are installed in the four intensive macro-plots (Plots B, C, K, and L) in the genetic soil horizons. Water chemistry in nine compartments (wet and bulk precipitation, canopy and ground vegetation throughfall, forest floor (H + O) layer, and soil A, B, BC, and C horizons) was determined. The following chemical parameters were measured: major anions and cations (*i.e.*,

$\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ ,  $\text{SO}_4^{2-}$ ,  $\text{NO}_3^-$ , and  $\text{Cl}^-$ ), by means of ion chromatography, ultraviolet absorbency, and alkalinity (Vogt and Aas, 2001). Prior to analysis in the laboratory, the quality was controlled in a soil analysis intercalibration study (Austnes *et al.*, 2002). Measured data from Plots B and C were used for NuCM calibration in this study. For further details see Larssen *et al.* (2004).

### *Model description*

The model theory of NuCM was derived from the results of the IFS projects, literatures, the ILWAS model, and the OR-NATURE model (Liu *et al.*, 1991). A full description of the model was given by Liu *et al.* (1991) and only a few relevant details are repeated below.

NuCM depicts nutrient cycling at the level of a stand, where the ecosystem is represented as a series of vegetation and soil components. The model provides for one generic conifer and one generic deciduous species of specified biomass and nutrient concentration (foliage, branch, bole, and root). The model routes the precipitation through the canopy and soil layers, and simulates evapotranspiration, deep seepage, and lateral flow. The soil includes multiple layers (up to 10), and each layer can have different physical and chemical characteristics. The movement of water through the system is simulated using the continuity equation and Darcy's equation for permeability and differences in moisture content. Percolation occurs between layers as a function of layer permeability and difference in moisture content. In these simulations, meteorological data from the period January 2001 through December 2002 have been used to generate hydrologic fluxes. NuCM tracks 16 solution-phase components.

The nutrient pools associated with soil solution, ion exchange complexes, minerals, and soil organic matter are all tracked explicitly. The processes that govern interactions among these pools include organic matter decay, nitrification, anion adsorption, cation exchange, mineral weathering, and Al dissolution/precipitation with user-specified rates. Organic matter decay is represented as a series reaction, with first-order dependencies on the reactant mass or concentration. The decay rate coefficients are a function of litter and microbial C:N ratios. The decay products include plant nutrients and organic matter, both solid and solution phases. One of the major products of litter decay is  $\text{NH}_4^+$ . The oxidation of  $\text{NH}_4^+$  to  $\text{NO}_3^-$  in soil is described with the help of a Michaelis-Menten reaction rate expression. NuCM simulates the noncompetitive adsorption of  $\text{SO}_4^{2-}$ ,  $\text{PO}_4^{n-}$ , and organic acids.  $\text{SO}_4^{2-}$  adsorption is simulated using a Langmuir isotherm;  $\text{PO}_4^{n-}$  and organic acid adsorption was represented by linear isotherms. Cation exchange is represented by the Gapon equation. The exchange of each cation is calculated in relation to  $\text{Ca}^{2+}$ . The selectivity coefficients are calculated using the initial soil solution cation concentrations and the amount adsorbed in soil. Mineral weathering is described with the help of a rate expression depending on the mass of minerals present and solution-phase  $\text{H}^+$  concentration taken to a fractional power. Changes in soil solution concentrations with time are also included.

## RESULTS

### *Parameter grouping*

There was no snow at the study site during the monitoring period (2001–2002). Cloud deposition, understory canopy, and stream processes were not considered during the simulation. The NuCM parameters related to snow and cloud chemistry, understory canopy, and stream processes were removed. Thus the total number of parameters required by NuCM was reduced from 120 to 108. The parameters were subjectively divided into three groups related to parameter estimation: 34 routinely or easily measured, 11 more or less established knowledge, and 63 calibrated.

