Necessity for consideration on hydrological controls of biogeochemical cycling to develop a catchment scale ecosystem model

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Introduction

There are several types of numerical models for estimating the biogeochemical dynamics in the terrestrial ecosystem (Running and Coughlan, 1988; Parton et al., 1988; Aber and Federer, 1992). Some of them have a function to calculate the discharge fluxes of nutrients into the stream system. The PnET model, for example, can successfully simulate the monthly average NO_3^- concentration in streamwater, although the hydrological modeling is quite simple without any sub-model describing water storage effect in soil profile and groundwater systems (Aber et al. 1997).

The discussion that I want to present here is based on the question how this kind of model can provide a good agreement of the calculated stream NO_3^- concentration with the observation without any realistic hydrological modeling. To examine the mechanisms behind this model performance on the application to the data from the northeastern United States, the climatic and hydrologic characteristics of these forested catchments should be carefully looked into.

Differences in seasonal variations of stream NO_3^- concentration between Japanese and the northeastern US catchments

Biogeochemical cycles in forested ecosystems are generally controlled by the climatic conditions under which those ecosystems are located. Although large number of case studies on biogeochemistry and hydrology in forested ecosystems has been done in temperate climate region, the variations in seasonal patterns of precipitation and temperature are not sufficiently large to discuss the geographical varieties. Major part of those studies has previously been conducted mainly in the northeastern part of the American continent and northern Europe.

Asian monsoon brings about distinctive climatic features in the East Asia and Oceania regions. Monsoon Asia has high precipitation in summer growing season, and is contrasting to the northeastern American and northern European climate which has commonly flat seasonal patterns in precipitation. High precipitation in warm summer provide suitable environment allowing soil microbial systems to decompose and mineralize soil organic matters (Mitchell et al. 1997), and also provides high hydrologic capability of nutrient export from soil system to the stream, while the nutrient pool is minimized by plant uptake exceeding the mineralization rate, and the nutrient export is retarded by the dry condition in the European and the northeastern American forests (Figure 1).

Our field investigations in the Kiryu Experimental Watershed (KEW) in the central Japan has been showing suggestive seasonal patterns in stream discharge and nutrient concentration in the streamwater affected by the monsoon rainy season (Ohte et al., 2003). This pattern indicates that the hydrological seasonality is a more dominant factor to control that of the nutrient export from soil system to the stream than the seasonal changes of the nutrient pool size controlled by microbial and plant uptake.

The mechanisms for the seasonal patterns in stream NO_3^- concentrations in the KEW emphasize the importance of changes in hydrological conditions in summer in Japan, where precipitation, groundwater levels, and runoff rates are high. In other words, in Europe and the northeastern American, the simultaneous effects of smaller pools of inorganic nitrogen due to high plant uptake and lower transporting forces due to low precipitation and high transpiration during the summer may let ones underrate the effect of hydrological conditions on seasonality in stream NO_3^- concentrations.

PnET application to the case of the catchment under Asian monsoon climate

If the hypothesis described in the last sentence of the previous chapter is true, the catchment ecosystem model included a less realistic hydrologic sub model might not be able to reproduce the seasonal pattern in the NO_3^- export from the catchment whose NO_3^- export is highly depending upon seasonally changing hydrologic condition instead of the seasonal variations of soil nitrogen dynamics. In order to discuss this issue, I tried to apply the PnET-CN model to the dataset from the most headwater portion of the KEW (Matzu-zawa catchment).

