Assessment of Root Zone Nitrogen Leaching as Affected by Irrigation and Nutrient Management Practices

K. Nakamura, T. Harter,* Y. Hirono, H. Horino, and T. Mitsuno

ABSTRACT

Multiple or split N fertilizer applications during a single cropping period is a recommended practice for controlling N (specifically NO_3–N) leaching into groundwater. Here, we demonstrate the benefit of split fertilizer applications in two typical upland soils of Japan (sand and Andosol) using a combination of a laboratory experiment and modeling. Soil water flow and N transport properties of the soils were measured using standard procedures. Transient N and water transport experiments were conducted in cylindrical soil columns under single (lumped) and split NH_4–N applications. The column experiments were successfully simulated using Richards' equation and an advection–dispersion model with equilibrium nonlinear sorption conditions and first-order transformation for N speciation. Using the model for the two soils, several irrigation and fertilizer management scenarios were then simulated based on 1992 through 2000 meteorological data to investigate the long-term effects of lumped and split fertilization schedules for a representative set of crop and irrigation conditions. In comparison with lumped applications, split fertilizer applications were found to consistently reduce the amount of N leaching, even though year-to-year differences of N leaching reductions between sand and Andosol were significant. For unstressed crops, the actual reduction in N leaching are shown to depend on the timing of precipitation and irrigation events, on soil type, and on plant N uptake behavior. However, across all scenarios, two split applications instead of a single, lumped application reduced the N leaching fraction by approximately one-third. In the sandy soil, a three-way split resulted in further leaching reductions compared with the two-way split. Six-way split applications did not result in further N leaching improvements in either sand or Andosol. After adjusting N application rates to account for reduced N use efficiency, N leaching rates for unstressed crops under lumped fertilization were found to be several times higher than under split applications.

GROUNDWATER NO_3 contamination is a common problem in field crops and dairy areas of Japanese uplands. Quantitative, technical information is needed to help farmers make management decisions that support profitable yields while avoiding environmental degradation. Various management practices have been proposed to control NO_3 leaching. These include, for example, crop rotation (Delgado et al., 2001), controlled-release fertilizer (Paramasivam et al., 2001), fine-tuned irrigation and N management based on soil testing programs (Power et al., 2001) or chlorophyll meter readings of the crop (Schepers et al., 1995), center-pivot fertigation (Spalding et al., 2001), groundwater table control (Drury et al., 1997), and reduced till or no-till practices (Power et al., 2001). Whatever management practices may be adopted, it is important to consider the simultaneous transport of water and N to evaluate the potential for NO_3 groundwater pollution.

Numerous models have been proposed for modeling the transport of N in soils. The conceptual N model by Tanji et al. (1977) is very simple with few input data and is based on the principles of mass balance and steady state. The extended conceptual model proposed by Tanji et al. (1979) is also simple and is applicable to transient conditions. The Nitrate Leaching and Economic Analysis Package (NLEAP) model combined with GIS is used to identify potential NO_3 hot spots in shallow alluvial aquifers under irrigated agricultural areas (Shaffer et al., 1995, 1996; Follett, 1995). The SOILN model simulates daily N and C fluxes in agricultural systems, including plant growth and N uptake (Jabro et al., 2001).

Nitrate leaching is considered to occur mainly during high precipitation or during irrigation; hence, transient dynamic models of water and N transport and N transformation are more adequate to evaluate the risk of NO_3 leaching into groundwater under various water and fertilizer management scenarios. The Water Heat and Nitrogen Simulation Model (WHNSIM), which simulates transient water, heat, and N movements, including N transformations, satisfactorily predicted NO_3 concentration in the soil solution and N uptake originating from experimental sites (Huwe and Totsche, 1995). Modeling of urea, NH_4, and NO_3 transport and transformations conducted by Ma et al. (1999) includes urea and NH_4 adsorption, urea diffusion and hydrolysis, diffusion of NH_4 and NO_3, nitrification, and denitrification in flooded soil. Antonopoulos and Wyseure (1998) evaluated the transient water movement, mass transport, and N transformations of restored and undisturbed soil. The HYDRUS code (Šimůnek et al., 1998, 1999) simulates water, heat, and solute movement in one- and two-dimensional variably saturated media. The solute transport equations incorporate the effects of zero-order production, first-order degradation, and first-order decay and production reactions that provide the required coupling between the solutes involved in the sequential first-order chain.

