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ORIGINAL ARTICLE

Applications of a hydro-biogeochemical model and long-term simulations of the effects of logging in forested watersheds

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Abstract We simulated hydrological and biogeochemical responses to logging in a forested watershed to determine the vulnerability and/or resiliency of the forest ecosystems in the Lake Shumarinai Basin in northern Hokkaido, Japan. We used a biogeochemical model (PnET-CN) and a rainfall–runoff model (HYCYMODEL) to predict ecosystem responses. The PnET-CN model simulated well the observed NO_3^- concentrations in streamwater, particularly at high concentrations during snowmelt; however, the model could not simulate small increases in NO_3^- during the summer. By considering hydrological processes within the watershed and combining the model with the HYCYMODEL (PnET + HYCYMODEL), the seasonality of streamwater NO_3^- concentrations was better simulated. Using these models, the long-term effects of logging were simulated for coniferous, deciduous, and mixed forests. NO_3^- concentrations in streamwater increased in response to the logging disturbance in both coniferous and deciduous forests. In the coniferous forest, NO_3^- concentrations reached a maximum 10 years after logging, and high concentrations persisted for 30 years. In contrast, NO_3^- concentrations in the deciduous forest reached a maximum within 3–4 years and recovered to pre-disturbance levels after 15 years. We also used the models to determine the effects of different sizes and types (coniferous, deciduous, and mixed forest) of logging areas on Lake Shumarinai. The model results indicated that large areas of cutting require more than 100 years for complete lake recovery. Whereas the annual discharge to the lake minimally increased, the annual NO_3^- load greatly increased. Our simulation results elucidate the vulnerability and resiliency of forest ecosystems and provide valuable information for ecosystem management.

Keywords Biogeochemistry · HYCYMODEL · Hydrology · Nitrate · PnET-CN · Simulations

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Introduction

A current focus of biogeochemical research is to evaluate the present conditions of basin environments and predict the responses of these systems to global climate change, forest disturbances, and changes in land use at regional scales. However, broadly applicable conclusions from intensive research around the world remain elusive, because basin environments are complex systems of diverse land uses, such as forest, farmland, residential areas, rivers, lakes, and coastal regions. Moreover, responses to environmental change usually occur over long time scales of more than several decades; thus, it is difficult to evaluate short-term responses and subsequently extrapolate these to long-term responses based only on field observations. Therefore, simulation models provide an effective tool to complement field research, because they can be used to reproduce conditions in the past and present and to predict conditions in the future for both gauged and ungauged basin ecosystems.

In Japan, approximately 67% of the land area is forested, and these systems often encompass the headwater areas of basin environments. The general public has been concerned with the benefits of forests for public welfare, and to address this concern, researchers must accurately estimate the public functions of forests, which often include many ecosystem services (Costanza et al. 1997). Therefore, the process-based modeling of ecosystems is important for the valuation of such ecosystem services. Biogeochemical processes within forest ecosystems are intricately linked with ecosystem functions, such as carbon fixation and water quality, and reflect interactions between the biosphere and geosphere within the forest ecosystem (Schlesinger 1997). However, it is difficult to characterize these processes based only on field monitoring, because the changes in the ecosystem (and, consequently, in water chemistry) in response to certain factors, such as forest disturbances, are highly variable in these diverse ecosystems. Moreover, it remains unclear as to how disturbances of varying scale that occur in various forest types will affect biogeochemical processes. In contrast, process models can estimate such responses and help determine the mechanisms driving certain ecosystem functions. A combination of both monitoring and modeling is essential for measuring diverse biogeochemical processes and the spatio-temporal variability therein across global or regional scales (Aber and Driscoll 1997; Waring and Running 2007). To construct such models and improve the accuracy of estimations, it is crucial to parameterize the models using sufficient field observations and to conduct a scenario analysis of potential responses to changes in the environment.

In this study, we examined a forest–lake environment in northern Hokkaido, Japan. This basin is composed of headwater forests, farmlands, rivers, and a lake. Assuming that logging in the headwater area affects the basin system, we used a process-based model to describe the responses of the forest ecosystem to logging and to estimate the long-term variation in water and nitrate runoff. To construct a biogeochemical model at a basin scale, precise knowledge of the water cycle is required. Distributed parameter hydrological models, such as TOPMODEL (Beven 1997), that can describe hydrological processes in small sub-catchments are sometimes used in such contexts (Hornberger et al. 1994; Stieglitz et al. 2003). However, for these hydrological models to clearly identify differences among sub-catchments, model and parameter uncertainty must be reduced through discreet parameter identification based on a substantial number of observations. While such watershed biogeochemical models are typically used by scientists, they will also be increasingly used by policy makers and the general public, who are stakeholders in development plans for strategic environmental assessments. Therefore, the models need to be simple, easy to apply, and capable of precisely simulating the appropriate processes.