Figures 2a-d represents climatic conditions of KEW that I used for application of PnET model. As I mentioned above, seasonal pattern of monthly precipitation has an obvious influence by the Asian monsoon rain, contrasting to that of the northeastern United States, such as the case of Hubbard Brook (Figure1). Using the default parameter settings for Red Pine stands which are most similar type for the Kiryu vegetation, the long term simulation (1750-2030) was done to reproduce the current status in nitrogen dynamics. Figures 3a and 3b showed the calculated stream NO_3^- concentration and the monthly discharge. The observed stream NO_3^- concentration averaged during 2001-2004 was shown in Figure 3c. Calculated monthly discharge reflected the seasonal variation of the precipitation with monsoon effect reasonably. Contrasting to this, the seasonal pattern of the stream NO_3^- concentration was completely different from the observed one. The calculated stream NO_3^- concentration depleted remarkably in summer growing season, and peaked in winter. This seasonal pattern was obviously similar to that of the Hubbard Brook case. As I mentioned above, this was usually interpreted by the reflection of seasonal variation of NO_3^- pool which is minimized by plant uptake exceeding the mineralization rate in summer. The seasonal pattern of the observed NO_3^- did not reflect this kind of biogeochemical seasonality in soil system. This was already pointed out by Ohte et al. (2003) stating that the seasonal variation in the stream NO_3^- concentration is strongly controlled by the mixing ratio of the subsurface and groundwater.

These suggests that the PnET is not able to simulate sufficiently the seasonal variation in the stream NO_3^- concentration in the catchment where the hydrologic seasonality, such as groundwater level and soil moisture conditions, is reflected in the export of NO_3^- into the stream. Many cases of the temperate forest watersheds in the monsoon Asia have this type of hydrologic characteristics.

In order to develop more robust model for ecosystem scale water and nutrient cycle, I can state that more realistic hydrologic sub model is needed to be built in, especially focusing on the solute storage in groundwater body.

Towards the universal catchment model considering the hydrological storage

There are various types of hydrological model for the catchment scale water cycle simulation. Most of them consider the storage and mixing effects of the soil and ground waters. The HYCY (Hydrologic Cycle model) model for the forested watershed was developed by Fukushima and Suzuki (1986), and is one of the most comprehensive models to mechanistically express the water storage and flow in the head water system. As the first step for combining the nutrient cycle model and the hydrologic model, the HYCY model was tested its performances on the simulation of the storage effect on solute export of the soil and ground waters. The model structure of the HYCY model is shown in Figure 4. The model has two different tanks (Su and Sb) expressing soil water and groundwater storages.

According to the simulation experiments with the PnET model described above, I assumed that the "leaching N" calculated in PnET is mostly form of NO_3^-, and is the leachate only from the soil system instead of the whole catchment. The leachate N concentration as the output from PnET was used as the input of the groundwater tank Sb of the HYCY model. Water flux was initially given as the observed precipitation in hourly basis. The mass balance of the NO_3^- in the groundwater storage and concentration of the stream NO_3^- was formulated as follows:

$$\frac{dS_g C_g}{dt} = Q_{in} C_{leach} - Q_g C_g \qquad (1)$$

$$C_{str} = \frac{Q_g C_g + Q_d C_d}{Q_g + Q_d} \qquad (2)$$

Here, Sg, Cg is the water storage and NO_3^- concentration of the groundwater tank Sb. Qin and Cleach is the water flux from subsurface soil to the groundwater tank and its NO_3^- concentration which is obtained from the PnET output. Qg is the drainage flux from the groundwater tank. Streamwater consists of the direct runoff (Qd) and the base runoff from the groundwater tank (Qg).

The model calculates the hourly discharge water flux and stream NO_3^- concentration. Figure 5a-c shows the hourly and monthly stream NO_3^- concentration and the monthly discharge. The NO_3^- concentration of the base flow has gentle seasonal fluctuation being highest in the early June and remarkable dilution by direct runoff water. These phenomena agreed qualitatively with the observed facts in 2000-2004 (Katsuyama et al. 2001). The seasonal valuation in the simulated NO_3^- concentration reflected obviously the effect of the water storage in the groundwater body. The simulation (Figure 5b) reproduced the seasonal pattern of the monthly NO_3^- concentration (Figure 3c), although the concentration level did not successfully agree with the observations.

