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# Nitrogen Leaching in Intensive Cropping Systems in Tam Duong District, Red River Delta of Vietnam

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**Abstract** The environmental and economic consequences of nitrogen (N) lost in rice-based systems in Vietnam is important but has not been extensively studied. The objective of this study was to quantify the amount of N lost in major cropping systems in the Red River Delta. An experiment was conducted in the Red River Delta of Vietnam, on five different crops including rose, daisy, cabbage, chili, and a rice–rice–maize rotation during 2004 and 2005. Core soil samples were taken periodically in 20-cm increments to a depth of 1 m and analyzed for nitrate–nitrogen and ammonium–nitrogen. The results indicate appreciable leaching losses on N in high-rainfall and irrigation conditions, especially when fertilizer application was not well synchronized with crop N demand. Highest annual leaching losses of N were recorded in flowers with 185–190 mm of percolation and 173–193 kg N $ha^{-1}$, followed by vegetable (cabbage and chili) with 120–122 mm of percolation and 112–115 kg N $ha^{-1}$, while it was lowest in rice with about 50 kg N $ha^{-1}$. We developed a simple N transport model that combined water and N movement through the soil profile. In most cases, the model accurately predicted the seasonal dynamics of N as well as N flow between soil layers and the amounts of N lost from the soil profile. The simulated results of N leaching with soil "puddling" conditions illustrate the advantage of an impermeable or hardpan layer in increasing water and nutrient use efficiencies in these soils. These model results also showed that it is possible to accurately estimate N losses with only a few parameters and helped us identify the risks of N leaching.

**Keywords** Horticulture · Flowers · Vegetables · Rice · Nitrate · Nitrogen losses · Modeling

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## 1 Introduction

Plant recovery efficiencies of fertilizer N vary strongly, depending on cropping system, environmental conditions, and fertilizer management (Neeteson 1995; Janssen 1998), and in rice-based systems, values are usually between 30% and 40% (Dobermann et al. 2002). One of the loss pathways in the nitrogen cycle is nitrate leaching from the soil. The magnitude of leaching also strongly varies, depending on such factors as soil type, cropping system, weather conditions, and fertilizer regime (Di and Cameron 2002; Hauggaard-Nielsen et al. 2003; Verloop et al. 2006). High leaching losses from intensive agriculture may cause high nitrate concentrations in groundwater, which potentially carries health risks. Tripathi et al. (1997) calculated N leaching losses from heavily fertilized rice–vegetable systems in the range of 34 to 549 kg ha$^{-1}$, with the largest losses from rice–sweet pepper and rice–tomato rotations. Similar results were recorded in China, with leaching losses roughly between 30 and 450 kg ha$^{-1}$, at annual fertilizer inputs of 350 kg N ha$^{-1}$ for double rice and 920 kg N ha$^{-1}$ in horticulture (Fang et al. 2005). Comparing nitrate ($NO_3$-N) leaching from different land use domains in Japan, Babiker et al. (2004) established the highest mean $NO_3$-N concentrations in groundwater in vegetable fields with 57.1 mg L$^{-1}$, followed by urban areas with 30.8 mg L$^{-1}$ and paddy fields with 24.2 mg L$^{-1}$.

Measuring $NO_3$-N leaching from agricultural non-point sources is not easy, is expensive, and requires extensive field and laboratory measurements. Five methods are potentially suitable, i.e., porous ceramic cups, pan/trench samplers, lysimeters, large-scale drainage collection, and soil coring (Addiscott 1990). Each method has advantages and difficulties in terms of implementation, costs, reproducibility, relevance, effect, and interpretability. Nitrogen leaching can also be calculated or estimated in different ways. For example, Tripathi et al. (1997) calculated total apparent N losses as the balance of the sum of available soil N before cropping, fertilizer N applied and N addition from weed residues, and the sum of N removed and residual N in the soil after crop harvest. Liu et al. (2003) calculated N losses on the basis of measured $NO_3$-N concentrations in the course of time at different soil depths, and Chikowo et al. (2004) used differences in mineral N concentration at different sampling dates to calculate N leaching per soil layer and for the whole soil profile. Increasingly, models are being used to simulate N dynamics and leaching from the soil profile, based on water balance models (Addiscott and Whitmore 1987; Jemison et al. 1994; Ersahin and Rustu Karaman 2001; Helwig et al. 2002). Such models simulate both water and N balances with short time intervals and take into account other processes important in the N cycle, such as nitrogen mineralization, crop uptake, nitrogen volatilization, and denitrification to calculate nitrogen losses, as well as potential pollution to groundwater (Chowdary et al. 2004).

Tam Duong district, located in the Red River Delta of northern Vietnam (21° 26′ N, 105° 36′ E), is characterized in recent years by strong population and economic growth. Population increased by 4% in the last 10 years with about 1.5% per year in rural area and 6% per year in urban area. Thus, demand for food in the urban sector, both in terms of quantity and in number of commodities, has increased dramatically in recent years. One of the fast-growing commodities is vegetables, of which cultivated area and yield have been increasing, e.g., from 300 ha and 13.7 Mg ha$^{-1}$ in 1990 to 499 and 14.0 in 1995 to 719 ha and 16.2 Mg ha$^{-1}$ in 2003. Farmers' income from vegetables is much higher than that from other commodities (IRMLA 2005). The increase in cultivated area and in crop yield is associated with a substantial increase in the use of agrochemicals, such as fertilizers and pesticides (Van Wijk et al. 2006).

With the rising use and cost of fertilizer N, it is becoming increasingly important to accurately predict the uptake and loss of N from soils in order to maximize the efficiency of fertilizer use and minimize the deleterious environmental consequences of fertilizer losses. Because of the high cost of measuring soil mineral N, it would be useful to be able to accurately model mineral N dynamics and N loss in different cropping systems. Hence, one objective of this research study was to accurately measure the seasonal dynamics of mineral N ($NO_3$-N and $NH_4$-N) in the soil profile under the major crops grown in the Red River Delta. A second objective was to develop a simple water and N model that could be used to simulate these dynamics to assess N losses and thus identify better fertilizer management practices for these crops in this region.

## 2 Materials and Methods

### 2.1 Study Area

The study was conducted in Van Hoi commune, a flat area in Tam Duong district, about 70 km northwest of Hanoi, Vietnam. The soil is a sandy loam, derived from old alluvial deposits of the Red River system. It is classified as an Albi dystric plinthosol (FAO/UNESCO 1974; FAO 1976) and has been used traditionally for rice cultivation but is considered suitable for vegetables and horticulture (Chi and Bo 2002). The soil profile is strongly developed; clay content sharply increases with depth, while organic carbon and plant nutrient contents decrease (Table 1).

### 2.2 Experimental Setup

The experiment included five cropping systems:

1. Long-term rose (*Rosa* L.) cultivation in its third and fourth year
2. Daisy flowers (*Bellis perennis*) grown annually from September to May
3. Six successive cabbage (*Brassica*) crops per year
4. Chilies (hot pepper; *Capsicum*) grown annually from September to August
5. Spring rice (*Oryza sativa*)–summer rice–winter maize (*Zea mays*, L), the traditional rotation in the area

Soils were sampled six times annually, based on the growing periods of the six cabbage crops, i.e., in 2004 on March 21st, May 9th, July 6th, September 18th, and November 13th; in 2005 on January 11th, March 26th, May 9th, July 6th, September 18th, and November 28th; and in 2006 on January 19th. Rainfall, irrigation, and nitrogen fertilizer applied to each crop in each period are shown in Fig. 1.

### 2.3 Field Sampling, Soil, and Data Analysis

Soils were sampled with augers in 20-cm increments to a depth of 1 m. In each field, soil was sampled in triplicate, and the samples bulked for each depth. Subsamples were taken to the laboratory in polyethylene bags and stored at 4°C prior to extraction, usually within 2 days of collection. Aboveground plant samples were taken at the same dates, for determination of N content.

Twenty grams of field-moist soil were extracted in 50 ml 0.5 M KCl via shaking on a rotary shaker for 1 h, followed by filtering through Whatman no. 1 filter paper into polyethylene containers. Nitrate nitrogen ($NO_3$-N) and ammonium nitrogen ($NH_4$-N) in KCl extracts were determined by the steam distillation method. Another subsample of soil was dried at 105°C for 24 h to determine moisture content. Plant samples were oven-dried (65°C) for 12 h and weighed. N was determined by the micro-Kjeldahl method (Bremner 1996).

Data of $NO_3$-N and $NH_4$-N in all systems from each soil layer were analyzed using one-way ANOVA analysis of variance, using the GenStat statistical package (Lawes Agricultural Trust 2003). Total mineral N (Nmin) in each soil layer was calculated as the sum of $NO_3$-N and $NH_4$-N.