After initially testing the applicability of the models, we combined biogeochemical and rainfall–runoff models to simulate the long-term effects of logging on the water and nitrogen cycles. In particular, we focused on the scale of operations and forest type to evaluate the vulnerability and/or resiliency of forest ecosystems.

Materials and methods

Site description

The simulation models were applied to the Lake Shumarinai Basin (312.6 km^2) in northern Hokkaido, Japan. The landscape of the basin is primarily forested, with some portions of farmland. The majority of the forests are part of Hokkaido University's Uryu Experimental Forest (UREF; 44°22′N, 142°15′E). According to Shibata et al. (2004, 2007), precipitation is relatively evenly distributed throughout the year, with approximately 50% falling as rain between May and November, and the remainder falling as snow (water equivalent). The annual precipitation observed at the headquarters of the UREF averages 1375 mm year^{-1}, but ranged between 1120 and 2200 mm year^{-1} over the period on record from 1973 to 1997. The average annual temperature is 2.5°C and ranged between 0.3 and 4.7°C over the period of recording. The region is underlain by tertiary andesite, and the vegetation is cool temperate mixed natural forest, composed primarily of *Abies sachalinensis*, *Quercus crispula*, *Picea glehnii*, *Betula ermanii*, *Acer mono*, *Kalopanax pictus*, and *Magnolia obovata*.

The Lake Shumarinai Basin is composed of six river watersheds. Using geographic information systems (GISs) with a digital elevation model (DEM; 50 × 50-m resolution; Geographical Survey Institute of Japan 1999) and a vegetation inventory (UREF, unpublished data), we divided each watershed into several small catchments of several square kilometers and used the vegetation map to calculate the ratio of coniferous to deciduous forest in each small catchment. Our models were tested and validated primarily using the Dorokawa watershed, one of the six river watersheds in the basin. The area of this watershed is 36.1 km^2, 35.4 km^2 of which is mixed forest. The areas covered by coniferous and deciduous species are 12.0 and 23.3 km^2, respectively. Detailed descriptions of the watershed were provided by Ogawa et al. (2006) and Xu and Shibata (2007). The simulation models were applied to each small catchment and summed by river watershed to calculate the load to the lake.

Model structure

PnET-CN model

To describe the biogeochemical dynamics of the forest ecosystem, we used the PnET-CN model (Fig. 1; Aber et al. 1997; Ollinger et al. 2002). The PnET-CN model is a generalized lumped-parameter model including carbon, water, and nitrogen interactions in forest ecosystems and was developed for the northeastern United States. It is relatively easy to use and functions on a monthly time step. This model designates river water chemistry as the result of interactions among and productivity generated from photosynthesis, the decomposition of organic matter by microbes, and nutrient utilization by vegetation. The climatic conditions (cool temperate, with heavy snow input in the winter), forest vegetation (primarily cool temperate natural mixed forests of deciduous and coniferous species), and geomorphological characteristics (relatively gentle slope gradient) of northern Hokkaido and the northeastern United States are similar; therefore, the PnET-CN model is suitable for application to our study system.

HYCYMODEL

To describe the hydrological processes within the watershed, we applied the HYCYMODEL (Fig. 2; Fukushima 1988). The HYCYMODEL is a simple, lumped-parameter model of rainfall–runoff processes in forested catchments. The hydrological structure of the catchments is clearly conceptualized in this model. It can predict both short- and long-term hydrographs, because the model parameters are independent of time. In this model, the storage and flow in channels, unsaturated shallow soils, and saturated deep soils are each described as reservoirs, and the predicted hydrographs are affected by the storage and mixing of soil water and groundwater. PnET-CN also contains hydrological structure; however, its simulations are conducted on monthly time steps, whereas nutrient cycling and biogeochemical dynamics in nature occur on a daily (or finer) time scale in downstream lake ecosystems. Moreover, in the Asian monsoon region with high precipitation and high discharge during the summer, there is clear seasonality in streamwater NO_3^- concentrations (Ohte et al. 2001). The climate at the Hubbard Brook Experimental Forest (HBEF) in the northeast United States (Likens and Bormann 1995), where the