This trial simulation suggests substantial necessity to include a hydrological sub model which is able to calculate the effects of the groundwater storage. Additionally, the storage effects of groundwater body is important not only as the water flow regulator, but also as the hot spot of the unique biogeochemical reactions such as the denitrification and methane production, because the groundwater body can usually be under the reduced condition. In order to formulate this kind of conditions and reactions in the ecosystem model, the groundwater sub model will strongly be required.

References

Aber, J.D. and Federer, C.A. (1992), Oecologia 92, 463-474.

Aber, J.D., Olinger, S.V., and Driscoll, C.T. (1997) Ecological Modeling, 101, 61-78.

Fukushima, Y. and Suzuki, M. (1986) Bulletin of Kyoto University Forest, 57, 162-185.

Katsuyama, M., Ohte, N., and Kobashi, S. (2001) Hydrological Processes, 15, 249-260

Mitchell, M. J., Driscoll, C. T., Murdoch, P., Likens, G. E., Kahl, J. S. and Pardo, L. (1996) Environmental Science and Technology 30, 2609-2612.

Mitchell, M. J., Iwatsubo, G., Ohrui, K. and Nakagawa, Y. (1997) Forest Ecology and Management 97, 39-51.

Ohte, N., Tokuchi, N., Katsuyama, M., Hobara, S., Asano, Y. and Koba, K. (2003) Hydrological Processes 17, 237-249

Parton, W.J., Stewart, W.B. and Cole, C.V. (1988) Biogeochemistry, 5, 109-131.

Running, S.W. and Coughlan, J.C. (1988) Ecological Modeling 42, 125-154.

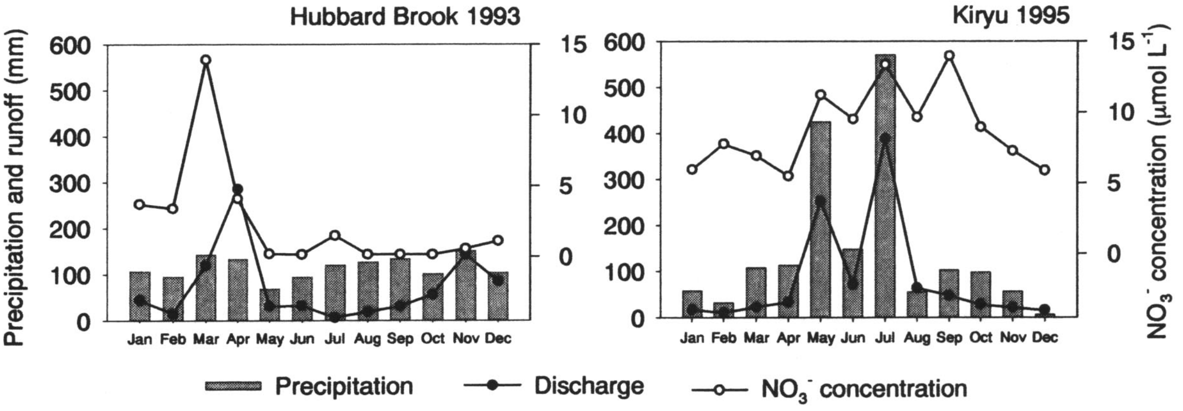

Figure 1. Monthly precipitation, discharge and averaged NO_3^- concentration in streamwater at the Hubbard Brook watershed in the northeastern United States and the Kiryu watershed in central Japan. The data for Hubbard Brook was cited from Mitchell et al. (1994).

