SPATIAL SIMULATION OF NITROGEN LEACHING FROM INTENSIVE AGRICULTURE IN NORTHERN VIETNAM

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ABSTRACT

In this study, a spatial dynamic model was developed, to simulate nitrogen dynamics in Van Hoi commune, Tam Duong district, Vietnam, for different soil and land use types, under different irrigation and fertilizer regimes. The model has been calibrated using measured nitrogen concentrations in soil solution in March and August 2004 and validated for data from March and August 2005. Lateral flow was low in this level area. Percolation was the main process leading to high nitrogen leaching losses to groundwater. Calculated annual leaching losses varied from 88 to 122 kg N ha^{-1} in flowers, 64 to 82 in vegetables of the cabbage group, 51 to 76 in chili, 56 to 75 in vegetables of the squash group, and 36 to 55 in rice. Model accuracy needs to be improved through further calibration in both vertical and lateral dimensions and more combinations of soil and land use.

1. INTRODUCTION

High fertilizer and manure use in intensive agriculture is one of the main sources of nutrient leaching losses to the environment, and the associated reduction in groundwater quality (Wolf *et al.*, 2005). In many regions the annual leaching load exceeded 20 kg ha^{-1} (Lin *et al.*, 2001), while in about 2.5% of the land area occupied by terrestrial ecosystems it exceeded 30 kg ha^{-1}; especially in areas with heavy fertilizer application, such as the United States, Europe, and China, the maximum leaching load was 133 kg ha^{-1} yr^{-1}. In Vietnam, the population has rapidly increased, leading to increased food demand. In response, agriculture has intensified, increasing the pressures on soil and environment. In northern Vietnam, Vinh Phuc province is one of these rapidly developing regions. Intensification of farming is associated with strongly increasing inputs of nitrogen fertilizer.

Nitrogen leaching from agriculture originates from non-point pollution sources and is difficult to quantify. At plot scale, various methods for measuring N leaching have been applied, in different soils, and under different land use systems (Riley *et al.*, 2001; Mai *et al.*, 2007a). Alternatively, N leaching has been estimated using decision support systems (Johnsson *et al.*, 2002) and models at appropriate scales (Ersahin and Rustu Karaman, 2001; El-Sadek *et al.*, 2003), combining spatial and non-spatial data on soils, crops, and fertilization. At watershed scale, N leaching losses vary both temporally (different seasons, rainfall and fertilizer application regimes, and crop calendars), and spatially (different elevations, soils, land uses, rainfall patterns, irrigation and fertilizer patterns). The objectives of this study were: (i) to develop a spatial-dynamic model for N leaching in an intensive agricultural region with high fertilizer use and (ii) to apply the model for quantifying N leaching losses from intensive farming systems, with very high irrigation and fertilizer inputs, in Van Hoi commune, Tam Duong district, northern Vietnam.

2. METHODOLOGY

2.1 Study area

Van Hoi commune is located in a flatland area of Tam Duong district (21°26′ N, 105°36′ E), 60 km north of Hanoi. The commune has a total area of 290 ha, with arable land belonging to two soil texture groups: clay loam (126 ha; 53.8%) and sandy loam (109 ha; 46.2%). Representative soil profiles were described for both the sandy loam and clay loam soils, including their properties, such as hydraulic conductivity, porosity, and field capacity. Rainfall, temperature, radiation, wind speed, and sunshine hours were recorded at Vinh Yen meteorological station, about 2 km from the study area.