### *Calibration for Plot B*

Three soil layers in Plot B, 3–12 (B1 horizon), 12–27 (B2 horizon), and 27–40 (B2 horizon) cm, were considered in the calibration. Generally, the observed seasonal variations in soil solution chemistry

were mainly caused by the dynamics in meteorologic and soil temperature data. As these data were quite accurately determined in the field, the simulated seasonal variations were not significantly altered because of adjustments of model parameters.

Darcy's equation was used to simulate permeable media flow in soil. Adjusting the coefficient of evaporation and the saturated conductivity so that the simulated output for water matched the observed produced a satisfactory fit between observed and simulated  $\text{Cl}^-$  concentrations in different soil layers (Fig. 1).

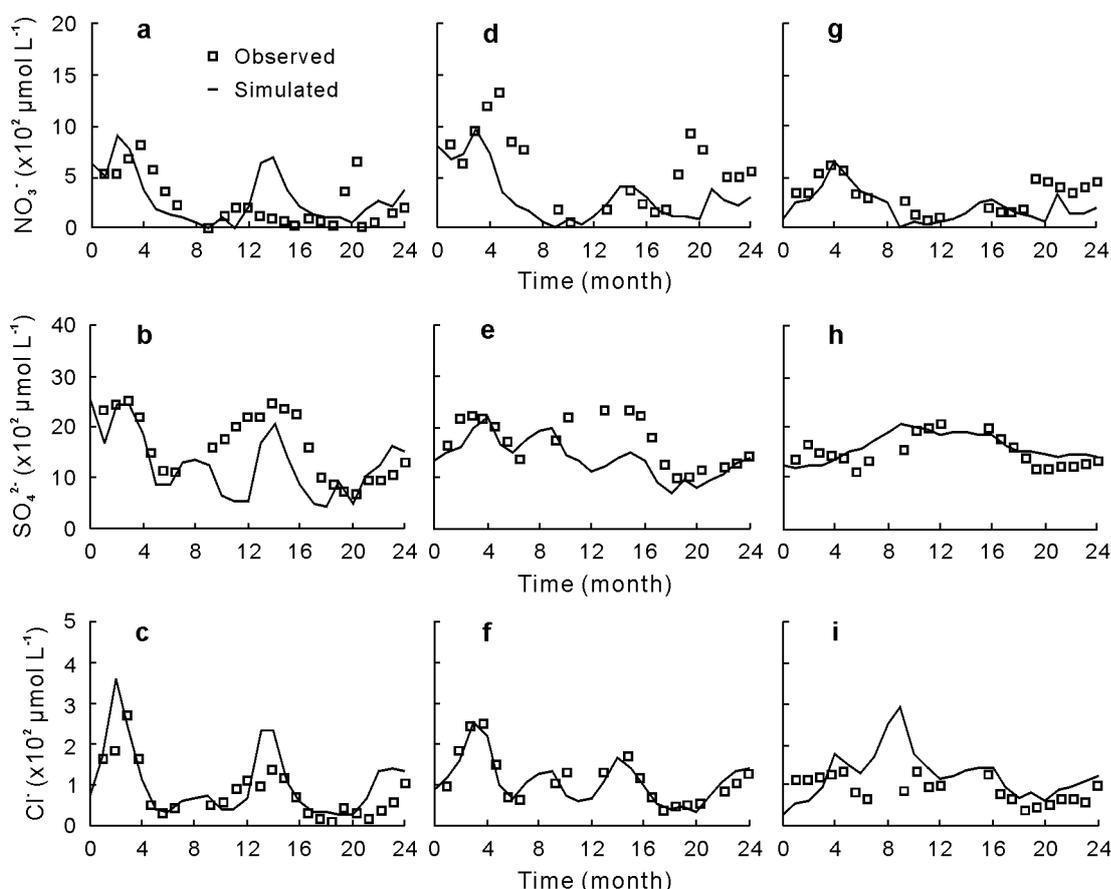


Fig. 1 Simulated *versus* observed soil solution  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{Cl}^-$  concentrations in Plot B of the study site: 3–12 cm (B1 horizon) (a, b, and c), 12–27 cm (B2 horizon) (d, e, and f), and 27–40 cm (B2 horizon) (g, h, and i) layers.