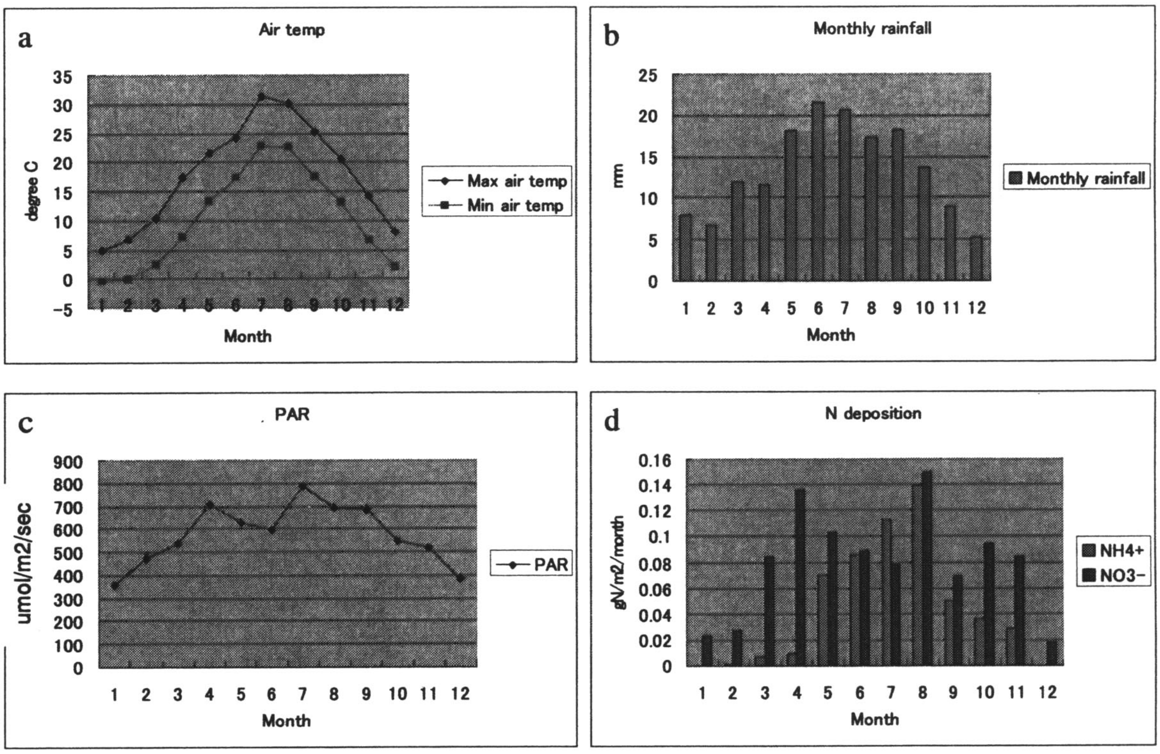

Figure 2. Climatic conditions of the Kiryu Experimental Watershed as the input data for PnET. a, monthly maximum and minimum temperature; b, monthly precipitation; c, monthly mean photosynthetically active radiation; d, monthly total inorganic nitrogen deposition.