2.2 Land use and fertilizer use

Currently, the main rotation is double rice followed by an upland crop, such as maize, potato, sweet potato, or vegetables during winter. For vegetables, high value crops, with very high fertilizer and biocide inputs, two groups are distinguished: group 1 (‘cabbage’ group) consisting of paprika, cabbage, egg plant, and kohlrabi, in which cabbage is the major crop; group 2, including chili, cucumber, tomato, and squash, with chili and squash as major crops. For rice, all farm yard manure (FYM), all phosphorus, and 20 to 30% of the N fertilizer is applied as basal dressing. The remaining N fertilizer is applied in 2 to 3 splits, at the start of tillering and before booting. Maize is mostly grown in the winter season, FYM and phosphorus fertilizer are applied as basal dressing, while chemical N fertilizers are applied each week, till the 9-leaf stage, through ‘bucket irrigation’. For vegetable group 1, all FYM and phosphorus fertilizer are applied at planting, whereas dissolved N fertilizers are applied in the early stages through ‘bucket irrigation’. Cabbage is grown very intensively with up to seven harvests per year. In chili, FYM is applied as basal dressing under submerged conditions between the beds, followed by monthly additions, while chemical nitrogen fertilizer is applied weekly on the soil surface. In cucumber, tomato and squash, FYM and phosphorus are surface-applied before planting, followed by weekly applications of sludge and chemical N fertilizers through ‘bucket irrigation’. Flowers (mainly rose and daisy) require high doses of fertilizers to compensate for nutrient export in the weekly cuttings. Liquid compost, consisting of a mixture of manure, N-rich materials such as bean residues, urine, and food processing wastes are surface-applied each week through ‘bucket irrigation’.

2.3 Field measurements

Groundwater samples (at 52 locations, randomly selected), at 1 m depth, were taken at four dates, 6th March and 15th August 2004, and 26th March and 8th August 2005, using an open porous pipe and a hand pump, and were analysed for nitrate- and ammonium-nitrogen content (Mai *et al.*, 2007b). Irrigation and fertilizer application were recorded for each land use type as inputs for calculation of the water and soil mineral nitrogen balances. Soil samples were taken on 1st February 2004, and analysed for Nmin as initial condition for the simulation model.

2.4 Model description

To allow analysis in the specific geo-morphological conditions of the study area, a spatial dynamic model was developed. It simulates N leaching, using PCRaster, a computer language for construction of dynamic spatio-temporal environmental models (Van Deursen, 1995; Karssenberg *et al.*, 1996). It includes water and nitrogen modules and uses a daily time step (Figure 1). Both, the water and nitrogen modules have been applied in simulations at plot scale (Mai *et al.*, 2007a). In spatial dynamic simulation, three main components are distinguished: the space dimension, the time dimension, and the dynamic process. In the soil profile, three horizons are distinguished, while the model consists of four compartments, with thickness of 40, 40, 20 and 300 cm, respectively (Figure 1). The model was fully described in Mai (2007).

