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Evaluation of soil nitrogen emissions from riparian zones coupling simple process-oriented models with remote sensing data

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A B S T R A C T

Riparian ecosystems have critical impacts on controlling the non-point source pollution and maintaining the health of aquatic ecosystems. In this study, a process oriented soil denitrification model was extended with algorithms from a simple nitrogen (N) cycle model and coupled to land surface remote sensing data to enhance its performance in spatial and temporal prediction of gaseous N emissions from soils in the riparian buffer zone surrounding the Guanting reservoir (China). The N emission model is based on chemical and physical relationships that govern the heat budget, soil moisture variations and nitrogen movement in soils. Besides soil water and heat processes, it includes nitrification, denitrification and ammonia (NH_3) volatilization. SPOT-5 and Landsat-5 TM satellite data were used to derive spatial land surface information and the temporal variation in land cover parameters was also used to drive the model. A laboratory-scale anaerobic incubation experiment was used to estimate the soil denitrification model parameters for the different soil types. An *in situ* field-scale experiment was conducted to calibrate and validate the soil temperature, moisture and nitrogen sub-models. An indirect method was used to verify simulated N emissions, resulting in a coefficient of determination of $R^2 = 0.83$ between simulated and observed values. Then the model was applied to the whole riparian buffer zone catchment, using the spatial resolution (10 m) of the SPOT-5 image. Model sensitivity analysis showed that soil moisture was the most sensitive parameter for gaseous N emissions and soil denitrification was the main process affecting N losses to the atmosphere in the riparian area. From the aspect of land use management around the Guanting reservoir, the spatial structure and distribution of land cover and land use types in the riparian area should be adapted, to enhance faster ecological restoration of the wetland ecological system surrounding this strategically important water resource.

1. Introduction

Riparian ecosystems are well known to play an important role in controlling non-point source pollution (NPSP) and maintaining the health of aquatic ecosystems (Lowrance et al., 1997; Nina, 2005). In many countries, ecological restoration projects of riparian buffer zones are widely accepted as measures to improve catchment hydrological and water quality conditions (Muscutt et al., 1993; Kuusemets and Mander, 1999; McKergow et al., 2003). Since the 1990s, much riparian eco-engineering works have been carried out in China, for example, in Erhai Lake, Tai Lake and Guanting reservoir. However, riparian restoration projects are usually expensive and time consuming, and may result in other environmental problems in absence of adequate spatial considerations and management. For example, the byproducts of processes of soil nitrification and denitrification, mainly nitrous oxide (N_2O) and nitric oxide (NO) (Bedard-Haughn et al., 2006; Beuning, et al., 2008), are important greenhouse gases (IPCC, 1996; Lee et al., 1997).

Gaseous N emissions from soils are a very complex process. In the last three decades, numerous laboratory and field studies were conducted to measure soil gaseous N fluxes from various ecosystems. It was found that the main processes related to N emissions include soil denitrification (Pinay et al., 1993), nitrification (Wolf and Russow, 2000), chemodenitrification (Li et al., 2000) and ammonium volatilization (Langford et al., 1992). Soil factors affecting gaseous N emissions include soil microbial activity, substrates like organic

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carbon (OC), NH^{+}_4, NO^{-}_2 NO^{-}_3, soil temperature, moisture, redox potential (or Eh) and pH. On the basis of field and laboratory observations, several processes models were developed, such as CREAMS model (Knisel, 1980), "Hole-in-the-pipe" model (Firestone and Davidson, 1989), EPIC model (Sharply and Williams, 1990), CERES model (Godwin and Jones, 1991), CENTURY model (Parton et al., 1996) and PNET-N-DNDC model (Li et al., 1992a,b, 2000; Liu et al., 2006) etc. Most of these models perform well at the field scale.

In recent years, remote sensing data have been well recognized as a valuable source of spatially comprehensive and temporally repeatable information useful to ecologists and ecological modelers (Plummer, 2000). Just a frequently cited quotation by remote sensing scientists states that *Global understanding is an impossible task to achieve without extensive and intensive use of remotely sensed data* (Graetz, 1990), we need to find scientific approaches linking remotely sensed data to ecological process models at a variety of spatial and temporal scales.

Plummer (2000) discussed five alternative strategies to improve links between scientists from the remote sensing and ecological modeling disciplines. He pointed out that the most common rational for interfacing remote sensing and ecosystem models was applying remotely sensed data to generate model initial conditions and/or parameter values. With the development of remote sensing technology, medium to high resolution remote sensing data can be used to capture and generate land surface information, by inversion of remote sensing data in relation to ground conditions. Typically used remote sensing sensors include Advanced Very High Resolution Radiometer (AVHRR), Moderate resolution imaging spectrometer (MODIS), Landsat thematic mapper (Landsat TM) and enhanced thematic mapper (ETM), SPOT and Ikonos, Quickbird, etc. The input data derived from remote sensing data often include incident and reflected photosynthetically active radiation, surface temperature and vegetation cover related information like the Normalized difference vegetation index (NDVI), leaf area index (LAI) or land cover and land use changes and practices (Running and Nemani, 1988; Running et al., 1994; Baret and Guyot, 1991).