By adjusting the coefficient of nitrification and denitrification rate, an approximate fit was achieved between observed and simulated soil solution  $\text{NO}_3^-$  concentrations (Fig. 1). Because of low vegetation uptake and low nitrate leaching during the dormant season, the soil solution  $\text{NO}_3^-$  concentrations generally increased in winter (0–3 and 12–15 months). Later in spring and summer (4–9 and 16–20 months), it decreased to a very low level because  $\text{NO}_3^-$  was largely taken up by vegetation. The decrease in soil solution  $\text{NO}_3^-$  is also probably attributed to higher nitrate leaching caused by intensive precipitation in summer.

Sulfate adsorption was simulated using both linear and Langmuir (saturation) adsorption isotherms. Soil solution  $\text{SO}_4^{2-}$  concentrations were sensitive to the half saturation coefficient. By adjusting the half saturation coefficient for different soil layers, the observed  $\text{SO}_4^{2-}$  concentration level was approximately simulated by NuCM (Fig. 1).

Cation exchange reactions and complexes play an important role in the status of forest nutrients. The cation exchange process proceeds rapidly and thus provides effective short-term buffering. The

simulated base cation concentrations, as well as simulated anion concentrations, were highly sensitive to initial soil solution concentrations. Multiple iterations were conducted to match simulated and observed solution phase  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and  $\text{K}^+$  concentrations (Fig. 2). The focus should be on deeper soil layers (e.g., B2 horizon) as both the simulated and observed concentrations were less susceptible to short-term fluctuations. The simulated base cation concentrations were not significantly affected by changes in the vegetation uptake rate, weathering rate coefficients, and weathering dependence on soil solution  $\text{H}^+$  concentration.