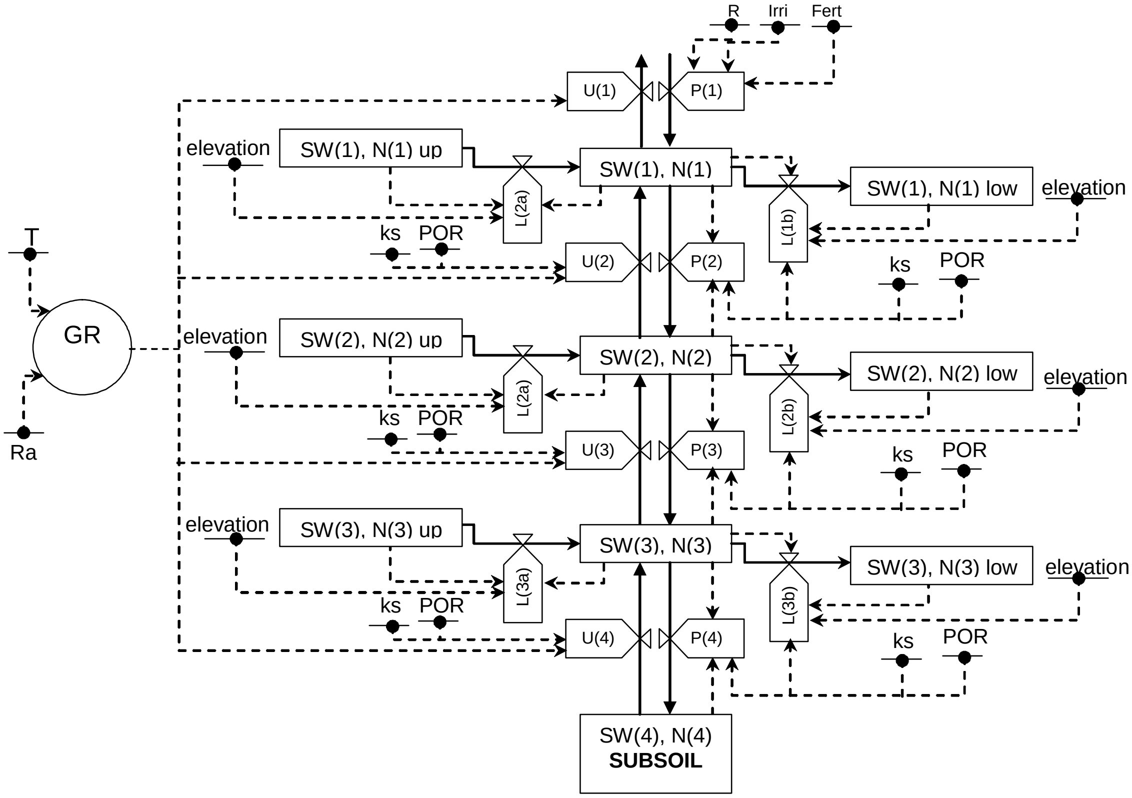

Figure 1. Relational diagram for soil moisture and nitrogen dynamics in the soil; where R is rainfall; Irri, irrigation; Fert, fertilizer, SW(1), soil water content (layer); L(1a), lateral inflow rate; N, nitrogen concentration; P, percolation and leaching rates; U, evapo-transpiration and nitrogen uptake rates; T, temperature; Ra, radiation; GR, crop growth; ks, soil conductivity; L(1b), lateral outflow; and POR, is soil porosity.

2.5 Model calibration and validation

The most important parameter influencing percolation and N transport rates is *ks*. As no data were available for calibration of lateral flows, N mineralization and transformation of nitrogen into gaseous form, only *ks* was used for calibration. Goodness of fit of simulated values was calculated following Jørgensen and Bendoricchio (2001):

$$Y = \sqrt{\frac{\sum \frac{(c_c - c_m)^2}{c_{m,a}}}{n}}$$

where, c_c is simulated Nmin, c_m the corresponding measured Nmin, $c_{m,a}$ average measured Nmin, and n the number of samples.

3. RESULTS

3.1 Input data

Input files with model parameters are given in Table 1.

Table 1. Input parameters for the model (all maps are in raster mode with a resolution of 5 m).

Input file	Description
Rain.tss	Daily rainfall
Irrig.tss	Daily irrigation for each land use type
Evap.tss	Daily evapo-transpiration for each land use type (calculated outside the model)
Fert.tss	Daily fertilizer application for each land use type, 15% reduced in 2005
Soil.map	Soil map
Soil.tbl	Attribute table with different soil properties for each soil type
Dem.map	Digital elevation map
Ldd.map	Local drainage network map derived from Dem.map, which is raster-formatted with codes from 1 to 9 showing drain directions to the neighbouring cells (Karssenberg *et al.*, 1996)
Landuse.map	Land use map that is linked to the irrig.tss, evap.tss and fert.tss files through land use types
Landunit.map	Overlay from soil and land use type maps
Kslandunit.tbl	Multiplication factor for *ks* values in each land unit
InitSW.map	Initial soil water map
InitN.map	Initial nitrogen concentration (mg kg^{-1}) map from soil samples taken on 1st February 2004 at 1 m depth

3.2 Spatial N distribution

The spatial distribution of simulated Nmin concentrations in the third layer for March 6th 2004 and March 26th 2005 is shown in Figure 2, illustrating the calibration and validation results. In general, Nmin was lower in 2005 than in 2004. Overall, the spatial patterns were similar, but in 2004, Nmin was similar in rice soil and in vegetable soil, whereas in 2005 it was lower in rice.