### 2.4 Nitrogen Transport Model

#### *2.4.1 Water Balance*

The dynamics of Nmin were simulated based on a water balance model with daily time step, for a 1-m soil profile with compartments of 0.2 m. Soil water

**Table 1** Soil properties at the experimental site

| Soil depth | Particle size distribution (%) | | | Bulk density (g cm$^{-3}$) | OC (%) | N total (%) | P total (% $P_2O_5$) | K total (% $K_2O$) |
|---|---|---|---|---|---|---|---|---|
| | Clay | Silt | Sand | | | | | |
| 0–20 | 8.3 | 20.9 | 70.8 | 1.31 | 1.5 | 0.09 | 0.130 | 0.22 |
| 20–40 | 16.9 | 13.6 | 69.5 | 1.29 | 1.8 | 0.05 | 0.045 | 0.15 |
| 40–60 | 24.4 | 11.8 | 63.8 | 1.29 | 1.0 | 0.04 | 0.018 | 0.37 |
| 60–80 | 34.8 | 11.9 | 53.3 | 1.25 | 0.6 | 0.05 | 0.017 | 0.63 |
| 80–100 | 39.9 | 9.0 | 51.1 | 1.25 | 0.4 | 0.05 | 0.018 | 0.97 |

*OC* organic carbon

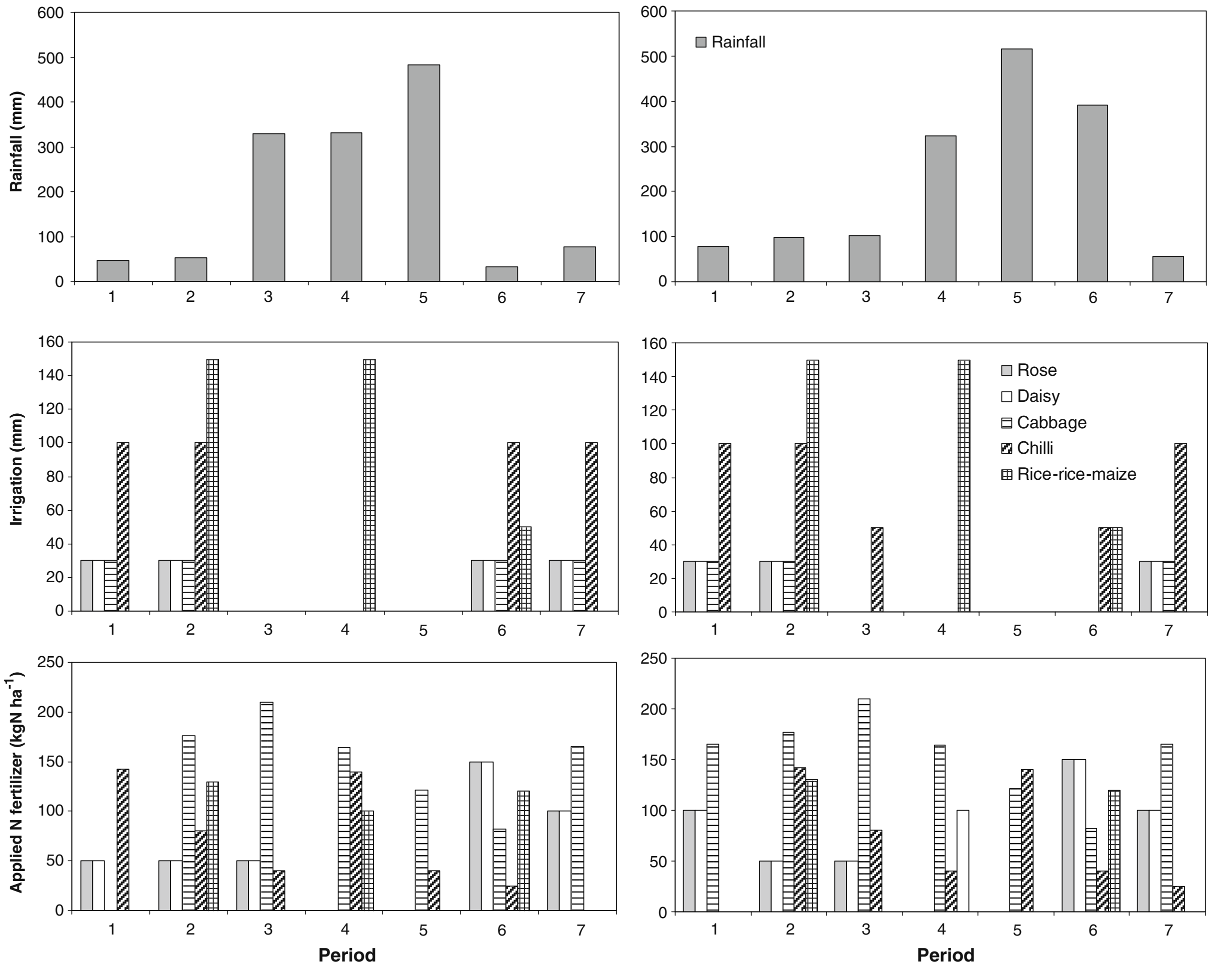



**Fig. 1** Rainfall (mm), irrigation (mm), and applied N fertilizer (kg N ha$^{-1}$) in different periods ending on Jan 1st, Mar 21st, May 9th, Jul 7th, Sept 18th, and Nov 13th in 2004 (*left*) and Jan 11st, Mar 26th, May 05th, Jul 6th, Sept 18th, and Nov 28th in 2005, and Jan 19th 2006 (*right*). Period 1 in 2005 is identical to period 7 in 2004

(SW) in each soil layer at time *t* was calculated as the sum of soil water in that layer at time $t-1$ and net flow (NFL) into the layer at time *t*. Net flow into the *i*th soil layer was calculated as the balance of inflow (FL), outflow (i.e., inflow into the $i+1$th soil layer), and evapotranspiration from the *i*th layer.

$$SW_{i,t} = SW_{i,t-1} + NFL_{i,t} \times \Delta t \quad (1)$$

$$NFL_i = FL_i - FL_{i+1} - ET_i \quad (2)$$

For the surface layer, inflow equals:

$$FL_1 = R + IRR - Q \quad (3)$$

where $SW_i$ is soil water content in the *i*th layer (mm), R rainfall (mm day$^{-1}$), IRR irrigation (mm day$^{-1}$), $ET_i$ contribution of *i*th layer to evapotranspiration (mm day$^{-1}$), $FL_i$, $FL_{i+1}$ flow over upper and lower boundary of layer *i* (mm day$^{-1}$), respectively, $\Delta t$ the time step of the model (day), and Q surface runoff (mm day$^{-1}$).

Total ET was calculated using the Penman–Monteith method (Allen et al. 1998). Hasegawa and Kasubuchi (1993) showed that water extraction by roots varies in time with variations in root distribution in the soil profile. Models of water extraction by roots have been reviewed by Molz (1981), including the empirical model proposed by Molz and Remson (1970):

$$s = \frac{-1.6 \times T}{v^2} \times z + \frac{1.8 \times T}{v} \quad (4)$$

where *s* is root water extraction, *T* transpiration rate, *z* soil layer depth, and *v* the depth of the root zone. If the root zone is divided into four layers of equal thickness, this equation indicates that water extracted from the successive layers is 40%, 30%, 20%, and 10%, respectively, of the transpiration rate (Hasegawa and Kasubuchi 1993).

Following this principle, in our model, total root water extraction was partitioned in the proportions 0.4, 0.3, 0.2, and 0.1 over four soil layers, each representing a quarter of the total rooting depth.

Flow into the *i*th soil layer, either saturated or unsaturated, depending on soil moisture content (Radcliffe et al. 1998), is described by Darcy's law:

$$FL_i = -k_i \frac{\mathrm{d}h_i}{\mathrm{d}z} \tag{5}$$

$$k_i = ks_i \quad \text{if } \theta_i = \theta s_i \tag{6}$$

$$k_i = kr_i \times ks_i \quad \text{if } \theta_i < \theta s_i \tag{7}$$

$$kr_i = \left(\frac{\theta_i - \theta r_i}{\theta s_i - \theta r_i}\right)^{\lambda} \tag{8}$$

where $\mathrm{FL}_i$ is water flow into soil layer $i$ (mm $\mathrm{day}^{-1}$), $k_i$ soil hydraulic conductivity of soil layer $i$ (mm $\mathrm{day}^{-1}$), $\mathrm{d}h_i/\mathrm{d}z$ the moisture potential gradient between layers $i$ and $i-1$, $kr_i$ (Averjanov 1950; Brutsaert 1966) the proportionality factor for actual soil hydraulic conductivity ($0 \le kr_i \le 1$); $\theta_i$, $\theta r_i$, $\theta s_i$ are water contents in the *i*th layer to which $kr_i$ applies, residual water content, and water content at saturation, respectively ($\mathrm{cm}^3\,\mathrm{cm}^{-3}$); $\theta r$ is defined as the water content in the soil that does not participate in flow (immobile water). In practice, $\theta r$ corresponds to the content at which the moisture capacity of the soil approaches zero ($\mathrm{d}\theta/\mathrm{d}h \rightarrow 0$; Zaradny 1993), and it varies from 0.005 for light-textured soils to 0.1 for heavy-textured soils (Lal and Shukla 2004); $\lambda$ is an empirical coefficient of 3.5 (Averjanov 1950) or $2 \le \lambda \le 5$ (Brutsaert 1966).

In this flat area, individual fields are surrounded by bunds, so that surface runoff only occurs when rainfall exceeds bund height (Chowdary et al. 2004). Surface runoff is estimated by:

$$Q = \mathrm{Max}(0, \mathrm{R} + \mathrm{IRR} + (\mathrm{SW}_1 - \mathrm{POR}_1 - \mathrm{BH})/\Delta t) \tag{9}$$

where $\mathrm{SW}_1$ and $\mathrm{POR}_1$ are soil water content (mm) and saturated soil water content in the first layer; BH is bund height (mm), in this study set to 50 mm for flowers and cabbage and 100 mm for chili and rice, the crops for which rain water is stored in the field.