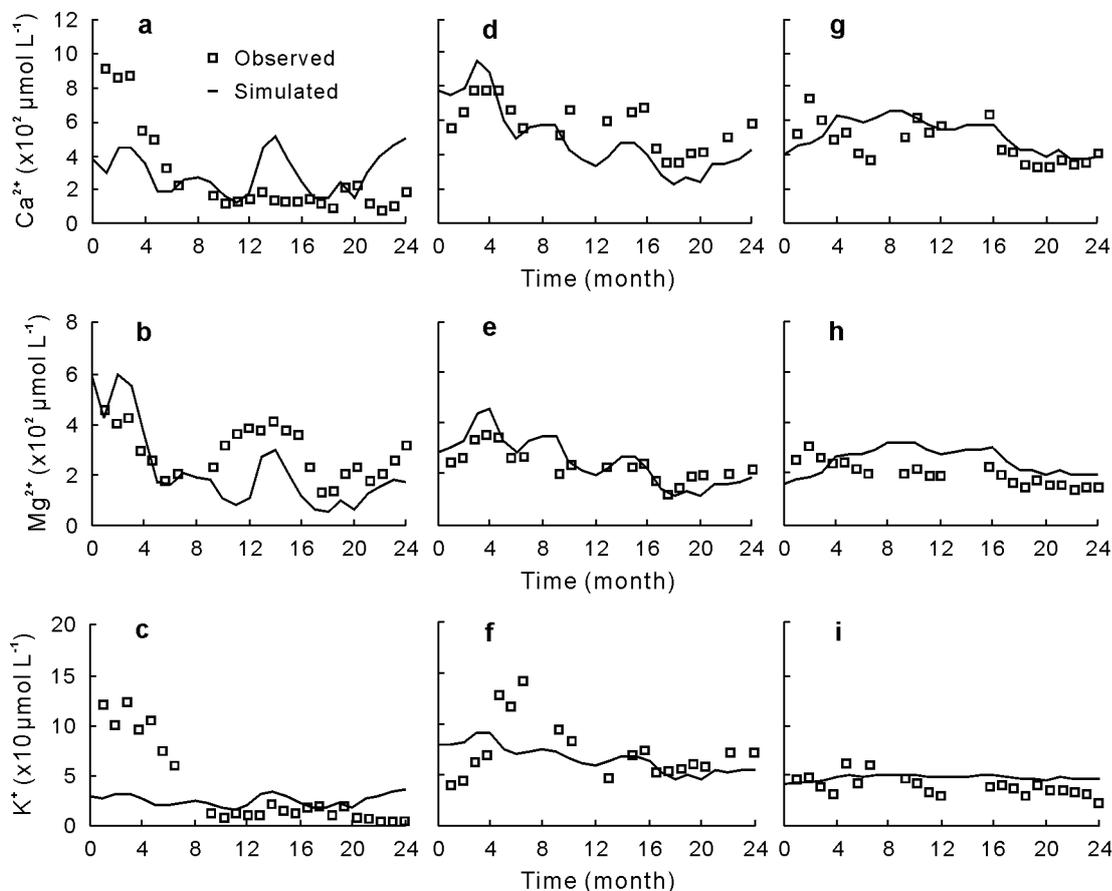


Fig. 2 Simulated *versus* observed soil solution  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and  $\text{K}^+$  concentrations in Plot B of the study site: 3–12 cm (B1 horizon) (a, b, and c), 12–27 cm (B2 horizon) (d, e, and f), and 27–40 cm (B2 horizon) (g, h, and i) layers.

The base cation concentrations were mainly controlled by cation exchange reactions and total anion concentrations as well. Total base cations in NuCM or in the real world must balance total anions. The solution concentrations of total measured cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ ,  $\text{Na}^+$ , and  $\text{Al}^{n+}$ ) and total measured anions ( $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$ , and  $\text{PO}_4^{n-}$ ) in different soil horizons are shown in Fig. 3. NuCM well simulated total cations and total anions, and there was a good balance between total cations and total anions.

Equations for calculating the release of base cations and  $\text{SO}_4^{2-}$  from organic matter decay had minor influence on the concentrations of these ions. Changing reaction rate coefficients and microbial C:N ratios in the intervals given in NuCM did not significantly change the simulated ion concentrations either.

High soil solution anion and cation concentrations were observed in the first several months (Figs. 1–3). It probably was artifact connected to disturbance because of soil solution sampler installation. The simulated values matched those observed better when the sampler system worked more stable several