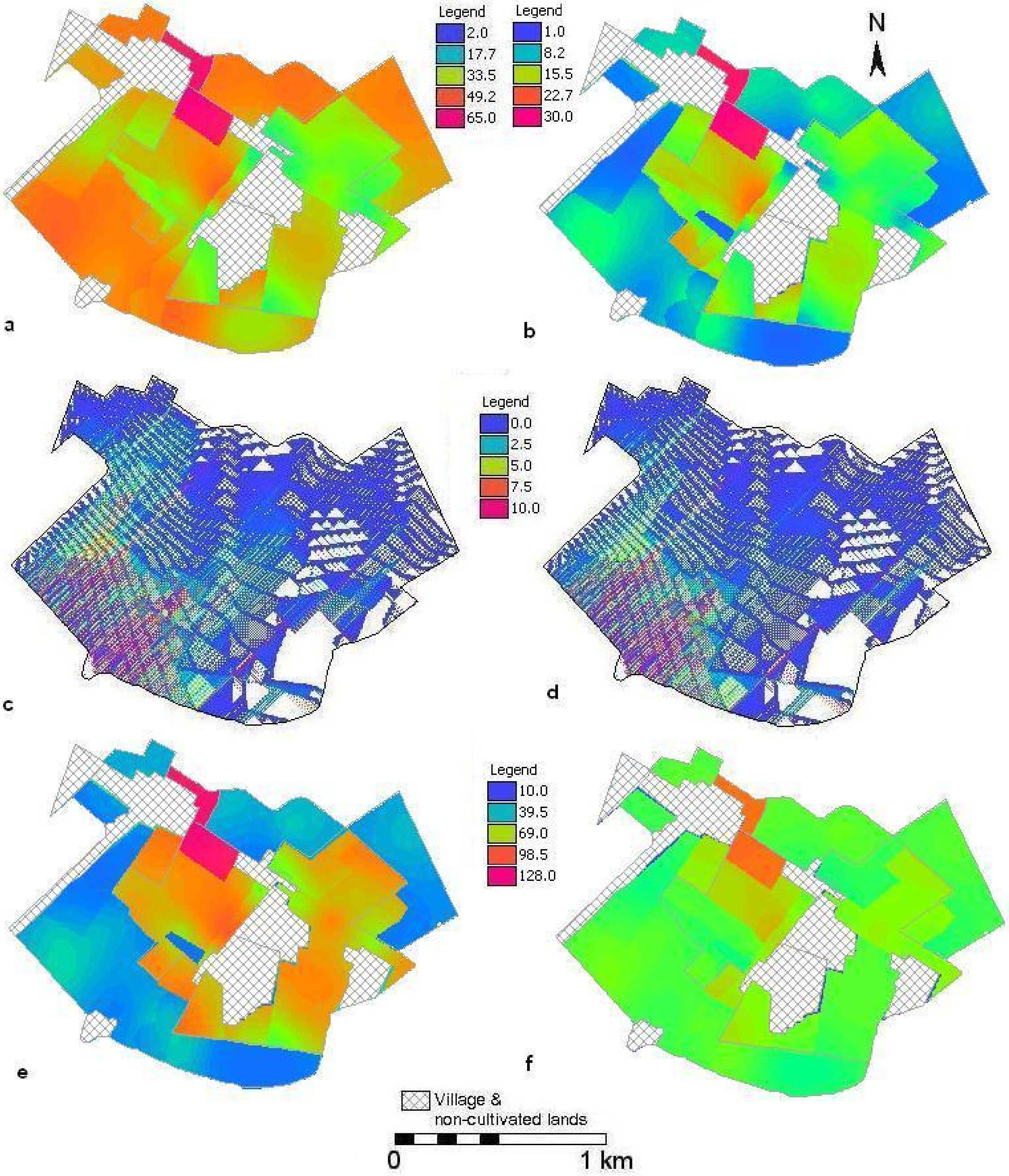

Figure 2. Simulated soil mineral nitrogen concentration (Nmin, mg l^{-1}) on 6th March 2004 (a), and 26th March 2005 (b); simulated cumulative lateral N transport (kg ha^{-1} yr^{-1}) in 2004 (c) and in 2005 (d); and simulated annual N leaching (kg ha^{-1} yr^{-1}) in 2004 (e), and in 2005 (f).