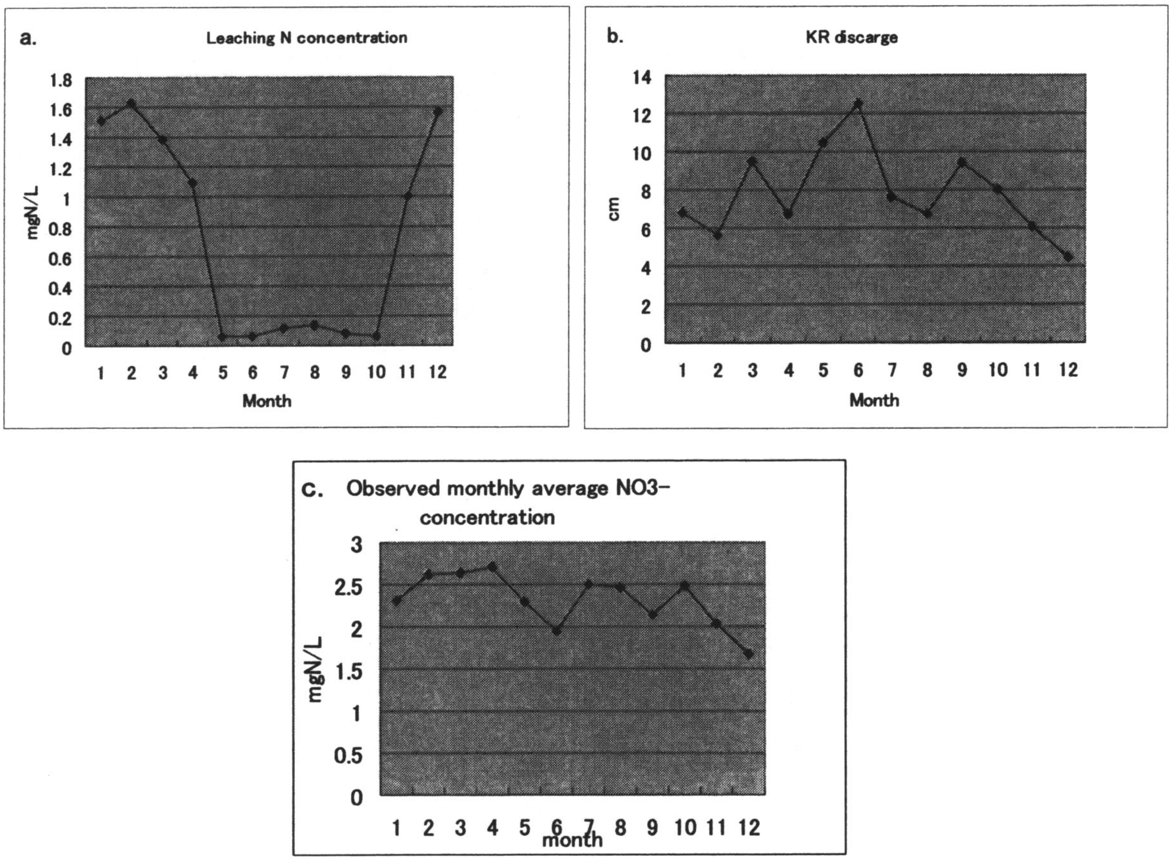

Figure 3. Calculated monthly leaching N concentration (a), discharge water flux(b) by PnET and the observed monthly average stream NO_3^- concentration (c).

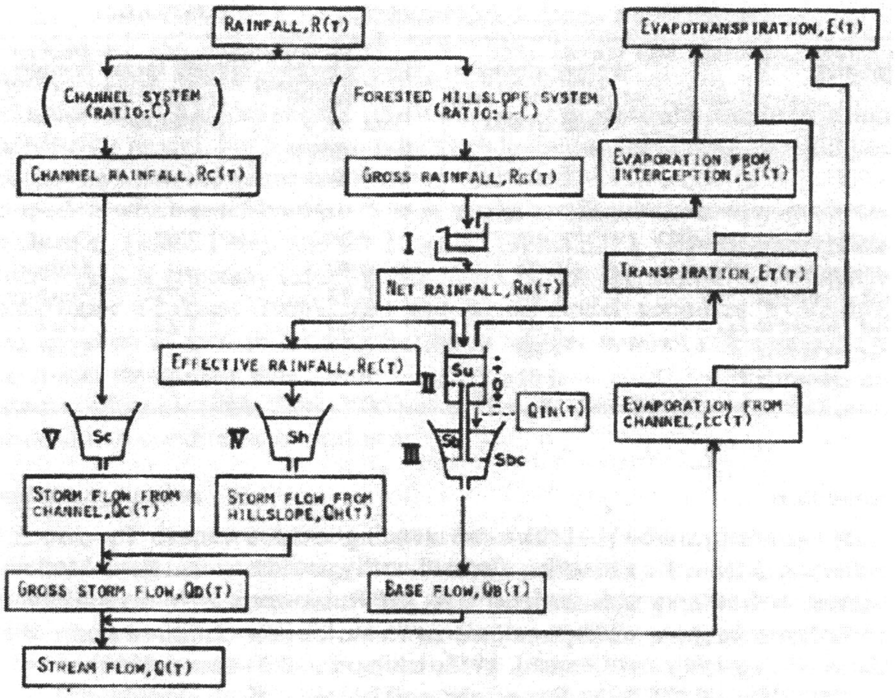

Figure 4. Structure of the HYCY model (Fukushima and Suzuki, 1986)