Several long-term studies have been conducted to evaluate the effects of proposed best management practices on NO_3–N leaching, aquifer water quality, and crop yields (e.g., Pang et al., 1997a, 1997b; Delgado et al., 2001; Jaynes et al., 2001; Paramasivam et al., 2001). Most existing models have been evaluated on an annual or a crop season basis (e.g., Jabro et al., 2001; Delgado et al., 2001). Long-term studies are effective for evaluating potential NO_3 leaching at the field or watershed scale

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Table 1. Chemical and physical properties of used soils.†

	pH (H_2O)	EC	TN	TC	C/N	NH_4–N	NO_2–N	NO_3–N	CEC	Specific gravity	Clay content	Silt content	Sand content
		μS cm^{-1}	mg N kg^{-1}	mg C kg^{-1}		mg N kg^{-1}			mol kg^{-1}	g cm^{-3}	%		
Sand	6.1	10.8	360	4 880	13.7	3.6	2.1×10^{-2}	10	0.026	2.64	2.0	0.3	97.7
Andosol	6.5	205	3750	54 000	14.4	7.6	9.4×10^{-2}	117	0.27	2.54	6.0	23.2	70.8

† EC, electric conductivity; TN, total N; TC, total C; C/N, ratio of TC to TN; CEC, cation exchange capacity.

under variable weather conditions. However, the various data measurement needs for calibration and validation of models are extensive as well as laborious. Research budgets often do not allow for implementation of frequent NO_3 flux measurements or residual soil NO_3. Therefore few studies have provided a rigorous assessment of the potential benefits of split fertilizer applications.

To overcome experimental limitations, we investigated the long-term effects of split application on N leaching through a combination of experiments and simulations. Split fertilizer applications are generally considered more laborious and costly to implement for farmers than a single ("lumped") application, particularly when using broadcast methods (as opposed to fertigation). Split applications have been recommended for controlling NO_3 leaching regardless of the irrigation method. In the past recommendations have been based on zero-order long-term N budget models. Here we evaluate the effect of split applications using a more realistic physical model that considers transient water and N movement in the root zone.

Lumped and split NH_4 application treatments were performed on soil columns, and batch tests were implemented to determine water flow and N transport properties. Results were compared with simulations performed using the HYDRUS software package (Šimůnek et al., 1998). The effects of split N fertilizer application on long-term N concentrations in leachate below the root zone were further evaluated using a transient long-term simulation of water and N transport in the root zone. Simulations were based on typical crop rotations and a 9-yr time series of weather data from the study region in Japan.

MATERIALS AND METHODS

Batch Tests

The soil sampling sites are located on farm land in Tottori Prefecture, Japan. Collected test soils were Andosol (sandy loam) covering the volcanic piedmont and Hojyo dune sand ("sand") from a location near the coast. Disturbed soil samples were taken from the 0- to 30-cm depth. Soils were air-dried for about 1 mo to minimize residual levels of NH_4 in the soil, then sieved through a 2-mm sieve. Basic soil characteristics are given in Table 1.

Ammonia nitrification rates and NH_3 sorption isotherms were determined from batch experiments. Aliquots of air-dried soil corresponding to 50 g of dry soil were placed into 225 mL of containers. $(NH_4)_2SO_4$ solution was titrated onto the soil to ensure homogeneous soil moisture distribution corresponding to 80% saturation. For the batch experiment, $(NH_4)_2SO_4$ treatments included 0, 50, 100, 200, and 500 mg N kg^{-1} dry soil (this unit is represented simply as mg N kg^{-1} below). Bulk density was 1.61 and 0.94 g cm^{-3} for sand and Andosol, respectively. All containers were wrapped in aluminum foil punctured with small air vents. After the NH_4 solution was added, containers were incubated in the dark at 20°C for 0, 1, 2, 5, 8, 12, 16, 20, 24, and 28 d. Separate containers were prepared for each N level and each incubation period length. At the end of each incubation period, concentrations of NH_4–N, NO_2–N, NO_3–N, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} in the soil solution were measured by ion chromatography after extraction with distilled water (e.g., Tabatabai and Basta, 1991) (CDD-6A, Shimadzu Corp., Kyoto, Japan). Total NH_4–N in soil was determined by using absorption photometry after extraction with 100 g L^{-1} of KCl solution (Keeney and Nelson, 1982) (UV-1200, Shimadzu Corp.). All treatments were duplicated, and average concentrations are reported here. The total number of treatments (containers) was 200 (2 soils × 5 concentrations × 10 time periods × 2 replicates).