### 2.4.2 Nitrogen Balance

Nitrogen uptake by the crop is calculated as the product of transpired water volume and mineral nitrogen concentration in each soil layer. Transpiration ($T_i$) is calculated from potential evapotranspiration ($\mathrm{ET}_i$), taking into account current leaf area index (LAI). The partitioning between $T_i$ and soil evaporation ($E$) was derived from WOFOST, a crop growth model (Boogaard et al. 1998) that was calibrated for rice and maize for the study area (Mai et al. 2007, manuscript in preparation). Simulated $T_i$ is a very small fraction of $\mathrm{ET}_i$ at the onset of crop growth and increases with increasing LAI, to account almost completely for ET at the time of maximum LAI. Based on these results, an equation was derived to calculate $T_i$ from $\mathrm{ET}_i$:

$$T_i = \frac{\min(t, \mathrm{Du\_LAI_{max}})}{\mathrm{Du\_LAI_{max}}} \mathrm{ET}_i \tag{10}$$

where $t$ is time after sowing (day); $\mathrm{Du\_LAI_{max}}$ is the duration (day) of the period from sowing until maximum LAI (Table 2), and $\mathrm{ET}_i$ is ET from the *i*th soil compartment.

**Table 2** Cropping calendars (date of sowing of maximum LAI and harvest) for different crops

| Crop | Date | | |
|---|---|---|---|
| | Sowing | LAImax | Harvest |
| Rose | Sept 15th[a] | Oct 30th | After Oct 30th |
| Daisy | Sept 15th | Nov 15th | May 15th |
| Cabbage[b] | Feb 5th | March 15th | March 21st |
| Chili | Sept 1st | Dec 1st | Jul 15th |
| Spring rice | Feb 5th | May 5th | Jun 5th |
| Summer rice | Jun 25th | Aug 19th | Sept 19th |
| Winter maize | Sept 20th | Dec 5th | Jan 10th |

[a] For rose, sowing date is starting time for fertilizer application

[b] For cabbage, planting is repeated after harvesting of the preceding crop

The dominant influences on movement of Nmin in the soil are those due to mass transport, uptake by the plants and microbial biomass, and gaseous losses; redistribution in the soil profile by diffusion is ignored as is adsorption on negatively charged soil particles. Only downward transport of nitrogen is considered on the basis of the “perfect mixing” principle, as described by Van Keulen and Seligman (1987):

$$S_{\mathrm{n}} = S_{\mathrm{ni}} - S_{\mathrm{no}} \tag{11}$$

$$S_{\mathrm{ni}} = N_{i-1} \times \mathrm{FL}_i \tag{12}$$

$$S_{\mathrm{no}} = N_i \times \mathrm{FL}_{i+1} \tag{13}$$

where $S_{\mathrm{n}}$ is the rate of change in nitrogen content in $i$th layer due to transport (kg ha$^{-1}$ day$^{-1}$), $S_{\mathrm{ni}}$ the rate of inflow of nitrogen in $i$th layer (kg ha$^{-1}$ day$^{-1}$), $S_{\mathrm{no}}$ the rate of flow of nitrogen out of $i$th layer (kg ha$^{-1}$ day$^{-1}$), $\mathrm{FL}_i$, $\mathrm{FL}_{i+1}$ rate of water flow into the appropriate soil layer (mm day$^{-1}$), $N_i$, $N_{i+1}$ the nitrogen concentrations in the appropriate soil layer (kg ha$^{-1}$mm$^{-1}$)

All nitrogen present in a soil layer and that flowing into it are mixed with all the moisture associated with it to calculate an average nitrogen concentration. For the present purpose, this description adequately represents the transport dynamics of nitrogen in the soil. Diffusion along developing concentration gradients, which will generally result in downward movement, particularly in the case of fertilizer application, will be partly compensated by upward movement of nitrogen with moisture evaporating at the soil surface. The distribution of nitrogen in the soil profile calculated in this way will be different from that achieved with detailed process models, but that will hardly affect its availability to the crop that has access to mineral nitrogen over the whole rooted depth. Upward movement of nitrate from below the rooted depth to the root zone is unlikely to contribute substantially to plant-available nitrogen and can be ignored.

The total mineral nitrogen balance for a soil layer is now described by:

$$C_{\mathrm{ni}} = S_{\mathrm{n}} + R_{\mathrm{nfi}} + R_{\mathrm{nsi}} - T_i \times N_i - N_{\mathrm{di}} - N_{\mathrm{gas}} \tag{14}$$

where

$C_{\mathrm{ni}}$ Rate of change in nitrogen in the $i$th layer (kg ha$^{-1}$ day$^{-1}$)

$R_{\mathrm{nfi}}$, $R_{\mathrm{nsi}}$ Rate of release of mineral nitrogen during decomposition of fresh and stable organic material, respectively, in the $i$th soil layer (kg ha$^{-1}$ day$^{-1}$)

$T_i$ Rate of moisture uptake (transpiration) from $i$th soil layer (mm day$^{-1}$)

$N_{\mathrm{di}}$ Rate of nitrogen uptake by diffusion from the $i$th layer (kg ha$^{-1}$ day$^{-1}$)

$N_{\mathrm{gas}}$ Rate of nitrogen loss to the air by volatilization and denitrification (kg ha$^{-1}$ day$^{-1}$)

Nitrogen uptake includes mass flow via transpiration ($T_i \times N_i$) and via diffusion ($N_{\mathrm{di}}$). It is very difficult to quantify the contribution of N uptake by diffusion, especially since data for the local circumstance are very rare. Uptake via diffusion strongly depends on conditions such as water flow, soil moisture content, and difference between N concentration in the soil and in plant root. According to the research of Miller and Gardiner (2001), N uptake via diffusion can be assumed as 20% of total uptake.

In the cropping systems considered here, green manure and straw were not applied, while the contribution of residual root biomass was ignored; therefore, supply of fresh organic material was assumed to be zero. Stable organic material was applied in the form of FYM that also contains mineral nitrogen, which was directly added to the mineral nitrogen pool, while the organic component was assumed to gradually decompose. Decomposition is assumed to take place in the upper soil layer and is simulated according to Yang’s model (Yang 1996):

$$R_{\mathrm{nsi}} = R_9 \times \mathrm{f} \times (\mathrm{f} \times \mathrm{t})^{-s} \tag{15}$$

$$Y_t = Y_0 \times e^{-R_9 \times (f \times t)^{1-s}} \tag{16}$$

$$f = 2^{(T-9)/9} \text{ for } 9 < T \leq 27^{\circ}\mathrm{C} \tag{17}$$

where $R_9$ is defined as the initial relative mineralization rate (day$^{-1}$) at a temperature ($T$) of 9°C, set to 0.82 for FYM (Yang 1996), $f$ temperature correction factor, $S$ rate of aging or decrease in decomposability of the substrate, set to 0.49 for FYM (Yang 1996). $Y_0$ and $Y_t$ are quantities of substrate at times zero and $t$, respectively (mg kg$^{-1}$). For the roses and daisy, “manure” consisted of slurry, a mixture of feces and urine, nitrogen-rich materials such as bean residues, and food processing wastes. Organic C content (%), total N content (%), and mineral N content (mg $L^{-1}$) of this material were 6.25, 1.39, and 346, i.e., higher than the 2.96, 0.53, and 147, respectively for FYM. As no data were available for decomposition of this material, relative mineralization rate and rate of aging have been set to 0.4 and 0.2, respectively.

Mineral nitrogen may be lost from the upper soil layer through volatilization, as part of the ammonium produced during hydrolysis is transformed into gaseous form. In the denitrification process, $NO_3$ is converted to NO, $N_2O$, and $N_2$, which may partly be lost to the atmosphere. The rates of these processes depend on the concentrations of $NH_4$ and $NO_3$ in the soil, aeration, and soil pH, and mostly follow first-order dynamics (Chowdary et al. 2004). Reported values of rate constants vary from $1.54\times10^{-4}$ (Chin and Kroontie 1963) to 0.3 $day^{-1}$ (Jemison et al. 1994) for volatilization and from 0.0027 (Rolston and Marino 1976) to 0.2 (Jansson and Anderson 1988) for denitrification. In this study, gaseous nitrogen loss to the atmosphere, accounting for both volatilization and denitrification, was assumed to depend on Nmin in the first layer (0.2 m), following first-order dynamics. Hence, the rate of the gaseous nitrogen loss in these processes ($N_{gas}$ in kilogram N per hectare per day) is:

$$N_{gas} = k_{gas} \times N_{min} \times e^{-k_{gas} \times t} \qquad (18)$$

where $k_{gas}$ is a combined rate constant for both volatilization and denitrification, with an assumed value of 0.01 per day; $t$ is time.

### 2.4.3 Model Calibration and Simulation

In the water balance model, the strongest determining factor is $k$ (Radcliffe and Rasmussen 2000) that determines inflow and outflow of water for each soil layer, while soil porosity determines soil water holding capacity. Because of the strong textural gradient in the soil profile, $k$ decreases with increasing soil depth (Table 3), especially below 40 cm, which restricts water flow and thus N leaching from the root zone.