Due to the spatial heterogeneity of soil and landscape features, it's difficult to describe and evaluate the mechanism of N emissions on a detailed spatial scale using process models only. It was shown that it is possible to improve the accuracy of simulating N removal by coupling detailed N transformation models with semi-distributed hydrological models. Heinen (2006a) provided comprehensive reviews of various existing coupled models for nitrogen behavior in soils. Pohlert et al. (2007) coupled a detailed biogeochemical model with SWAT for improved N predictions. In this paper, we try to integrate simple processed-based models with remote sensing data to describe soil N emissions, using meteorological and land cover remote sensing data as model forcing parameters. This works complements earlier research (Wang et al., 2009), combining a simple soil denitrification model and remote sensing data to estimate spatially explicit soil denitrification rates in riparian buffer zones around reservoirs.

In this work, besides the soil denitrification model, a model of nitrification and ammonia volatilization was included to evaluate the soil N emissions. Experimental data, from a laboratory experiment on soil potential denitrification and from a field-scale experiment on the soil temperature, soil moisture and nitrogen budgets were used to calibrate and validate the new model at the field scale. The validated model was then used to estimate the soil N emissions in the whole riparian zone catchment using the remote sensing and weather data as model forcing data. The main purposes of this work are to (1) present a method based on the integration of a simple process-oriented model with remote sensing data to quantify spatial and seasonal variations of gaseous N emissions from soils in a riparian zone catchment; and (2) analyze the impacts of different land uses on the soil nitrogen emission process in riparian areas.

2. Materials and methods

2.1. Site description

This case study was conducted at Guanting reservoir located northwest of Beijing, China, with the research focusing only on the riparian buffer zone of the reservoir catchment. According to the boundary set by the administration for non-point source pollution (NPSP) prevention, the riparian zone is defined by a 5 km buffer from the highest water level of 479 m. The reservoir, which was constructed in 1954, is located approximately 100 km northwest of Beijing city (31° to 41° N, 112° to 117° E) and has a surface water area of 46.77 km^2 (Fig. 1). The region has a temperate continental monsoon climate with four distinct seasons. Average annual precipitation is 406 mm and most of the rainfall occurs between July and August. The mean annual water inflow of the reservoir is 1.463×10^9 m^3. The yearly mean air temperature is 2° to 8 °C. The highest temperature occurs between June and August and the annual average summer temperature is 21.6° to 27.2 °C. The average monthly wind speed is 3.1 to 4.1 m s^{-1}.

2.2. Experiments and data collection

2.2.1. Laboratory and field experiments

A laboratory experiment was carried out to measure the potential denitrification capacity (D_p) of soil samples collected from the research site (Wang et al., 2009). A riparian plot experiment using three test plots, with size: 4 m×3 m×1 m (see Fig. 2) was carried out at Yanqing experimental station, located in the northeast of research area (40°29′ N, 115°58′ E). The experimental ponds were separated from groundwater interaction by a concrete bottom. The plant species used in the experiments included reed (*Rhizoma Phragmitis*), alfalfa (*Medicago sativa*), the Chinese Arborvitae (*Cacumen Platycladi*) and Sabina vulgaris (*S. vulgaris Ant*). A 15-channel HOBO Weather Station was used to monitor the daily weather, soil temperature and moisture data. Soil samples were collected from the major soil series in the research area i.e., Typical cinnamon soil (TCS), Chao soil (CS) and Chao cinnamon soil (CCS). The soil parameters analyzed included pH, soil bulk density (SBD), total nitrogen (TN), total phosphorus (TP), nitrate nitrogen (NO_3–N), ammonia nitrogen (NH_4–N), soil water content at field capacity (SW_{FC}) and wilting point (SW_w) and soil organic matter (OM). Soil characteristics are listed in Table 1.

2.2.2. Database

Input data for the model included meteorological data, soil physical and chemical data and remote sensing data. The weather data was a forcing parameter of the model and the remote sensing data generated the temporal land surface parameter variations at the required spatial resolution. The daily climate data, including sunshine duration, air temperature, relative humidity, precipitation, wind speed and surface temperature from March to September in 2007, were collected from two national basic weather stations (Yanqing and Huailai stations) and the experimental weather station in the area (Fig. 1). Soil data, including bulk density, soil nutrients content (TN, NO_3–N, NH_4^+–N), soil texture and pH, were derived from the Second National Soil Survey results combined with field investigations in the research area. The thematic maps of land use, land cover and soil type were derived by interpreting remote sensing data (Wang et al., 2009). The soil water content, soil temperature and soil nutrient data were experimentally obtained to build the model's initial conditions.

Considering the band characteristics and the resolution of the remote sensing data and to minimize the influence of differences between satellite systems, multi-temporal images acquired by the same Landsat 5-TM sensor system were used. Seven cloud-free image data (TM5 path 123–124, row 32, from March to September) were used in the study. These data were acquired on March 2007, April 2007, May 2007, June 2006, July 2005, August 2008 and September 2007. Seven