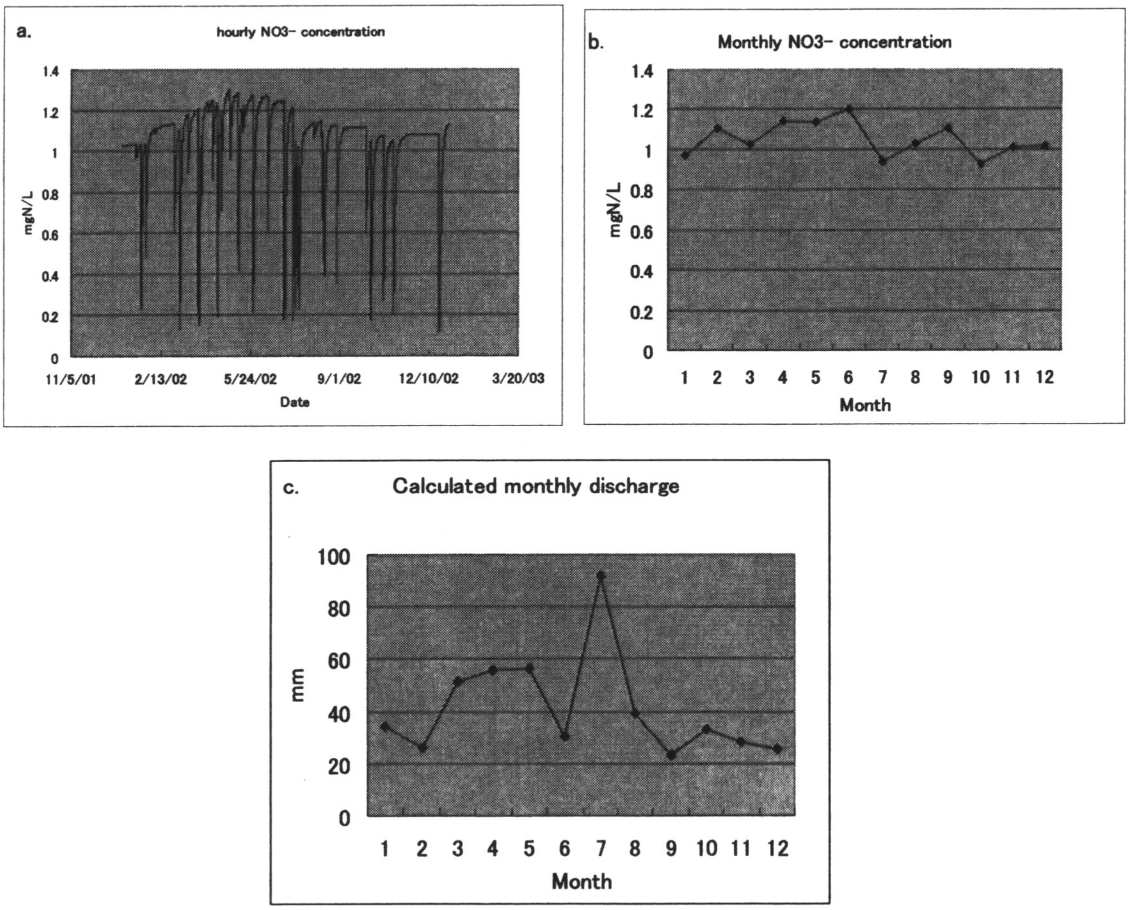

Figure 5. Calculated hourly (a) and monthly (b) stream NO_3^- concentration and the monthly discharge (c).