Through trial and error, best-performing values, in terms of soil N dynamics, for *ks* were established. This yielded multiplication factors for *ks* for each layer (Table 4).

For the rice system, downward flow of water and hence transport of N strongly depends on the puddling effect, defined by Chen and Liu (2002) and Wopereis et al. (1992) as the presence of an "impermeable" layer with a thickness of about 7.5 cm and a saturated hydraulic conductivity ranging from 0.027 to 0.083 cm $day^{-1}$, i.e., 20 to 30 times lower than that of the subsoil. In the study area, such an impermeable layer is present in most of the rice soils at a depth between 15 and 22 cm; therefore, the calibrated *ks* was very low for the first layer and higher for the deeper layers (Table 4).

## 3 Results

### 3.1 Measured Nitrogen Dynamics

### 3.1.1 $NO_3$-N Dynamics

Figure 2 shows appreciable differences in $NO_3$-N dynamics between 2004 and 2005, as a result of differences in rainfall, i.e., 1,172 mm in 2004 and 1,560 mm in 2005. Patterns are more similar from July onwards, i.e., the rainy season, during which most nitrogen leached in 2004, while it started earlier in 2005.

Rose is a perennial flower crop that is cut weekly from late October until April and has a life span from 5 to 7 years. It was heavily fertilized before the production period with nitrogen-rich mixed manure. The sludge was applied every 10 days, combined with "bucket irrigation" of urea fertilizer solution. During the summer season, growth was minimal because the crop was damaged by very high radiation and rainfall, but the N content in the surface layer remained high because of the residual manure. Hence, N leaching continued throughout the year. $NO_3$-N was very high on the soil surface during January–June and lower in deeper soil layers while there was large change in $NO_3$-N during July–September, especially in 2004, because rose grows very poor during this time with little nutrient uptake while rainfall was very high in this time, excessive for downward water movement.

The production period for daisy largely overlaps with that for rose, but the daisy is an annual crop, planted in September and uprooted at the end of May, with the soil being fallow in the intercrop period. Fertilizer regime was similar to that for roses, in both

**Table 3** Saturated hydraulic conductivity (*ks*), porosity, and field capacity (FC) of the soil in the experiment

| Soil layer (cm) | Soil texture class | *ks* (cm day$^{-1}$) | Porosity (%) | FC (cm$^3$cm$^{-3}$) |
|---|---|---|---|---|
| 0–20 | Loamy sand | 146.4 | 43.7 | 33.3 |
| 20–40 | Loamy sand | 62.10 | 45.3 | 33.3 |
| 40–60 | Sandy clay loam | 10.32 | 39.8 | 60.6 |
| 60–80 | Sandy clay loam | 10.32 | 39.8 | 60.6 |
| 80–100 | Sandy clay | 2.88 | 43.0 | 65.0 |

quantity and timing. Therefore, $NO_3$-N trend is also similar to $NO_3$-N trend of rose that is very high on soil surface during January–June and very high in the deeper soil layers during July–September with large of $NO_3$-N during this time.

Cabbage is an intensive crop, with six harvests per year, where seedlings are produced in a corner of the field. A high dose of manure was applied as a basal dressing, followed by weekly applications of high doses of urea fertilizer by bucket irrigation until 25 days after planting. Soil $NO_3$-N was high in the rainy season because of continuous high fertilizer application and lower in dry season, when crop uptake is high. However, $NO_3$-N in the deeper soil layers of cabbage field was high not only during rainy season but also lately to winter time because, after rainy season, cabbage started its main production crop with intensive fertilization. Either high late rainfall or high irrigation causes high downward water movement in this time.

Chili is sown in August and transplanted in early September. A high dose of manure was applied at 40 days after planting, followed by biweekly fertigation of urea fertilizer. Manure was applied again after the onset of flowering by dissolving it into the standing water; this was repeated every 2 months from November to April, when yields are high. From May to July, very little or no fertilizer was applied, the crop growing on residual nutrients. In addition, chili was irrigated abundantly during the dry season, resulting in high $NO_3$-N contents deeper in the profile in the dry season, exceeding those in summer. It is easily to observe that $NO_3$-N in the deeper soil layers are high most of time because of either high rainfall in rainy season or excessive irrigation in dry season, showing continuous water movement and $NO_3$-N leaching through the soil profile.

In the rice rotation, fertilizer application was high for spring rice in March, for summer rice in June and July, and for winter maize in September and Novem-

**Table 4** Initial soil moisture content (SW; cm$^3$cm$^{-3}$) and initial soil mineral nitrogen content (mg kg$^{-1}$) for the simulation model for the various crops and calibration factors for *ks* (see text for explanation)

| Crop | Layer | | | | |
|---|---|---|---|---|---|
| | 1<br>Initial SW | 2 | 3 | 4 | 5 |
| For all crops | 0.18 | 0.16 | 0.18 | 0.18 | 0.19 |
| Initial N | | | | | |
| Rose | 131.6 | 60.6 | 53.6 | 57.5 | 63.6 |
| Daisy | 117.7 | 59.9 | 53.6 | 57.5 | 63.6 |
| Cabbage | 113.6 | 60.2 | 53.6 | 57.5 | 63.6 |
| Chili | 65.6 | 50.8 | 45.4 | 48.7 | 63.6 |
| Rice | 113.6 | 57.5 | 30.9 | 35.4 | 48.9 |
| *ks* | | | | | |
| Rose | 0.8 | 1.0 | 1.0 | 2.0 | 2.0 |
| Daisy | 0.5 | 1.0 | 1.0 | 1.0 | 1.0 |
| Cabbage | 0.5 | 4.0 | 0.2 | 2.0 | 2.0 |
| Chili | 0.5 | 3.0 | 1.5 | 2.0 | 2.5 |
| Rice (without puddling) | 0.5 | 1.0 | 1.0 | 2.0 | 1.5 |
| Rice (with puddling) | 0.005 | 0.4 | 1.0 | 5.0 | 1.0 |

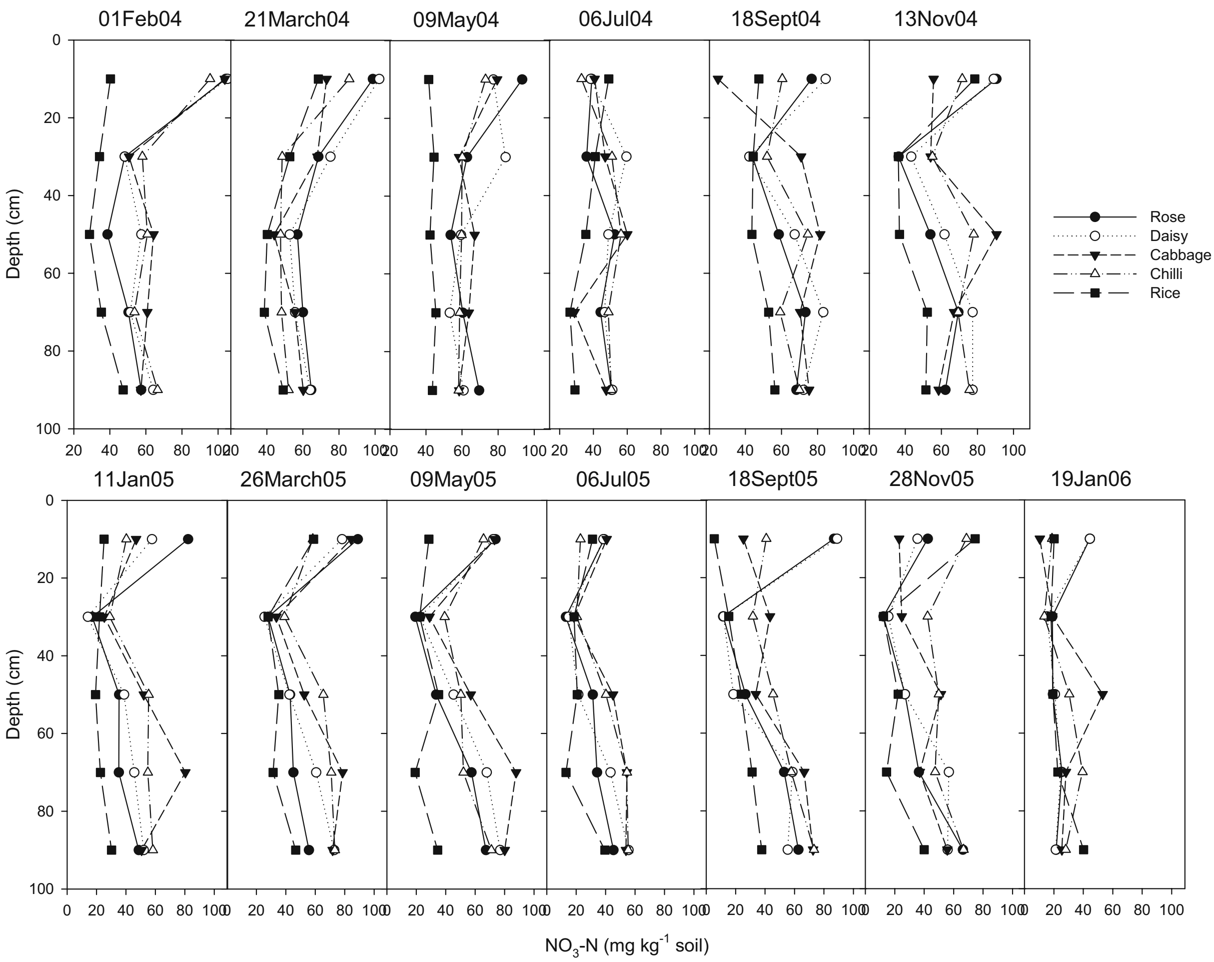



**Fig. 2** Nitrate-N concentration (mg N $kg^{-1}$ soil) at different soil depths in 2004 (*top*) and 2005 (*bottom*) for five rotations

ber. The $NO_3$-N concentrations in this rotation were lower than in the other crops. However, occasionally, the $NO_3$-N concentration was high (Fig. 2) due to high fertilizer application and low nitrogen uptake, i.e., in the tillering period of rice and after planting of maize (February and March for spring rice that is effected by cold weather; plant uptake may be zero due to bad plant root formation; July for summer rice that is also effected by low nutrient uptake and additive nutrient from manure, soil organic and plant residue decomposition; October for winter maize when after sowing with high basal fertilization and slow growing of young maize).