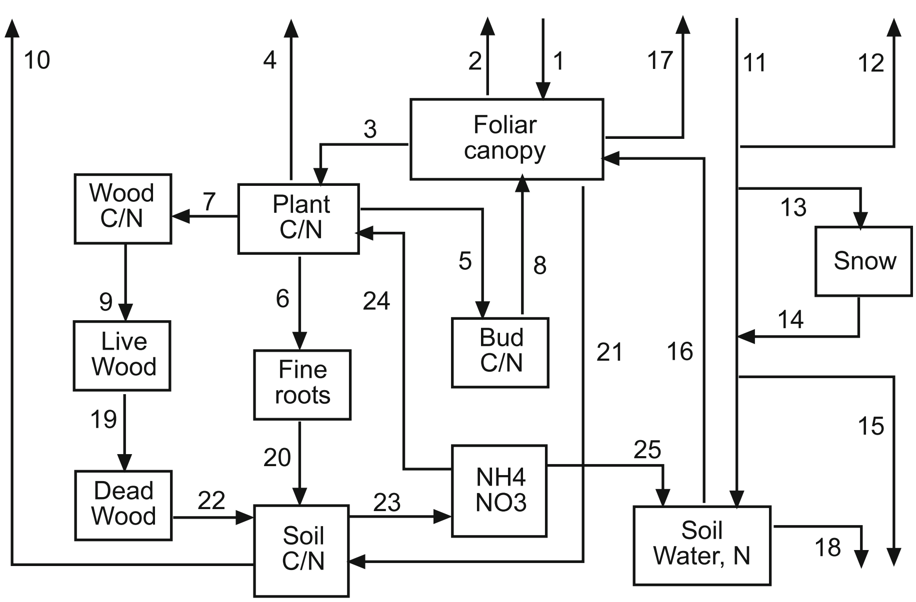

Fig. 1 Structure of the PnET-CN model (Ollinger et al. 2002). The *boxes* represent pools and the numbered *arrows* represent fluxes as follows: *1* gross photosynthesis and ozone uptake, *2* foliar respiration, *3* transfer to mobile pools, *4* growth and maintenance respiration, *5* allocation to buds, *6* allocation to fine roots, *7* allocation to wood, *8* foliar production, *9* wood production, *10* soil respiration, *11* precipitation and N deposition, *12* canopy interception and evaporation, *13* snow–rain partitioning, *14* snowmelt, *15* macro-pore flow, *16* plant uptake, *17* transpiration, *18* H_2O drainage, *19* woody litter, *20* root litter decay, *21* foliar litterfall, *22* wood decay, *23* N mineralization and nitrification, *24* plant N uptake, *25* N transfer to soil solution

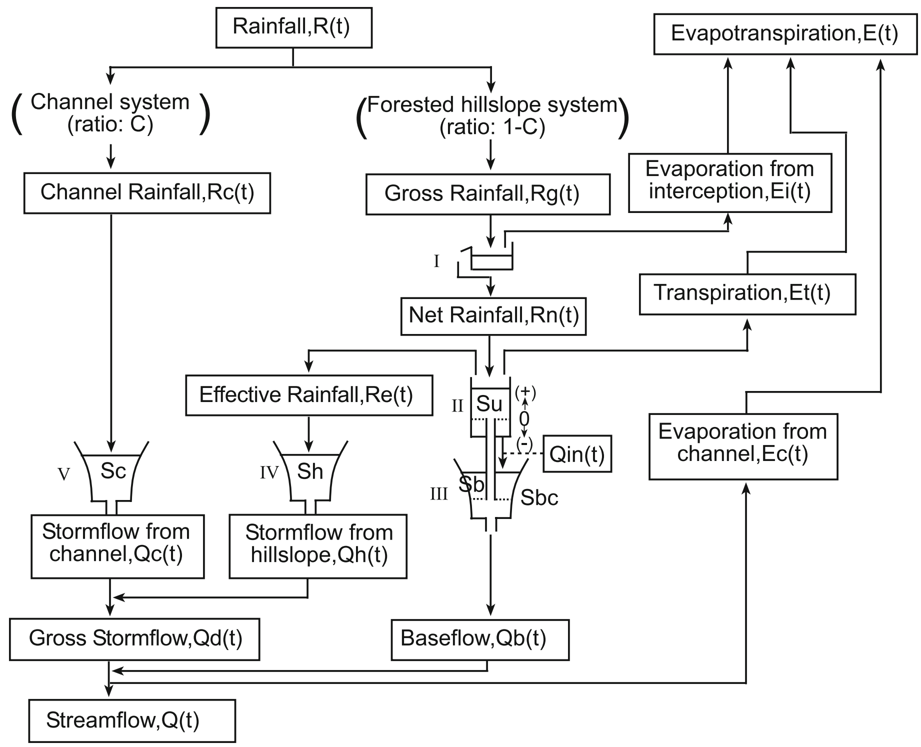

Fig. 2 Structure of the HYCYMODEL (Fukushima 1988)