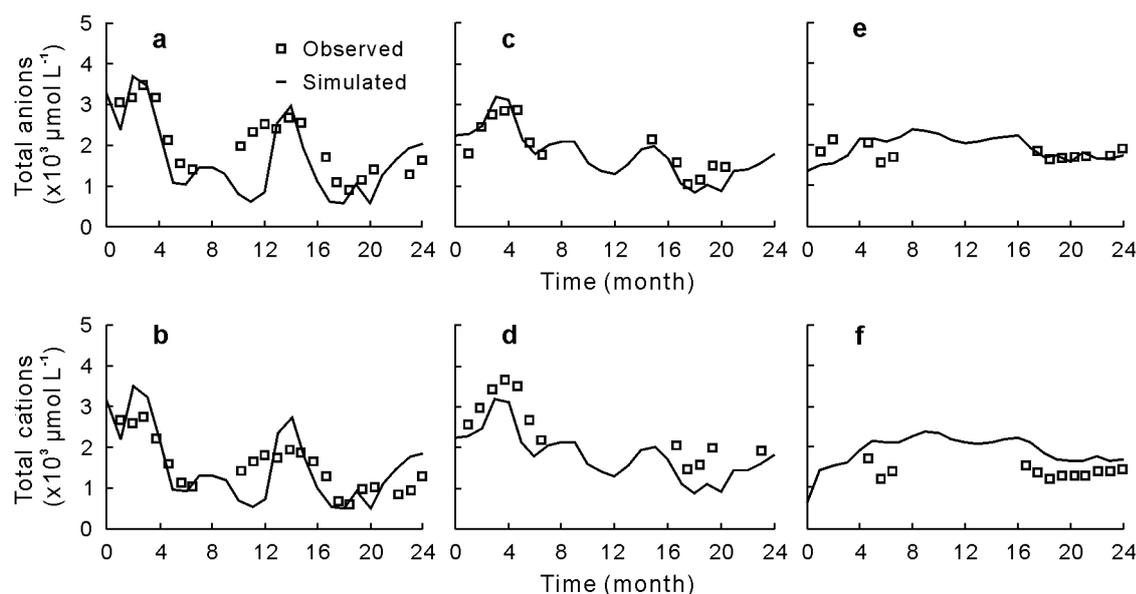


Fig. 3 Simulated *versus* observed total cation and total anion concentrations in Plot B of the study site: 3–12 cm (B1 horizon) (a and b), 12–27 cm (B2 horizon) (c and d), and 27–40 cm (B2 horizon) (e and f) layers.

months after it being installed.

#### Calibration for Plot C

The same meteorologic, deposition and soil temperature data files were used in calibration for Plot C as for Plot B. The physiologic parameters used in calibration for Plot B, except leaf area index, remained unchanged in calibration for Plot C. More and deeper soil layers were calibrated in Plot C than in Plot B. These include 12–22 cm (B2 horizon), 22–50 cm (B3 horizon), 50–70 cm (B3 horizon), and > 70 cm (BC horizon) layers. Since Plots B and C are from the same catchment and have similar topographical and vegetation characteristics, the same coefficient of evaporation for Plot B was used in the calibration for Plot C. Nevertheless, the soil hydrology conductivity for individual soil layers was adjusted in calibration for Plot C because different soil layers were considered. In the step of hydrology calibration, soil solution  $\text{Cl}^-$  concentrations were simulated satisfactorily for Plot C (Fig. 4). An approximate fit between observed and simulated  $\text{NO}_3^-$  and  $\text{SO}_4^{2-}$  (Fig. 4) was achieved after adjusting the relative parameters (*e.g.*, nitrification rate, half saturation coefficient, and the maximum adsorption capacity for individual soil layers). The model failed to reproduce the seasonal variation in soil solution  $\text{SO}_4^{2-}$  concentrations, but a mean value during the simulation period was well simulated.

Cation calibration for Plot C (Fig. 5) was as satisfactory as that for Plot B. Similarly, the simulated soil solution cation concentrations were extremely sensitive to initial soil solution concentrations, but they were not significantly affected by changes in weathering rate coefficients and weathering dependence on soil solution  $\text{H}^+$  concentration. Changes in uptake distribution in individual soil layers had little effect on the soil solution concentrations.

The balance between total cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ ,  $\text{Na}^+$ , and  $\text{Al}^{n+}$ ) and total anions ( $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$ , and  $\text{PO}_4^{n-}$ ) in different soil horizons were achieved in NuCM simulation, as well as in the observed results in the real world (Fig. 6).

## DISCUSSION

The model NuCM was calibrated using the observed data from two plots of the study site from 2001 to 2002. An approximate fit between simulated results and observed values was achieved for both the plots during the simulation period.