### *3.1.2 $NH_4$-N Dynamics*

Soil $NH_4$-N was much lower than $NO_3$-N. It was generally higher in the upper layers because most $NH_4$-N derives from fertilizer hydrolysis and is subsequently taken up by the crop. Under dry conditions, it is easily transformed to $NH_3$, which volatilizes. Under aerobic conditions, it is nitrified to $NO_3^-$ and easily leaches to deeper soil layers and the groundwater. When the concentration of $NH_4$-N is high and conditions are conducive to leaching, it may leach to deeper layers in a short time (Miller and Gardiner 2001). $NH_4$-N in soil under flowers was high during the rainy season, while in chili it was high in the dry season (Fig. 3). This was related to high rainfall and high rates of N mineralization from manure in the rainy season for the flowers and the combination of high irrigation and high fertilizer application in the dry season for the chili. Thus, the concentration of $NH_4$-N in the soil was much higher in the rainy season of 2005 than of 2004, associated with the much higher rainfall in 2005.

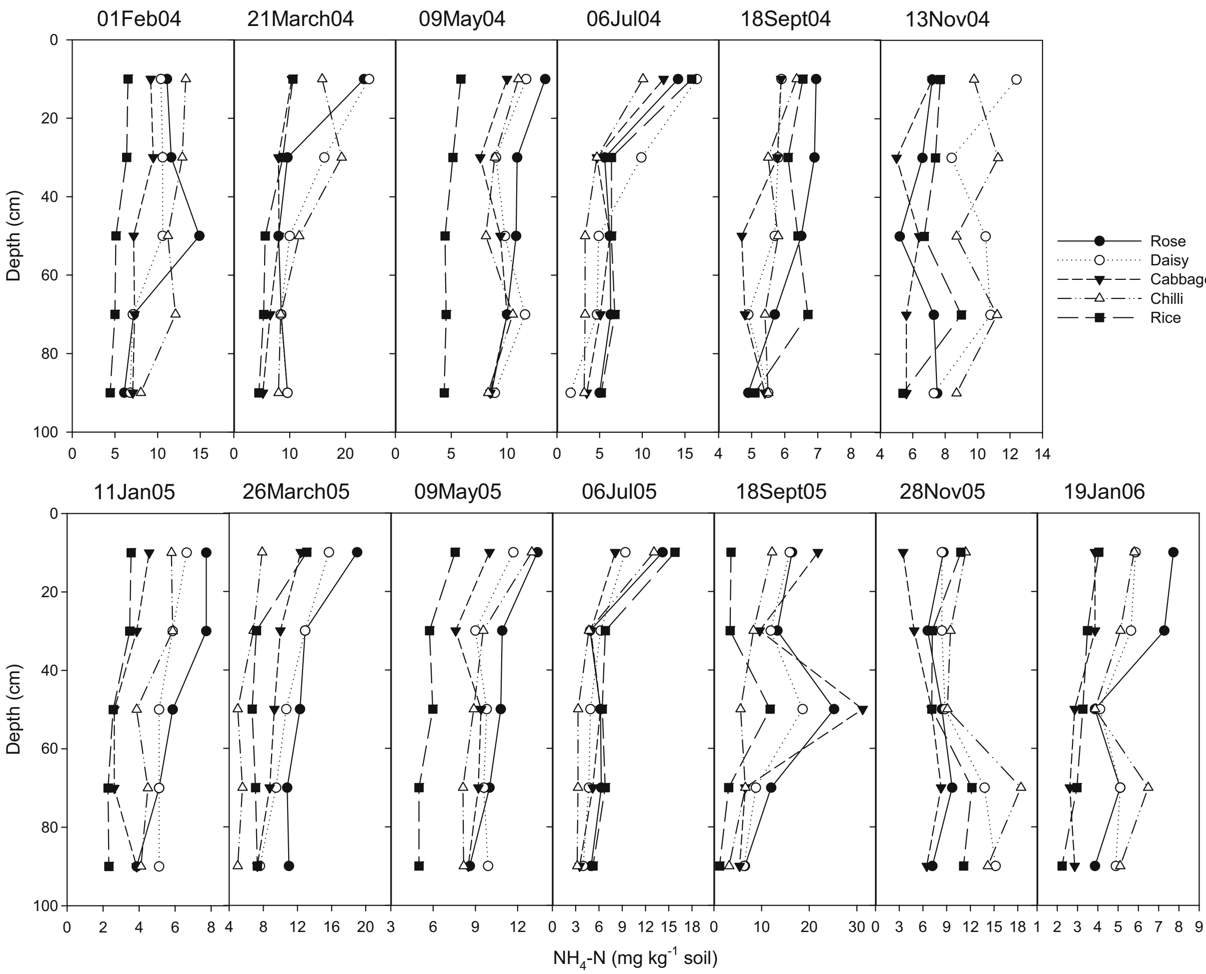



**Fig. 3** $NH_4$-N at different soil depths in 2004 (*top*) and in 2005 (*bottom*) for five crops (note: concentration scales are different)

### *3.1.3 Simulated Nitrogen Dynamics*

Water and mineral nitrogen (Nmin) balances were simulated for five crops with a daily time step during 2 years. Daily weather data from Vinh Yen station (2 km from the study area), crop calendars (Table 2), and soil properties (Table 3) were used.

### *3.1.4 Nitrogen Dynamics in Flowers*

Simulated patterns of Nmin in the roses agreed well with the measured values for time course, in terms of both amounts and trends (Fig. 4). In the summer, simulated Nmin in the surface layer was slightly underestimated relative to measured values, but for the other layers the simulated and measured values were comparable. For the deeper layers, Nmin dynamics and magnitude were accurately simulated, although the variation was smaller than in the measured values which showed a strong spatial variation (data not shown).

The pattern of Nmin in the daisies (Fig. 5) was very similar to that of the roses because the production period and irrigation and fertilizer regimes were similar. However, as in summer, the daisy land was fallowed and not fertilized; simulated Nmin in the surface layer was very low in this period. A substantial proportion of the manure was observed on the soil surface during this time and it continued to decompose and thus supply N to the soil.

### *3.1.5 Nitrogen Dynamics in Vegetables*

The two vegetable species planted in the area each require specific management. Cabbage is a shallow-

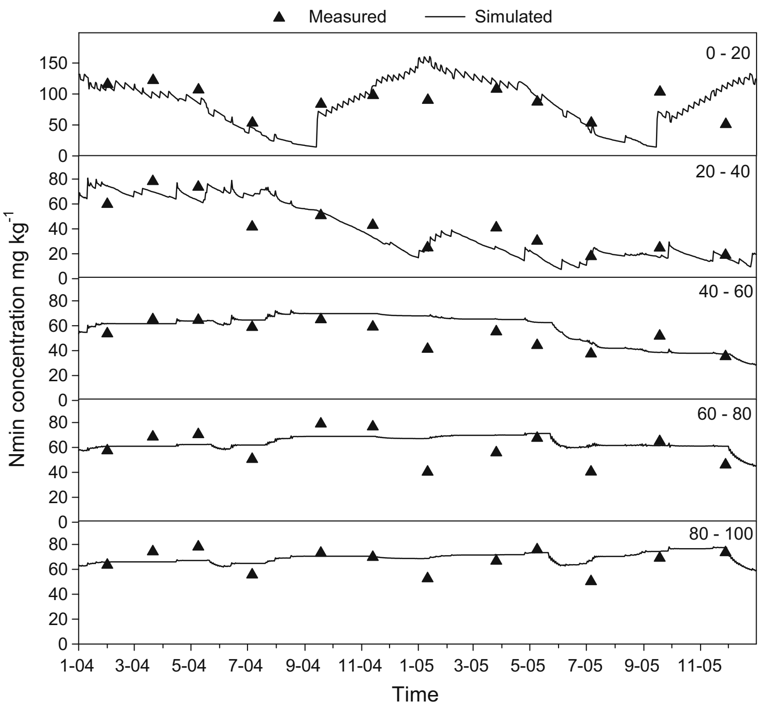



**Fig. 4** Measured and simulated mineral nitrogen concentration (mg $kg^{-1}$) at different depths for roses

rooting crop that requires frequent irrigation, especially with hand sprinkler and bucket irrigation, while chili is deeper rooting and thrives on high beds but requires high water and organic matter contents. Manure was therefore applied to cabbage as a basal dressing on the soil surface under aerobic conditions, while for chili it was surface-applied in the course of the growing period, dissolving in the standing water.