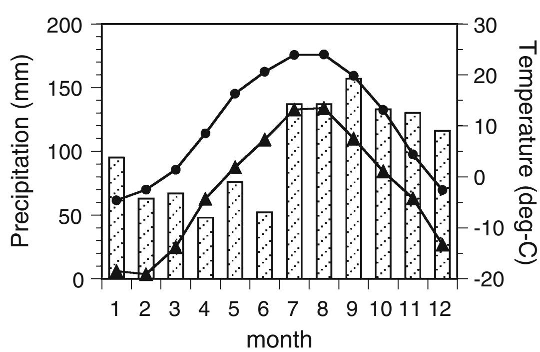

Fig. 3 Monthly precipitation and mean maximum and minimum temperature for the PnET-CN model

PnET-CN model was developed, and our site have similarity in the temperature seasonality and annual precipitation. However, higher precipitation is usually observed during summer in our site (Fig. 3) due to the Asian monsoon, while there were little seasonal differences in the HBEF. The HYCYMODEL can better account for the specific conditions of northern Hokkaido and can, thus, both compensate for and complement the PnET-CN model. We also chose the HYCYMODEL for its capacity to elucidate the hydrological processes of the study site and to simulate daily hydrographs.

Input data and parameters

Input data for the PnET-CN model included meteorological variables and nitrogen deposition data observed at the UREF. The long-term average of these variables was iteratively applied to all simulations. Figure 3 presents the monthly precipitation and mean maximum and minimum temperatures for the PnET-CN model. The default vegetation parameter sets for 'Northern Hardwood' and 'Spruce Fir' (Aber et al. 1997) were used for the deciduous and coniferous forests, respectively, because the vegetation types are similar between our site and the HBEF. Based on the ratio of deciduous and coniferous trees, the results of simulations using the pure forest parameters were proportionally allocated to the dataset for simulations of the mixed forest.

We used values of daily rainfall observed at the UREF in the HYCYMODEL, except for during the snowmelt season. To estimate daily snowmelt (input data for the winter season), we applied the degree-day method, which considers temperature, snow depth, and total precipitation. The degree-day factor for this region was 4.0 mm °C^{-1} day^{-1} (Kojima et al. 1983). In the HYCYMODEL, the residual between precipitation and evapotranspiration is allocated to the storage and runoff of each reservoir (Fig. 2). Therefore, the annual evapotranspiration of this region (<400 mm; Kondo et al. 1992; Ishii et al. 2004) was allocated monthly. Differences in evapotranspiration rates between the deciduous and coniferous forest were not considered.

To adequately describe the observed discharge behavior at small sub-catchments in the Dorokawa watershed, the parameters for storage and runoff were optimized using trial and error. The characteristics of rainfall–runoff are strongly controlled by geology (Shimizu 1980; Katsuyama et al. 2008), and this region is underlain by relatively homogeneous Tertiary andesite. Moreover, site-specific characteristics may have less of an effect on daily and monthly simulations. Therefore, we applied this parameter set across the Lake Shumarinai Basin, and differences between watersheds were not considered.

Field sampling

Streamwater samples were collected monthly from 12 sites in the Dorokawa watershed throughout 1 year. Samples were filtered through a 0.2-μm membrane filter and were analyzed in a laboratory at Hokkaido University. Concentrations of NO_3^- were measured using ion chromatography (Dionex DX-500).

Logging scenario

We evaluated the long-term effects of logging on the biomass and streamwater NO_3^- concentrations for three sizes of logging areas (small [0.8 km^2], moderate [4 km^2], and large [20 km^2]), and three forest types (coniferous, deciduous, and mixed forest) in the Dorokawa River watershed. In these simulations, NO_3^- concentrations calculated with the PnET-CN model were considered as the output for each forest, and the load transported to Lake Shumarinai depended on the daily discharge rate calculated by the HYCYMODEL.