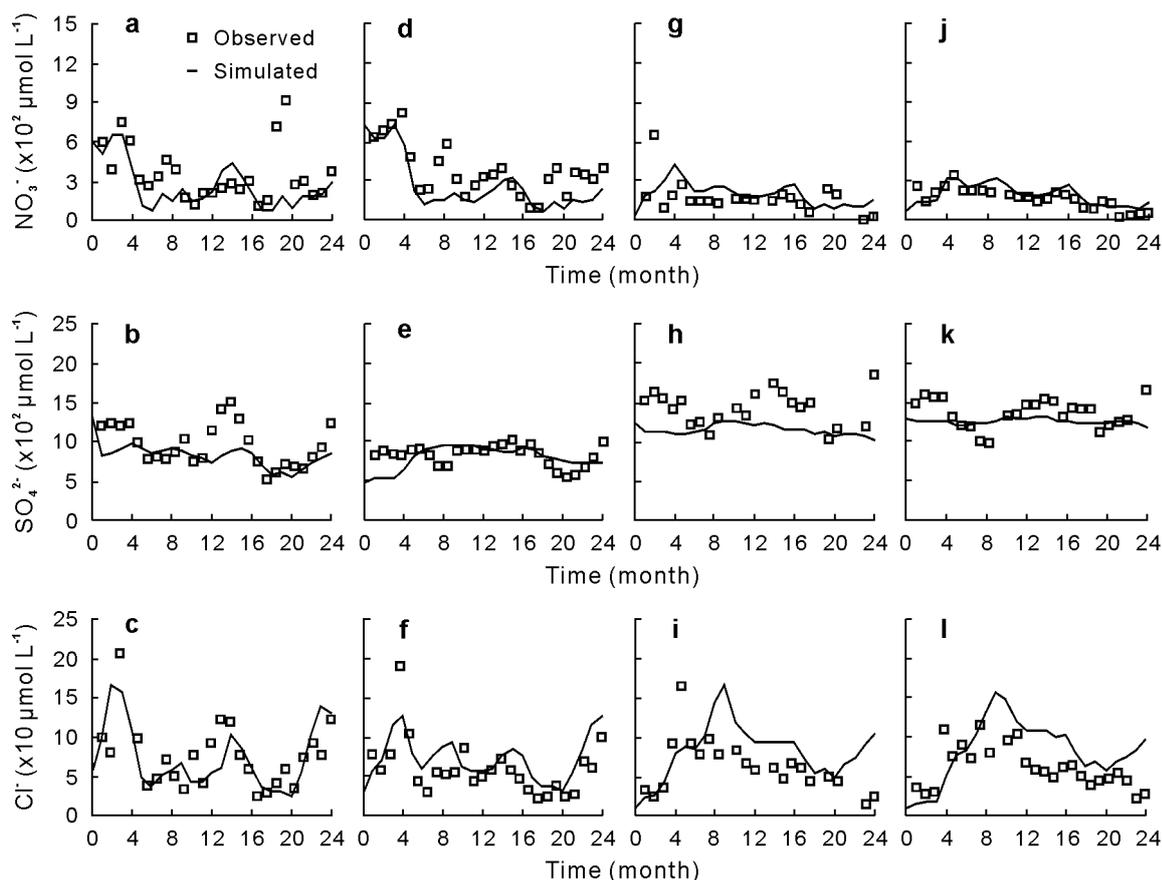


Fig. 4 Simulated *versus* observed soil solution  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{Cl}^-$  concentrations in Plot C of the study site: 12–22 cm (B2 horizon) (a, b, and c), 22–50 cm (B3 horizon) (d, e, and f), 50–70 cm (B3 horizon) (g, h, and i), and > 70 cm (BC horizon) (j, k, and l) layers.

Generally, the simulated concentration levels were highly sensitive to initial soil solution concentrations. This may be due to the relatively short simulation period (two years) of this study. The weathering reaction may become increasingly important as the simulation period increases.

NuCM could reproduce the mean value of soil solution ion concentrations during the two years. Seasonal variations in soil solution ion concentrations were observed, and the variation (*e.g.*,  $\text{SO}_4^{2-}$  and  $\text{K}^+$ ) was sometimes not reproduced by the model. Take  $\text{NO}_3^-$  as an example, soil solution  $\text{NO}_3^-$  concentrations were satisfactorily simulated in both plots. Nevertheless, the simulated values did not always match the observed data. It should be kept in mind that the calibration was not a real test of the model; it certainly did not validate the model. The disagreement between the observed and simulated data just showed that the model seemed incapable of reproducing the observed data.

