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Integrated biogeochemical modelling of nitrogen load from anthropogenic and natural sources in Japan

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ABSTRACT

This study proposed an integrated biogeochemical modelling of nitrogen loads from anthropogenic and natural sources in Japan. Firstly, the nitrogen load (NL) from different sources such as crop, livestock, industrial plant, urban and rural resident was calculated by using datasets of fertilizer utilization, population distribution, land use map, and social census. Then, the nitrate leaching from soil layers in farmland, grassland and natural conditions was calculated by using a terrestrial nitrogen cycle model (TNCM). The Total Runoff Integrating Pathways (TRIP) was used to transport nitrogen from natural and anthropogenic sources through river channels, as well as collect and route nitrogen to the river mouths. The forcing meteorological and hydrological data is a 30-year (1976–2005) dataset for Japan which were obtained by the land surface model, Minimal Advanced Treatments of Surface Interaction and Runoff (MATSIRO). For the model validation, we collected total nitrogen (TN) concentration data from 59 rivers in Japan. As a comparison result, calculated TN concentration values were in good agreement with the observed ones, which shows the reliability of the proposed model. Finally, the TN loads from point and nonpoint sources were summarized and evaluated for 59 river basins in Japan. The proposed modelling framework can be used as a tool for quantitative evaluation of nitrogen load in terrestrial ecosystems at a national scale. The connection to land use and climate data provides a possibility to use this model for analysis of climate change and land use change impacts on hydrology and water quality.

1. Introduction

As an integral component of many essential plant nutrients, nitrogen (N) is both an essential nutrient and a major pollutant in terrestrial ecosystems and plays important roles in increasing crop yields and crop quality (Brady, 1998; Baker, 2003; Oenema et al., 1998; Schepers et al., 1995). During the last century, the production of food and energy has markedly increased the amount of newly fixed N entering terrestrial and aquatic ecosystems. Compared with 1890, the amount of newly fixed N entering terrestrial systems annually had about doubled due to the production of synthetic fertilizers, increased biological N fixation associated with agricultural crops, and increased atmospheric N deposition associated with fossil fuel combustion (Galloway et al., 1995; Galloway, 2000). Moreover, excess nitrogen used in fertilization has undoubtedly disturbed the biogeochemical nitrogen cycle of natural ecosystems, resulting in various global, regional, and local environmental problems such as stratospheric ozone depletion, soil acidification, eutrophication, and NO_3^- pollution of ground and surface waters (Davis and Koop, 2006; Ding et al., 2006; Hantschel and Beese, 1997; Rijtema and Kroes, 1991). Especially, water quality associated with nitrate (NO_3^-) leaching from agricultural soils is an important environmental issue in the globe (Galloway, 1998, 2000; Galloway and Cowling, 2002; Galloway et al., 1995). The effect of agricultural nonpoint source (NPS) N pollution on water quality and aquatic ecosystems has been the subject of considerable research in recent years (Howarth et al., 2002; Hudson et al., 2005).

In Japan, the water quality has been improved remarkably during the past decades but Japanese rivers are still heavily impacted by canalization, loss of most dynamic flood plains, flow regulation, invasion by exotic species, and intensive urbanization (Yoshimura et al., 2005; Kimura and Hatano, 2007). Japanese agriculture has created high N surpluses in agricultural lands due to the increasing rate of chemical fertilizer application and disposal of livestock wastes per farmland area (Mishima, 2001; Kimura, 2005). As a consequence, agricultural activities, including intensive livestock production, have been widely criticized for producing environmental pollution (Kimura et al., 2004). It is necessary to take measures for sustainable agricultural production in better harmony with the environment in preserving and improving the natural cyclical

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functions of agriculture. It is considered that excess nitrogen from domestic wastewater, livestock wastewater, and nonpoint resource is the major reason that made some rivers nutrient polluted and cause some lakes and inner bay eutrophication in Japan. It is known from field tests that if water contains high nitrogen concentration and flows into paddy fields, high nitrogen removal would be performed (Nakasone et al., 2003). Furthermore, underground water contamination caused by nitrate nitrogen has begun to make itself noticed. The causes for this contamination are household wastewater discharge, agricultural waste resulting from cattle farming, and runoff from areas that are targeted by intensive farming methods reliant on the consumption of large quantities of fertilizers (Ministry of Environment of Japan). Therefore, the water quality is a big concern among water related issues in Japan. Furthermore, nitrogen pollution is one of the major pollutants but difficult to be estimated because its sources are widely spread and related to different complex sources including natural and anthropogenic sources. So far, the researches on nitrogen cycle study are mainly conducted at basin scale and the national or global scale study is few.

This study's objective is to estimate the nitrogen loads in Japan at a national scale and identify areas where sever water pollution might be taking place. The nitrogen loads from point and nonpoint sources are calculated separately and an integrated biogeochemical modelling of nitrogen export to Japanese streams was proposed in this study. Subsequently, we discuss methodology in Section 2 including land surface model (Section 2.1), the terrestrial nitrogen cycle model (Section 2.2), the river routing model (Section 2.3), biological N fixation and atmospheric N deposition (Section 2.4), denitrification in root zone (Section 2.5), and nitrate leaching (Section 2.6). The database for the point sources and nonpoint sources will be discussed in Section 3. The integrated simulation with the above model and database will be discussed in Section 4.