Results

Validation of the PnET-CN model

The PnET-CN model was applied to a small sub-catchment in the Dorokawa watershed. Monthly NO_3^- concentrations in the streamwater were simulated and compared to observed values (Fig. 4). The observed seasonal pattern was simulated well, except for during the summer season (June–September), though the simulated concentrations were lower than observed concentrations. During the winter (November–March), NO_3^- concentrations were relatively high and reached a maximum in April, during the snowmelt season. After snowmelt ceased, NO_3^- concentrations precipitously decreased, and simulated values fell to near zero during the summer, although observed values exhibited a small peak in July or August. The high concentrations during the dormant season and low concentrations during the active season can be attributed to biological activity involved in the nitrogen cycle (Stoddard 1994).

Our simulated seasonal variation in NO_3^- concentrations, especially for winter, was similar to results from the northeastern United States (Aber et al. 1997), for which the

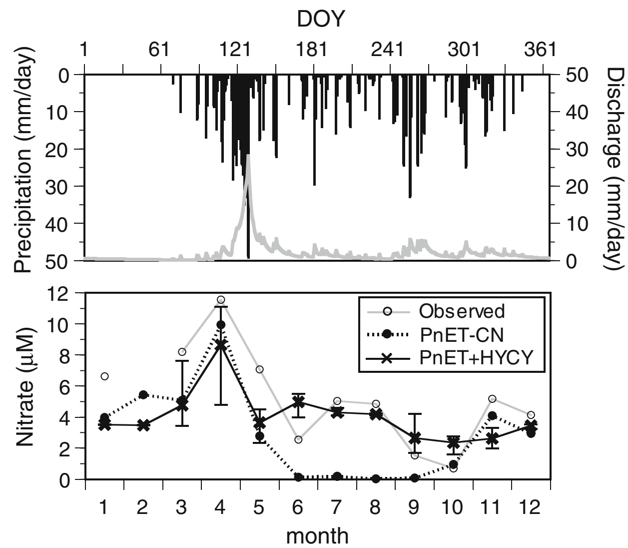

Fig. 4 Observed and simulated NO_3^- concentrations by PnET-CN and PnET + HYCYMODEL for the Dorokawa watershed. The NO_3^- concentrations generated from the PnET + HYCYMODEL are monthly averages. The *error bars* are maximum and minimum concentrations within each month

PnET-CN model was developed and validated. However, the observed increase in NO_3^- during the summer was not simulated. In Asian monsoon areas, high precipitation inputs and consequent high flow in the summer result in the movement of nitrogen solute to streams, and high concentration appears in the summer season (Ohte et al. 2001). This type of hydrological control is not an important component of the PnET model. Therefore, our site exhibits characteristics of both Japan and the northeastern United States; in our site, high concentration appeared with high flow in the snowmelt season like the northeastern United States and in the summer rainy season like other Japanese regions (Fig. 4). Comparative studies of biogeochemistry and hydrology are necessary to improve process descriptions and modeling (McDonnell and Tanaka 2001), and our study system may be valuable for identifying key state variables for a combined forest hydrology/biogeochemistry model.

Hydrogeomorphological control on streamwater NO_3^- concentrations

Streamwater NO_3^- concentrations exhibited some variation among sub-catchments in the Dorokawa watershed. Steeper catchments exhibited higher NO_3^- concentrations during both snowmelt (March and April) and non-snowmelt seasons (Fig. 5), highlighting the strong effect of hydrogeomorphology on streamwater NO_3^- concentrations. However, the PnET-CN model was unable to capture this temporal pattern.

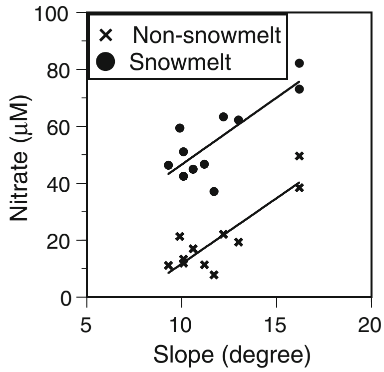

Fig. 5 Relationship between the catchment slopes and NO_3^- concentrations. Concentrations are annual means in the streamwaters of 11 sub-catchments. The topographic characteristics are described by Ogawa et al. (2006)

Improvement of hydrological structure within PnET-CN simulations

We combined the HYCYMODEL with PnET-CN simulations to improve the structure of hydrological processes and time resolution of the latter model. The HYCYMODEL has a clear, two-layered structure (Fig. 2). Reservoirs III and IV roughly correspond to the saturated groundwater layer and the unsaturated soil layer, respectively, and discharge from these reservoirs primarily contributes to direct runoff and baseflow. The nitrogen cycle considered in a biogeochemical model, such as PnET-CN, usually occurs within the unsaturated soil layer. Therefore, we applied the output from PnET-CN (N transfer to soil solution, arrow no. 25 in Fig. 1) to reservoir II and allocated the solute based on water flow in the HYCYMODEL to reservoirs III and IV. Hereafter, we refer to the improved model as the PnET + HYCYMODEL.