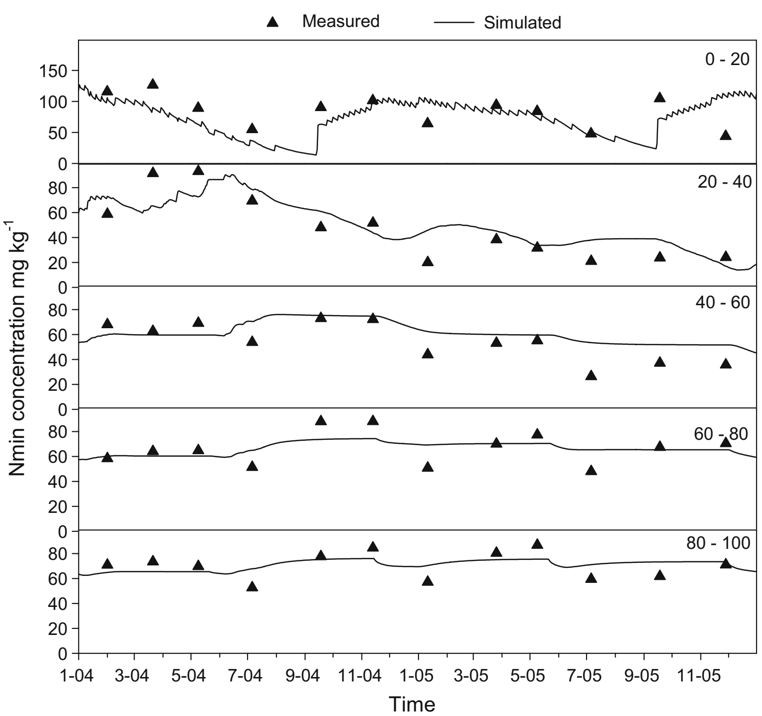



**Fig. 5** Measured and simulated mineral nitrogen concentration (mg $kg^{-1}$) at different depths for daisies

The main form of N fertilizer applied to cabbage was urea which contributed more Nmin to the surface layer than manure. Simulated Nmin in this layer closely followed measured values (Fig. 6), i.e., it was high in the early growth stages, when crop demand was low, declined in late summer as a result of high rainfall and lower fertilizer application in this period and was very low in winter with intensive cabbage cultivation with high fertilizer doses. Hence, N leaching was inversely related to N application, i.e., higher in summer than in winter, associated with the higher percolation in summer under high rainfall, whereas, in winter, irrigation was rarely in excess of crop water requirement; hence, water movement through the profile was limited.

Manure was applied at high doses in chili. In these soils, Nmin was slightly underestimated in the first layer for some time in the dry season (Fig. 7), which is usually a time of very high crop uptake. In the deeper layers, simulated Nmin agreed well with the measured values. The water balance submodel showed (results not shown) that water movement through the soil profile was higher in the rainy season than in the dry season, but Nmin in the deeper soil layers was lower in the rainy season, for two reasons. Firstly, smaller amount of fertilizer is applied during the rainy season when the potential for leaching is high, so that Nmin is diluted. Secondly, irrigation in the dry season was in excess of crop water requirements, and high fertilizer doses were applied early in the dry season, which continued until the end of this season. As a result, large quantities of Nmin were transported from the surface layers to the deeper soil layers.

### 3.1.6 Nitrogen Dynamics in Rice

Rice received mostly mineral fertilizer (urea) that is rapidly hydrolyzed, leading to high available N levels. Simulated Nmin in the surface layer agreed well with measured values (Fig. 8). Without puddling, Nmin in the second layer was strongly underestimated but overestimated in the deeper layers (Fig. 8, left). Inclusion of puddling reduced the *k* value in the first layer and increased it in deeper layers, thereby resulting in substantially improvement in model performance (Fig. 8, right). In these layers, simulated Nmin is fairly constant, associated with steady downward water movement.

**Fig. 6** Measured and simulated mineral nitrogen concentration (mg kg$^{-1}$) at different depths for cabbage

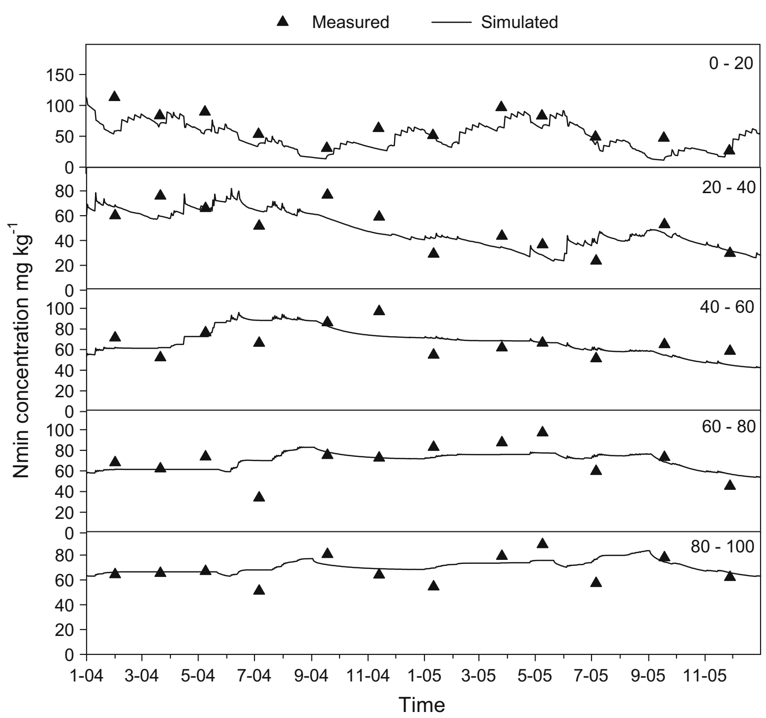
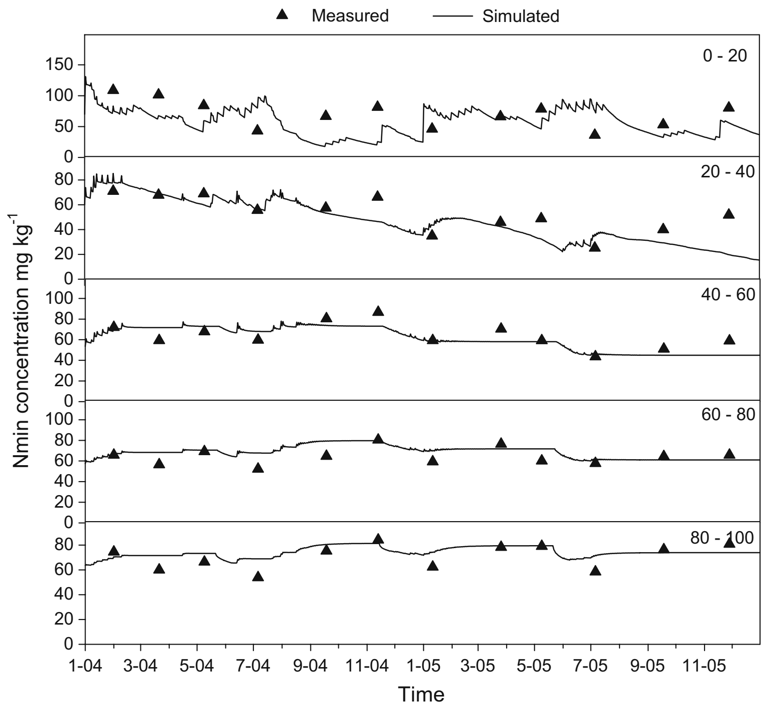


**Fig. 7** Measured and simulated mineral nitrogen concentration (mg kg$^{-1}$) at different depths for chili




### 3.1.7 Nitrogen Leaching Losses

Nitrogen leaching losses were calculated by multiplying simulated daily outflow from the bottom of the soil column (mm) and the simulated Nmin concentration (mg L$^{-1}$) in the bottom layer. Annual nitrogen leaching losses were accumulated from the daily losses (Table 5).