In the simulations, the rate of lateral nitrogen transport along the local drainage network (ldd; Table 1) was low, i.e. lateral water and N flows were less than 0.2 mm d^{-1} and 0.032 kg ha^{-1} d^{-1} in the first, 0.11 and 0.06 in the second, and 0.03 and 0.012 in the third layer, respectively. The highest rates usually occurred during irrigation of specific crops, creating moisture content gradients between plots with different land use types. However, at some locations, cumulative lateral Nmin transport was substantial (Figures 2c and d), due to frequent soil moisture gradients between the upper and lower cells. On the other hand, surface runoff also results in redistribution of soil water and nitrogen.

3.3 Nitrogen transport and leaching

Simulated percolation rates reached values up to 55.1 mm d^{-1} in the first layer, 1.74 in the second, and 0.9 in the third, with associated N leaching rates of 0.7 kg ha^{-1} d^{-1} in the first layer, 0.65 in the second, and 0.45 in the third. Percolation was more frequent than lateral flow and strongly associated with rainfall events. However, the rates vary spatially, due to differences in elevation, soil type and land use type, as well as temporally, due to differences in rainfall, irrigation, evapo-transpiration and crop uptake.

Total annual N leaching was higher in 2004 than in 2005 (Figures 2e and f) and varied among crops, as a result of differences in percolation volume under different irrigation and fertilizer regimes, i.e. from 88 to 122 kg N ha^{-1} yr^{-1} in flowers, 64 to 82 in the cabbage group, 51 to 76 in chili, 56 to 75 in the squash group, and 36 to 55 in rice.

4. DISCUSSION

Land use is the single most important factor influencing N leaching, as shown by significant differences in N-concentrations in the profile among crops (Mai *et al.*, 2007a). Among the cropping systems in this study, flowers showed the highest susceptibility to N leaching, because of the very high fertilizer doses applied. Large quantities of nitrogen-rich manure were applied that remained on the soil surface during the rainy season. Vegetables, in both the cabbage and squash groups and chili show a similar range in N leaching, with the higher values for cabbage, associated with the intensive short-duration rotation and the relatively long residence time of the fertilizer on the soil surface. N leaching is lowest in rice, because of the presence of the low-permeability layer. Land use type also strongly influences the water and nitrogen balances in the soil, through its effect on irrigation, evapo-transpiration, and fertilization. Therefore, *ks* should be calibrated for each soil horizon per combination of soil type and land use type.

The model could be improved by incorporating the effects of drainage canal systems and watershed effects. Closer to the drainage network, soil moisture gradients are steeper and lateral flow is therefore higher near the canal. At watershed scale, the water and nitrogen balances would be more accurately simulated, if the drainage pathway through the local drainage network to the outlet of the watershed, which leads to N accumulation in the watershed outlet, would be incorporated.

5. CONCLUSIONS

A spatial dynamic model was developed to simulate nitrogen dynamics and leaching under intensive agriculture with high fertilizer use in Van Hoi commune, a flatland area of Tam Duong district in Vietnam. The model is shown to be a suitable tool for quantifying nitrogen losses from agriculture and for environmental assessment at regional scale. It has been calibrated on the basis of measurements in March and August 2004 and validated for March and August 2005. Simulated result show that lateral flow was low, and that nitrogen leaching due to percolation was high. Simulated annual N leaching losses varied from 88 to 122 kg N ha^{-1} yr^{-1} in flowers, 64 to 82 in the cabbage group, 51 to 76 in chili, 56 to 75 in the squash group, and 36 to 55 in rice.

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