2. Methodology

2.1. Land surface model

A number of land surface models (LSMs) have been developed to be used in global or regional climate models (Sellers et al., 1996; Dickinson et al., 1998). These models incorporate the radiation transfer, the evaporation, the transpiration, the snow, the runoff, and so on considering the effects of vegetation, and solve the energy and water exchange between land and atmosphere as the vertical one-dimensional processes. In this study, we employ the Minimal Advanced Treatment of Surface Interaction and Runoff Model (MATSIRO) which is projected to be used for long-term simulations of climate studies (Takata, 2000, 2001; Takata et al., 2003). MATSIRO has a single-layer canopy and albedo. The bulk exchange coefficients are evaluated based on a multilayer canopy model. The fluxes are calculated from the energy balance at the ground and canopy surfaces in both snow-free and snow-covered portions that consider the subgrid snow distribution. Evaporation of water on the canopy and transpiration parameterized on the basis of photosynthesis (Sellers et al., 1996) are included. A simplified TOPMODEL (Beven and Kirkby, 1979) calculates baseflow runoff, in addition to surface flows. Snow has up to three layers depending on the snow water equivalent, and snow layer temperatures are calculated with thermal conduction equations. Snowmelt and refreeze are considered in this model. There are five soil layers in which energy and water movements are treated with physical equations that consider freezing and condensation. The mathematical formulas describing all these processes in detail can be found in Takata (2000, 2001). Model application results are also described in Hirabayashi et al. (2005). It has been validated both at the global scale (Takata, 2000) and at a local scale (Takata, 2001). A simulation coupled with an atmospheric general circulation model (AGCM) was described in Sakamoto et al. (2004). It reproduces well the observed seasonal cycles of the energy and water balance.

2.2. Terrestrial nitrogen cycle model

The TNCM (Fig. 1) is developed to consider the mass balance of nitrogen in the natural ecosystem integrated with the carbon cycle in vegetation and organic soil. It is based on the original model by Lin et al. (2000, 2001). The ecosystem was divided into an atmospheric and a terrestrial reservoir. The terrestrial nitrogen cycle consists in biological processes which depend on the variety of the environmental factors. The model contains eight variables: nitrogen in vegetation (N_{veg}, unit: tonne N km^{-2}), carbon in vegetation (C_{veg}, unit: tonne N km^{-2}), organic N in detritus (N_{det}, unit: tonne N km^{-2}), organic carbon in detritus (C_{det}, unit: tonne N km^{-2}), organic nitrogen in humus (N_{hum}, unit: tonne N km^{-2}), organic carbon in humus (C_{hum}, unit: tonne N km^{-2}), ammonium (N_{amm}, unit: tonne N km^{-2}), and nitrate (N_{nit}, unit: tonne N km^{-2}) as below.

$$\frac{\partial C_{veg}}{\partial t} = gpp - c_{trr} - c_f(1 - hvst) \quad (1)$$

$$\frac{\partial C_{\det}}{\partial t} = c_f - c_{dr} - c_{dh} \quad (2)$$

$$\frac{\partial C_{hum}}{\partial t} = c_{dh} - c_{hr} - c_{hcar} \quad (3)$$

$$\frac{\partial N_{veg}}{\partial t} = n_{uptake} - n_f(1 - hvst) + n_{fix} \quad (4)$$

$$\frac{\partial N_{\det}}{\partial t} = n_f - n_{dm} - n_{dh} \quad (5)$$

$$\frac{\partial N_{hum}}{\partial t} = n_{dh} - n_{hm} + fert\_hum + lst \quad (6)$$

$$\frac{\partial N_{amm}}{\partial t} = n_{dm} + n_{hm} + n_{ammd} - n_{uptake} \times \frac{N_{amm}}{N_{amm} + N_{nit}} - n_{nitrif} - n_{vola} + fert\_amm \quad (7)$$

$$\frac{\partial N_{nit}}{\partial t} = n_{nitrif} - n_{nitrgas} + n_{nitd} - n_{uptake} \times \frac{N_{nit}}{N_{amm} + N_{nit}} - n_{denitr} - n_{leach} + fert\_nit \quad (8)$$

where, gpp is flux of photosynthesis as in gross primary production (tonne N km^{-2} day^{-1}), c_{trr} is flux of respiration of trunk and root (tonne C km^{-2} day^{-1}), c_f is flux of litter-fall from leaf, trunk, and root as in carbon (tonne C km^{-2} day^{-1}), c_{dr} is flux of detritus decomposition as in carbon (tonne C km^{-2} day^{-1}), c_{dh} is flux of detritus huminification as in carbon (tonne C km^{-2} day^{-1}), c_{hr} is flux of humus decomposition as in carbon (tonne C km^{-2} day^{-1}), c_{hcar} is flux of humus carbonization as in carbon (tonne C km^{-2} day^{-1}), n_{uptake} is flux of nitrogen uptake by plant (tonne N km^{-2} day^{-1}), n_f is flux of litter-fall from leaf, trunk, and root as in nitrogen (tonne N km^{-2} day^{-1}), n_{fix} is flux of nitrogen fixation as in nitrogen (tonne N km^{-2} day^{-1}), n_{dm} is flux of detritus mineralization as in nitrogen (tonne N km^{-2} day^{-1}), n_{dh} is flux of detritus huminification as in nitrogen (tonne N km^{-2} day^{-1}), n_{hm} is flux of humus mineralization as in nitrogen (tonne N km^{-2} day^{-1}), n_{ammd} is flux of nitrogen deposition as in ammonium (tonne N km^{-2} day^{-1}), N_{amm} is potential nitrogen storage as in ammonium (tonne N km^{-2}), N_{nit} is potential nitrogen storage as in nitrate (tonne N km^{-2}), n_{nitrif} is flux of nitrification (tonne N km^{-2} day^{-1}), n_{vola} is flux of ammonia volatilization (tonne N km^{-2} day^{-1}), $n_{nitrgas}$ is flux of gaseous emissions during nitrification process (tonne N km^{-2} day^{-1}), n_{nitd} is flux of nitrogen deposition as in nitrate (tonne N km^{-2} day^{-1}),