The simulated daily hydrograph and NO_3^- concentrations are presented in Fig. 4. The simulation was conducted using a daily time step. NO_3^- concentrations generated from the PnET + HYCYMODEL are monthly averages. Because output from the PnET-CN model was on a monthly time step, monthly N transfer to the soil solution was assigned on the daily basis as the input for reservoir II. NO_3^- concentrations and the observed seasonal variation was simulated well, particularly the summer increase (Fig. 4). Discharge began to increase at the end of March with the onset of snowmelt, and the highest NO_3^- concentration occurred at the beginning of snowmelt well before the peak of stream flow. Meltwater and solutes sometimes exhibit similar patterns in NO_3^- concentrations (e.g., Ohte et al. 2004) and dissolved organic carbon (DOC; e.g., Hornberger et al. 1994; Boyer et al. 2000), perhaps characterizing a soil reservoir in which solute builds up during low flow periods and is flushed out by infiltrating meltwaters. On the other hand, the observed NO_3^- increase in summer, which could not simulated by the PnET-CN model, was simulated well by the PnET + HYCYMODEL. In other words, PnET + HYCYMODEL can describe the time lag of NO_3^- leachate because of the residence of groundwater within the watershed.

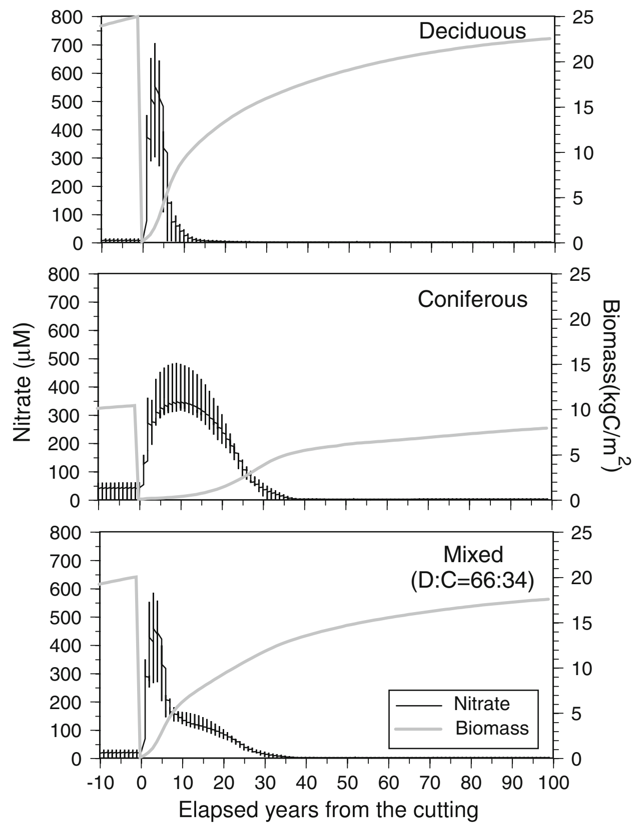

Fig. 6 Long-term simulations of streamwater NO_3^- and forest biomass after forest logging. Serrulate variations in NO_3^- concentrations are seasonal variations

These results indicate that the PnET-CN model can be improved if combined with a rainfall–runoff model, such as the HYCYMODEL, which clearly describes the hydrological processes of the catchments. Moreover, the improved model may be applicable to the watersheds in various climatic zones.

Long-term simulations of logging effects

The long-term effects of logging on monthly streamwater NO_3^- concentrations and annual biomass dynamics were simulated for deciduous, coniferous, and mixed forests using the PnET-CN model (Fig. 6). The ratio of deciduous to coniferous vegetation was 66:34 in the Dorokawa watershed.