Three classes can be distinguished in terms of annual percolation (Table 5): high values in rose and daisy

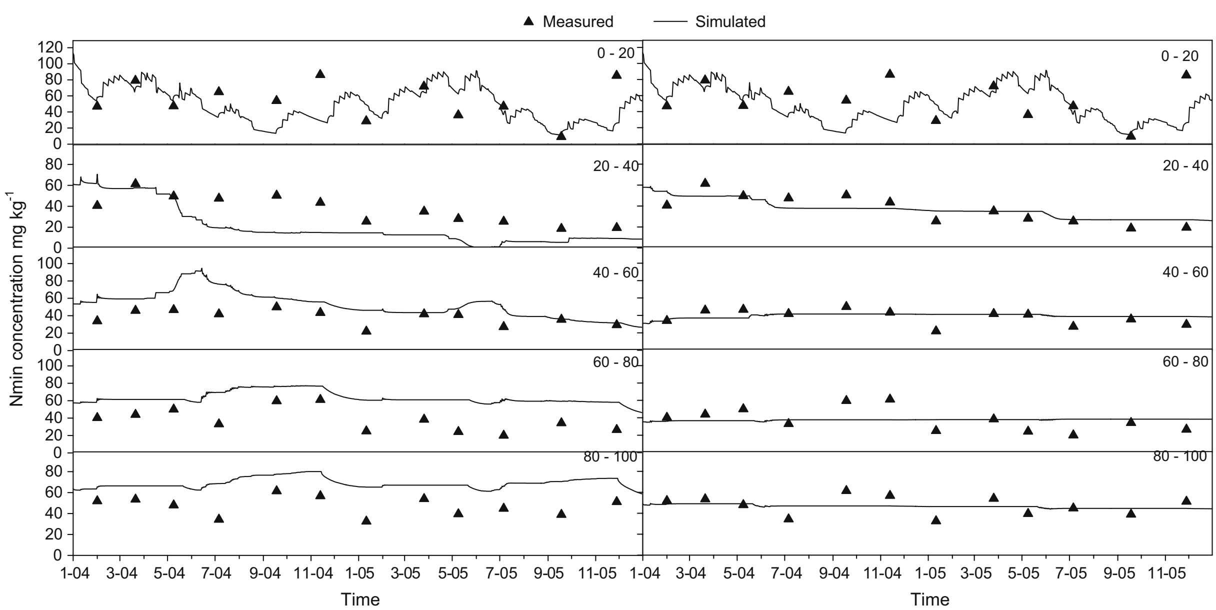



**Fig. 8** Measured and simulated mineral nitrogen concentrations (mg kg$^{-1}$) at different depths for rice without (*left*) and with puddling effect (*right*)

**Table 5** Annual percolation (mm), maximum percolation rate (max. per. rate; mm day$^{-1}$), nitrogen leaching losses (leached N; kg ha$^{-1}$ year$^{-1}$), maximum nitrogen leaching rate (Max. L. rate; kg ha$^{-1}$ day$^{-1}$), and nitrogen gaseous losses (leached N; kg ha$^{-1}$year$^{-1}$) for rose, daisy, cabbage, chili, and rice without (NP) and with puddling effect (P), in 2004 and 2005

| Leaching types | Year | Crop | | | | | |
|---|---|---|---|---|---|---|---|
| | | Rose | Daisy | Cabbage | Chili | Rice | |
| | | | | | | NP | P |
| Percolation | 2004 | 123.1 | 177.5 | 118.4 | 109.5 | 230.7 | 47.6 |
| | 2005 | 247.6 | 203.5 | 125.9 | 131.4 | 255.3 | 73.0 |
| Max. per. rate | 2004 | 5.5 | 3.2 | 3.5 | 4.3 | 6.0 | 1.7 |
| | 2005 | 11.8 | 3.3 | 15.0 | 0.4 | 6.1 | 6.9 |
| Leached N | 2004 | 101.2 | 160.4 | 106.8 | 100.6 | 207.4 | 31.0 |
| | 2005 | 284.7 | 185.8 | 122.8 | 122.9 | 214.2 | 48.8 |
| Max. L. rate | 2004 | 4.8 | 3.2 | 2.9 | 3.6 | 3.8 | 1.1 |
| | 2005 | 11.5 | 3.3 | 14.7 | 0.4 | 3.6 | 4.8 |
| Ngas loss | 2004 | 165.1 | 163.7 | 220.5 | 126.1 | 43.2 | 42.3 |
| | 2005 | 243.6 | 239.8 | 285.2 | 107.4 | 25.6 | 24.8 |

(185–190 mm year$^{-1}$), medium values in cabbage and chili (120–122 mm year$^{-1}$), and low values in rice (60 mm year$^{-1}$). Rice without puddling (NP, given for illustrative purposes only) has a very high value (243 mm year$^{-1}$). Total annual percolation and maximum rate of percolation are not strongly correlated because the length of the growing period is a confounding factor.

Also, annual percolation and annual N leaching losses are correlated (Table 5), with high leaching losses in rose and daisy (173–193 kg ha$^{-1}$year$^{-1}$), medium values in vegetables (112–115 kg ha$^{-1}$ year$^{-1}$), and low in rice (40 kg ha$^{-1}$year$^{-1}$). As parts of N loss, N loss via volatilization and denitrification was very high in cabbage (220.5–285.2 kg ha$^{-1}$ year$^{-1}$), high in rose (165.1–243.6 kg ha$^{-1}$year$^{-1}$) and daisy (163.7–239.8 kg ha$^{-1}$year$^{-1}$), medium in chili (107.4–126.1 kg ha$^{-1}$year$^{-1}$), and low in rice (24.8–43.2 kg ha$^{-1}$year$^{-1}$).

## 4 Discussion

### 4.1 Soil Mineral Nitrogen Dynamics

The highest concentrations of Nmin were observed in the second, fourth, and sixth sampling periods in the rice rotation, when high fertilizer doses were applied, while crop uptake was low. For flowers, daisy and rose have same production period, starting from autumn and productive in winter and spring season and very little grow in summer. Therefore, the course of Nmin dynamics similar with the highest peak of Nmin concentration appears in January–February (Fig. 4). It was high in flowers in most of the rainy season, when rainfall was high and N continued to be mineralized from manure and when crop uptake was very low. Soil Nmin concentrations were also very high for most of the time in cabbage with a new crop started every one and a half months with high fertilizer doses; they were also high in soils under chili with high rainfall during the rainy season. For chili, simulated Nmin showed a very well fit with a measured one. Nmin on the soil surface showed many peaks of Nmin concentration corresponding to each fertilizer application during crop season. For this crop, the driving forces are quite high most of the time due to either high rainfall in the summer or excessive irrigation with high fertilizer application in dry season. Ammonium N accumulated mainly in the surface layer. The highest $NH_4$-N concentrations were recorded in the rainy season, especially in 2005, associated with the very high rainfall and the consequently high percolation. In September, cabbage, rose, and daisy received fertilizers at the start of the production period. High rainfall in this period generated high rates of leaching, transporting excess $NH_4$-N to the deeper soil layers. Subsequently, rainfall rapidly declined, and only in chili did excess irrigation water continue to generate leaching of Nmin, transporting $NH_4$-N downwards.

### 4.2 Modeling Nitrogen Leaching Losses

The combined effects of environmental factors on soil and plant processes and the consequences for N transport through the soil profile are made explicit in the nitrogen transport model. The model accurately reproduced the observed dynamics of Nmin in the soil profile, and the calculated leaching losses can thus be considered with confidence. The model showed continuous downward movement of water under saturated conditions, similar to other models (Chen et al. 2002; Chowdary et al. 2004), while the flow rate decreased with a decrease in soil moisture content and the associated reduction in hydraulic conductivity (Mantovi et al. 2006; Yu et al. 2006). However, the model is somewhat incomplete because capillary rise from the groundwater table and lateral flow are not included because capillary rise may bring Nmin from deeper layer up and lateral flow may bring Nmin from adjoining higher cells/fields into standing cell/field or from standing cell/field into the adjoining lower cells/fields. Moreover, inclusion of a dynamic crop growth model may have improved performance of the transpiration and evapotranspiration calculations in the water balance submodel. The transport model, based on the perfect mixing principle, worked well for calculating N flows between soil layers. Simulated results for percolation and N leaching with the puddling effect are in agreement with reported data (Wopereis et al. 1992, 1994; Chen et al. 2002; Chen and Liu 2002) and illustrate the advantage of an impermeable or hardpan layer in increasing water and nutrient use efficiencies. Interpretation of the dynamic of N loss through volatilization and denitrification with calendars of fertilizer application showed that the gaseous N loss was high for high fertilization crops, high number of fertilizer application. The N loss accounted from 32% to 35% of applied N in rose, 33% to 36% in daisy and 35% to 40% in cabbage while it was lower in chili (23–27%) and much lower in rice (7–12%). The result did not show clearly the differences of gaseous N loss in rice crop with and without puddling effects

## 5 Conclusions

This study focused on leaching of N from the root zone to provide a scientific basis for land use planning and an environmental protection campaign. The results indicate that appreciable leaching losses N occurred in high rainfall and irrigation conditions, especially when fertilizer application was not well synchronized with the crop N demand. The greatest losses of N were recorded in flowers (101.2 kg $ha^{-1}$ in 2004 and 284.7 kg $ha^{-1}$ in 2005 for rose; and 160.8 in 2004 and 185.8 in 2005 for daisy), followed by cabbage (106.8 kg $ha^{-1}$ in 2004 and 122.8 kg $ha^{-1}$ in 2005) and chili (100.6 in 2004 and 122.9 in 2005), whereas the lowest losses were in rice cropping systems. In most cases, the simple N transport model accurately predicted the seasonal dynamics of N as well as N flow between soil layers and the amounts of N lost from the soil profile. The simulated results of N leaching with "puddling" (31 kg $ha^{-1}$ in 2004 and 48.8 kg $ha^{-1}$ in 2005) soil conditions illustrate the advantage of an impermeable layer in increasing water and nutrient use efficiencies in these soils and cropping systems. The simulated results showed that N loss via volatilization and denitrification was very high in crops with high dose of mineral fertilizer and large number of fertilizer applications. These model results also showed that it possible to accurately estimate N losses with only a few parameters and helped us identify the risks of N leaching. Ultimately, this will allow us to explore for improvements in soil and crop management practices in these cropping systems

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## References

Addiscott, T. M. (1990). Measurement of nitrate leaching: a review of methods. In R. Calviet (Ed.), *Nitrates-Agriculture-Eau* (pp. 157–168). Paris-Grignon: INRA (Institut National de Recherches Agronomique).