The disagreement between the observed and simulated data could possibly be interpreted as the uncertainties of the observed data. First, the soil was not homogeneous, and the vegetation and root distribution were variable in the soil-plant systems. The observed soil solution data might be different from the truth. Second, Liu *et al.* (1991) stated that NuCM is based on measurable parameters, but this statement was not fully supported. Only 34 of total 120 parameters required by NuCM were measured at the study site, 11 of them were from more or less established knowledge, and the model calibrated the other 63. Among these unmeasured parameters, soil temperature and monthly vegetation uptake rate were two important parameters, which controlled the simulated seasonal variations. In addition, monthly leaf area index and maximum canopy interception storage controlled the monthly throughfall input. The high number of uncertain parameters complicated the testing of processes in NuCM. These

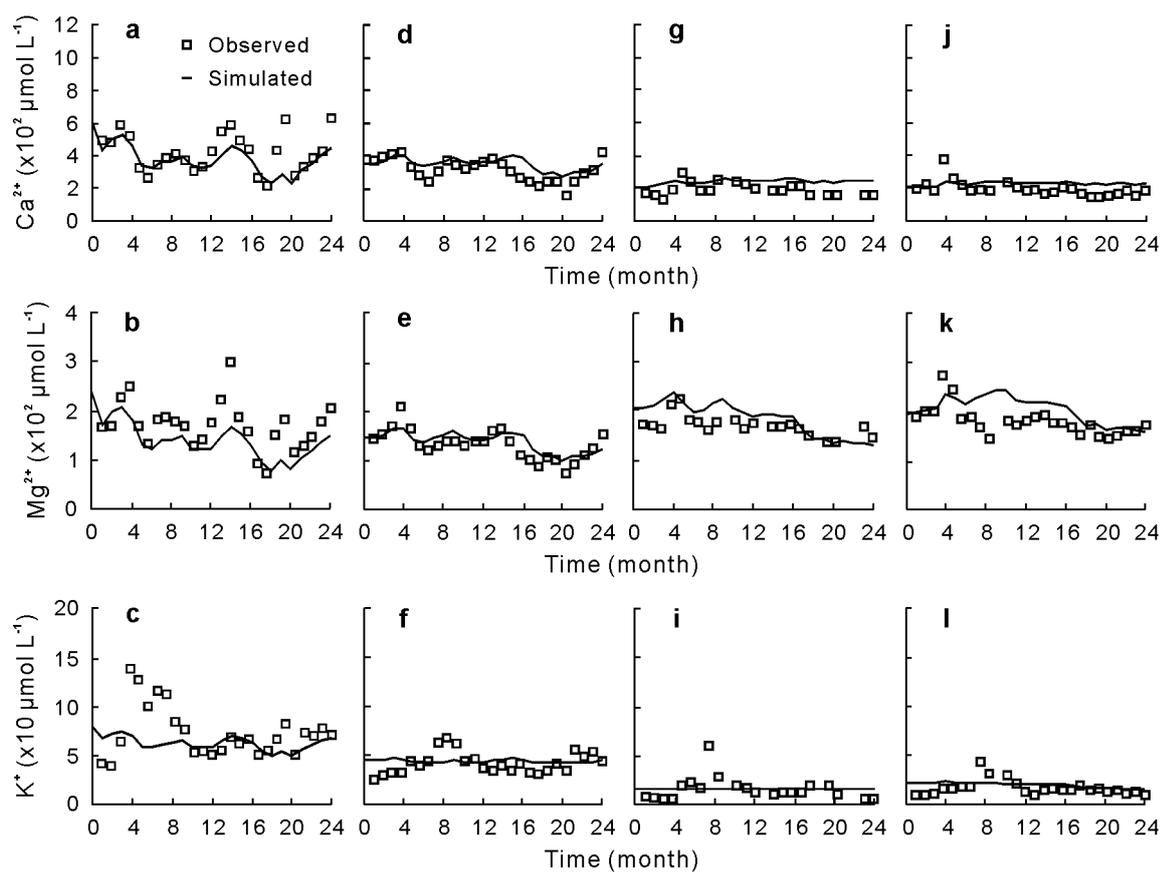


Fig. 5 Simulated *versus* observed soil solution  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and  $\text{K}^+$  concentrations in Plot C of the study site: 12–22 cm (B2 horizon) (a, b, and c), 22–50 cm (B3 horizon) (d, e, and f), 50–70 cm (B3 horizon) (g, h, and i), and > 70 cm (BC horizon) (j, k, and l) layers.