The responses of NO_3^- concentrations differed among forest types. The deciduous forest responded strongly:

NO_3^- concentrations reached a maximum 3 years after cutting, subsequently rapidly decreased, and then recovered to pre-disturbance levels 15 years after logging. In contrast, the coniferous forest responded only moderately to logging: NO_3^- concentrations reached a maximum 9 years after cutting. These high concentrations persisted for several years, slowly decreased, and then recovered to pre-disturbance levels after 30 years. Peak NO_3^- concentrations were higher in the deciduous compared to the coniferous forest. These patterns were also reflected in the dynamics of biomass. Biomass in the deciduous forest recovered quickly, indicating faster regrowth and active uptake of nitrate compared to the coniferous forest. The mixed forest exhibited intermediate responses, in that NO_3^- concentrations increased quickly, reached a high peak, and then slowly decreased.

Annual discharge rates were simulated using the HYCYMODEL for the breakpoints in the fluctuations of NO_3^- concentrations in the mixed forest, i.e., before logging, at the peak of NO_3^- concentrations (3 years after cutting), half of peak concentrations (6 years after logging), one-fourth of peak levels (15 years), one-eighth of the peak (23 years), and pre-disturbance levels prior to logging (30 years). Figure 7 presents the ratio of annual discharge rates as a fraction of the untreated level (100%). The parameters used for the mixed forest were determined according to the recovery of biomass in the mixed forest (Fig. 6) and Fukushima (2006), who simulated the effects of reforestation of bare land. Compared to pre-logging values, the annual discharge rate increased by approximately 170 mm, corresponding to approximately 15% of annual rainfall and 25% of annual discharge during untreated years, due to a decrease in evapotranspiration. Even 15 years after logging, the annual discharge rate was still larger (100 mm) than pre-disturbance levels.

Fig. 7 Annual discharge simulated with HYCYMODEL after the forest logging in the mixed forest. Ratio to the value of untreated status as 100%

Discussion

Incorporating hydrological processes in PnET-CN simulations

As described above, PnET-CN adequately simulated a large portion of the forested environment at our study site, and this model can be very useful for long-term predictions. However, to more precisely simulate the variability among sub-catchments and the observed NO_3^- increase during the summer, the hydrological component of the PnET-CN model structure required improvement. The PnET-CN model has a one-layered structure for the water drainage system (Fig. 1); thus, this model cannot adequately describe water storage, residence times, and delayed runoff of groundwater (Ohte 2006). Chen and Driscoll (2005) applied the End-Member Mixing Analysis (EMMA; Christophersen et al. 1990; Hooper et al. 1990) to examine the hydrological behavior of their study site, determine the geographic sources of the streamwater using monitored soil water and groundwater chemistry, and characterize the two-layered structure of the soil- and groundwater layers for hydrological processes. Chen and Driscoll (2005) then combined these results with a PnET-BGC model (Gbondo-Tugbawa et al. 2001), which is a more recent version of the PnET-CN model, and with this technique, they more precisely simulated the seasonality of streamwater chemistry. Although EMMA is an effective technique, it requires intensive field observations to identify the end members and their contributions. The combination of precise biogeochemical models and hydrological models, like our method, may be more flexible in its application at other sites if reliable model parameters can be estimated. Regardless of the model used, the components used and model results point to the importance of hydrological controls, such as the mixing of water components, standardization of concentrations within groundwater bodies, and residence and delay of runoff, to streamwater chemistry. Thus, our improved version of the PnET-CN model may be applicable within the Asian monsoon region, where streamwater chemistry is greatly affected by hydrological conditions.

The variability of NO_3^- concentrations among sub-catchments in the Dorokawa watershed can, potentially, be attributed to hydrogeomorphological controls. In general, the dominant component of streamflow is groundwater (sometimes called ‘old water’), even during the snowmelt season (e.g., Sklash 1990). Therefore, catchment geomorphology may affect the NO_3^- concentrations in the groundwater component. To describe such variation using the PnET + HYCYMODEL, we arbitrarily adjusted some of the parameters of the HYCYMODEL that affected the allocation to and runoff from reservoir III, the baseflow reservoir. Simulated streamwater NO_3^- concentrations increased (decreased) when the parameters were set to decrease (increase) the baseflow. However, these parameter adjustments do not directly reflect the hydrogeomorphology of the catchments. Buttle et al. (2004) pointed out that spatial variation in soil thickness was the main driver of streamflow generation in the landscape of their study system, and such variation should be considered in hydro-ecological monitoring and modeling studies. Therefore, to elucidate the relationship between hydrogeomorphology and streamwater chemistry and to more precisely simulate the differences among sub-catchments, the controls of hydrological factors in each catchment should be based on detailed observations. Our results suggest that the applicability and predictability of biogeochemical models will be improved if the models include clearly conceptualized hydrological processes within catchments.