Addiscott, T. M., & Whitmore, A. P. (1987). Computer simulation of changes in soil mineral nitrogen and crop nitrogen during autumn, winter and spring. *Journal of Agricultural Science, 109*, 141–157.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56*. Rome: FAO.

Averjanov, S. F. (1950). About permeability of subsurface soils in case of incomplete saturation. In: Engineering collection, vol. 7 (1950), quoted by P. Ya. Palubarinova, 1962. The theory of groundwater movement (English translation by I. M. Roger DeWiest) (pp. 10–21). Princeton: Princeton University Press.

Babiker, I. S., Mohamed, M. A. A., Terao, H., Kato, K., & Ohta, K. (2004). Assessment of groundwater contamination by nitrate leaching from intensive vegetable cultivation using geographical information system. *Environment International, 29*, 1009–1017.

Boogaard, H. L., Van Diepen, C. A., & Roetter, R. P. (1998). *WOFOST 7.1: User's guide for the WOFOST 7.1 crop growth simulation model and WOFOST Control Center*. Wageningen: DLO Winand Staring Centre.

Bremner, J. M. (1996). Nitrogen-total. In D. L. Sparks, A. L. Page, C. T. Johnston & M. E. Summer (Eds.), *Methods of soil analysis. Part 3. Chemical methods. SSSA Book Series No. 5* (pp. 1085–1121). Madison: SSSA.

Brutsaert, W. (1966). Probability laws for pore-size distributions. *Soil Science, 101*, 85–92.

Chen, S.-K., & Liu, C. W. (2002). Analysis of water movement in paddy rice fields (I) experimental studies. *Journal of Hydrology, 260*, 206–215.

Chen, S.-K., Liu, C. W., & Huang, H.-C. (2002). Analysis of water movement in paddy rice fields (II) simulation studies. *Journal of Hydrology, 268*, 259–271.

Chi, H. T., & Bo, L. V. (2002). *Suitability map of Vanhoi commune*. Vietnam: Soil and Fertilizer Research Station Vinh Phuc Agricultural and Rural Development Department. (Vietnamese).

Chikowo, R., Mapfumo, P., Nyamugafata, P., & Giller, K. E. (2004). Mineral N dynamics, leaching and nitrous oxide losses under maize following two-year improved fallows on a sandy loam soil in Zimbabwe. *Plant Soil, 259*, 315–330.

Chin, W., & Kroontie, W. (1963). Urea hydrolysis and subsequent loss of ammonia. *Soil Science Society of America, 27*, 316–319.

Chowdary, V. M., Rao, N. H., & Sarma, P. B. S. (2004). A coupled soil water and nitrogen balance model for flooded rice fields in India. *Agriculture, Ecosystems & Environment, 103*, 425–441.

Di, H. J., & Cameron, K. C. (2002). Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. *Nutrient Cycling in Agroecosystems, 64*, 237–256.

Dobermann, A., Witt, C., Dawe, D., Abdulrachman, S., Gines, H. C., Nagarajan, R., et al. (2002). Site-specific nutrient management for intensive rice cropping systems in Asia. *Field Crops Research, 74*, 37–66.

Ersahin, S., & Rustu Karaman, M. (2001). Estimating potential nitrate leaching in nitrogen fertilized and irrigated tomato using the computer model NLEAP. *Agricultural Water Management, 51*, 1–12.

Fang, B., Wang, G. H., Van den Berg, M., & Roetter, R. (2005). Identification of technology options for reducing nitrogen pollution in cropping systems of Pujiang. *Journal of Zhejiang University Science, 6b*, 981–990.

FAO (1976). *A framework for land evaluation*. Rome: FAO.

FAO/UNESCO (1974). *Soil map of the world, 1:5,000,000*. Paris: UNESCO.

Hasegawa, S., & Kasubuchi, T. (1993). Water regimes in fields with vegetation. In T. Miyazaki, S. Hasegawa & T. Kasubuchi (Eds.), *Water flow in soils* (pp. 223–250). New York: Marcel Dekker.

Hauggaard-Nielsen, H., Ambus, P., & Jensen, E. S. (2003). The comparison of nitrogen use and leaching in sole cropped versus intercropped pea and barley. *Nutrient Cycling in Agroecosystems, 65*, 289–300.

Helwig, T. G., Madramootoo, C. A., & Dodds, G. T. (2002). Modelling nitrate losses in drainage water using DRAINMOD 5.0. *Agricultural Water Management, 56*, 153–168.

IRMLA (2005). Country report from Tamduong project, Vietnam. http://www.alterra-research.nl/pls/portal30/docs/folder/irmla/irmla/p_frames_page.htm. Accessed November 2006.

Janssen, B. H. (1998). Efficient use of nutrients: an art of balancing. *Field Crops Research, 56*, 197–201.

Jansson, J. M., & Anderson, T. (1988). Simulation of runoff and nitrate leaching from an agricultural district in Sweden. *Journal of Hydrology, 99*, 33–47.

Jemison, J. M., Jabro, J. D., & Fox, R. H. (1994). Evaluation of LEACHIM. II. Simulation of nitrate leaching from nitrogen-fertilized and manured corn. *Agronomy Journal, 86*, 852–859.

Lal, R., & Shukla, M. K. (2004). *Principles of soil physics*. New York: Marcel Dekker.

Lawes Agricultural Trust (2003). *GenStat® release 7.1 reference manual*. Oxford: VSN International.

Liu, X., Ju, X., Zhang, F., Pan, J., & Christie, P. (2003). Nitrogen dynamics and budgets in a winter wheat-maize cropping system in the North China Plain. *Field Crops Research, 83*, 111–124.

Mantovi, P., Fumagalli, L., Beretta, G. P., & Guermandi, M. (2006). Nitrate leaching through the unsaturated zone following pig slurry applications. *Journal of Hydrology, 316*, 195–212.

Miller, R. W., & Gardiner, D. T. (2001). *Soils in our environment* (9th ed.). Upper Saddle River: Prentice Hall.

Molz, F. J. (1981). Simulation of plant-water uptake. In I. K. Iskandar (Ed.), *Modeling wastewater renovation: Land application* (pp. 69–91). New York: Wiley.

Molz, F. J., & Remson, I. (1970). Extraction term models of soil moisture use by transpiring plants. *Water Research, 6*, 1346–1356.

Neeteson, J. J. (1995). Nitrogen management for intensively grown arable crops and field vegetables. In P. E. Bacon (Ed.), *Nitrogen fertilization in the environment* (pp. 295–325). New York: Marcel Dekker.

Radcliffe, D. E., & Rasmussen, T. C. (2000). Soil water movement. In M. E. Summner (Ed.), *Handbook of soil science*. Boca Raton: CRC.

Radcliffe, D. E., Gupte, S. M., & Box, J. J. E. (1998). Solute transport at the pedon and polypedon scales. *Nutrient Cycling in Agroecosystems, 50*, 77–84.

Rolston, D. E., & Marino, M. A. (1976). Simulation transport of nitrate and gaseous denitrification products in soil. *Soil Science Society of America Journal, 46*, 860–865.

Tripathi, B. P., Ladha, J. K., Timsina, J., & Pascua, S. R. (1997). Nitrogen dynamics and balance in intensified rain fed lowland rice-based cropping systems. *Soil Science Society of America Journal, 61*, 812–821.

Van Keulen, H., & Seligman, N. G. (1987). *Simulation of water use, nitrogen nutrition and growth of a spring wheat crop. Simulation monographs*. Wageningen: Pudoc.

Van Wijk, S., Milwain, G., Zhang, X., Van den Bosch, R., Quang, V. Q., Thao, V. T., et al. (2006). *Opportunities and threats for safe vegetable markets in China, Vietnam and Thailand. MAPET Report 2, Alterra-report 1285-2*. Wageningen: Alterra.

Verloop, J., Boumans, L. J. M., Van Keulen, H., Oenema, J., Hilhorst, G. J., Aarts, H. F. M., et al. (2006). Reducing nitrate leaching to groundwater in an intensive dairy farming system. *Nutrient Cycling in Agroecosystems, 74*, 59–74.

Wopereis, M. C. S., Wösten, J. H. M., Bouma, J., & Woodhead, T. (1992). Hydraulic resistance in puddled rice soils: measurement and effects on water movement. *Soil & Tillage Research, 24*, 199–209.

Wopereis, M. C. S., Bouman, B. A. M., Kropff, M. J., Ten Berge, H. F. M., & Maligaya, A. R. (1994). Water use efficiency of flooded rice fields I. Validation of the soil-water balance model SAWAH. *Agricultural Water Management, 26*, 277–289.

Yang, H. S. (1996). Modelling organic matter mineralization and exploring options for organic matter management in arable farming in northern China. Ph.D. Thesis, Wageningen Agricultural University, Wageningen, the Netherlands.

Yu, H. M., Li, Z. Z., Gong, Y. S., Mack, U., Feger, K. H., & Stahr, K. (2006). Water drainage and nitrate leaching under traditional and improved management of vegetable-cropping systems in the North China Plain. *Journal of Plant Nutrition and Soil Science, 169*, 47–51.

Zaradny, H. (1993). *Groundwater flow in saturated and unsaturated soil*. Rotterdam: Balkema.