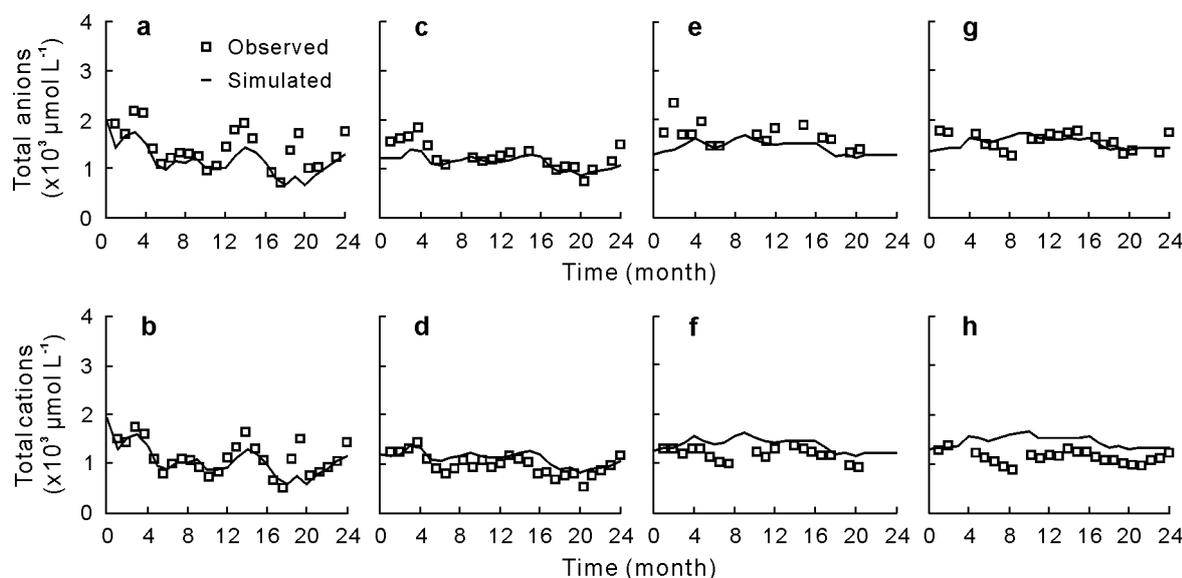


Fig. 6 Simulated *versus* observed total cation and total anion concentrations in Plot C of the study site: 12–22 cm (B2 horizon) (a and b), 22–50 cm (B3 horizon) (c and d), 50–70 cm (B3 horizon) (e and f), and > 70 cm (BC horizon) (g and h) layers.

uncertain factors could also be attributed to the model failing to reproduce the seasonal variation. To produce a better fit between simulated and observed data, adjustments of those highly uncertain parameters are necessary. Third, there were some limitations in NuCM. For example, the model was unable to simulate soil solution ion concentrations less than  $0.1 \mu\text{mol L}^{-1}$ . As the observed soil solution  $\text{NH}_4^+$  was often less than  $0.1 \mu\text{mol L}^{-1}$ , the simulated  $\text{NH}_4^+$  and  $\text{NO}_3^-$  from  $\text{NH}_4^+$  nitrification were likely overestimated. Finally, only two years of observed data were used for calibration. It came through a relatively dry year (959 mm precipitation in 2001) and a relatively wet year (1 558 mm precipitation in 2002) for the mean annual precipitation from 1970 to 1990 was 1 105 mm. The variation in climate condition may also increase the complexity of calibration. As mentioned by Sogn *et al.* (1995), more basic research is needed to understand, for example, how climate conditions affect the biogeochemical processes as the processes in NuCM might not be correctly described for simulating seasonal variations. The modeled results would fit the observed values better if the simulation period was longer and the calibration could be conducted on a yearly time step.

In general, the model NuCM was capable of reproducing the observed data at the study site even though the amounts of data available were limited. However, more study on adjustments of uncertain parameters should be conducted. The calibrated model used for forecasting the long-term effects of S and N deposition on soil water and leachate chemistry at the study site will be discussed in a forthcoming paper.

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