Effect of headwater logging on the lake environment

Based on the simulations of the PnET-CN model combined with the HYCYMODEL, the water and NO_3^- loads from the Dorokawa watershed to Lake Shumarinai were calculated. The values in Table 1 represent those from 3 years after logging, when NO_3^- concentrations had reached maxima in the mixed and deciduous forests. As the area of logging increased, the watershed-wide effects also increased. Although the deciduous forest exhibited a higher growth rate than the coniferous forest (Fig. 6), it required longer to recover forest biomass, because it had a larger stand volume per unit area. In the small and moderately sized areas of logging, the forest biomass recovered relatively quickly. In contrast, when large areas were logged in the deciduous forest, the system required >30 years for 80% forest biomass recovery and >100 years for complete recovery.

The annual discharge rate to Lake Shumarinai was minimally increased by small and moderately sized logging areas. The annual rainfall and evapotranspiration within this region are relatively small compared to averages for all of Japan, which is 1700 and 600–900 mm, respectively (Kondo et al. 1992). Therefore, the discharge rate increased less within this region, even though evapotranspiration was decreased by logging. However, the annual NO_3^- load increased greatly in all sizes of forest logging areas. Annual NO_3^- load increased by 1.5 times in small logging areas and by 20 times in large logging areas. The effects of logging in the deciduous forest were particularly strong. These results indicate that the lake ecosystem will suffer impacts from logging in headwater forest ecosystems. However, NO_3^- concentrations in the deciduous forest decreased relatively quickly compared to the coniferous forest (Fig. 6). Therefore, the effects of logging in the deciduous forest on the lake ecosystem may be relatively short term, whereas the effects may be more prolonged when logging occurs in the coniferous forest. The effects on the lake from logging in the mixed forest were intermediate: a higher and more prolonged load was transported to the lake. The redundant NO_3^- may cause eutrophication or water pollution in the downstream river or lake. Our results suggest that the intensity and duration of the effects of logging vary depending on the forest types and area of logging. Moreover, if farmland and/or residential areas are developed and simultaneously increase with logging operations, the lake ecosystem will respond rapidly and may suffer greatly. Indeed, dairy operations are active in other watersheds of the Lake Shumarinai Basin. Therefore, our simulations highlight the vulnerability and resiliency of forests and provide valuable information for forest ecosystem management.

Table 1 Effects of forest logging

Treatment		Effects on each watershed		Effects on Lake Shumarinai	
Cutting area	Treated forest	Forest biomass (residual, %)[a]	Recovery time (years)[b]	Annual discharge (%)[a]	Annual NO_3^- load (%)[a]
Small	Coniferous	98.9	0/3	101	144
Small	Deciduous	97.3	0/7	101	188
Small	Mixed	97.8	0/6	101	173
Moderate	Coniferous	94.3	0/16	104	318
Moderate	Deciduous	86.2	0/23	104	542
Moderate	Mixed	89.0	0/21	104	466
Large	Deciduous	31.1	37/>100	120	2310
Large	Mixed	44.8	31/82	120	1930

[a] Ratio of the value 3 years after logging to untreated status as 100%

[b] Required years to recover the forest biomass to 80/100% of the untreated status

Conclusions

Using a relatively simple process-based model, we simulated the biogeochemical responses to logging in forest ecosystems, with particular focus on the scale of operations and forest type. The seasonal variation in streamwater NO_3^- concentrations was adequately, but not perfectly, simulated by the model. Improvement of the hydrological structure of the model was effective in providing more precise simulations of seasonality. The improved model may be useful for describing the hydrogeomorphological controls of NO_3^- concentrations among sub-catchments. Therefore, the improved model may be applicable to the watersheds in various climatic zones when the biogeochemical and hydrological processes were sufficiently considered.

The long-term effects of logging on streamwater NO_3^- concentrations and the recovery of forest biomass were also simulated. Our results indicated the close relationship between the forest management and the lake ecosystems. Forest type and area of logging affected the resiliency of the forest ecosystem and highlighted the vulnerability of the downstream lake ecosystem.

Intensive field observations and simulation models are both necessary to characterize biogeochemical processes. Although there is uncertainty associated with simulations, comparisons across systems and the identification of the driving forces of hydro-biogeochemical processes promise to be quite valuable. The ecosystem-wide effects of disturbances will greatly impact the balance of ecosystem services. For example, forest harvesting increases timber supply but decreases water regulation. Thus, it is important to protect and use ecosystems while considering such trade-offs, and the approach presented in this study will be necessary for the planning of ecosystem management and development.

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