Infiltration Experiments

Column experiments were performed to investigate transient water and N transport during and after fertigation and to compare differences in NO_3 and NH_4 profiles due to lumped and split applications in the sand and Andosol. Soil columns with an inside diameter of 0.05 m and a length of 0.3 m were used (Fig. 1). The bulk density after air-dry packing was 1.37 and 0.80 g cm^{-3} for sand and Andosol, respectively. Soil col-

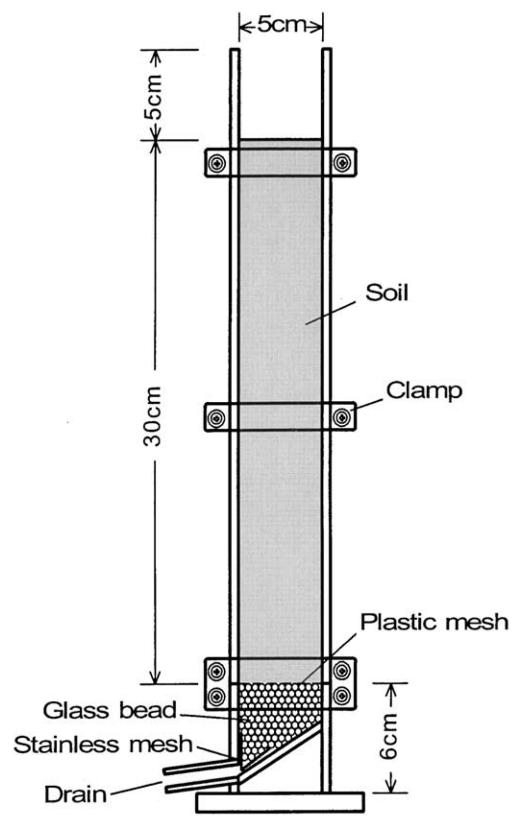

Fig. 1. Schematic diagram of the soil column.

umns were saturated with distilled water and successively drained (by gravitation) for 30 d. Irrigation with a top-dressing of $(NH_4)_2SO_4$ solution (fertigation) occurred in 5-d intervals. At each irrigation date, the fixed concentration solution was applied with a dropper (for uniform distribution) at constant concentrations. The amount of applied solution at the first fertigation equaled the amount of water lost by infiltration and evaporation during the prior 29-d draining period (i.e., the difference between column moisture immediately before fertigation and column field capacity). In subsequent fertigations and irrigations, the amount of applied solution was equal to the amount of water lost by seepage and evaporation from the soil columns during the respective preceding drainage period. Experiments were conducted for two fertigation regimes. The first experiment consisted of a lumped application of fertilizer with $(NH_4)_2SO_4$ solution at 200 mg N kg^{-1} applied in the first irrigation. Distilled water was applied in subsequent irrigations after 5 and 10 d (Exp. 1). The second experiment was a split application with $(NH_4)_2SO_4$ solution containing 66.7 mg N kg^{-1}, applied in each of the three irrigations (Exp. 2). Profile measurements were made immediately before each of the three irrigations and on the 15th day after the start of the experiments using replicate columns. For the profile measurement, soil columns were divided into six 5-cm-long sections. The soil water quality analysis for each section was conducted as described above for the batch experiments. The side faces of all soil columns were covered by aluminum foil to block the light, and all experiments were conducted in a temperature-controlled room at approximately 20°C. A total of 16 soil columns were prepared (2 soils × 2 fertigation regimes × 4 profile measurements).

Model Description

A numerical water flow and N fate and transport model was applied

- to investigate whether the fate and transport of N in the column experiments can be accurately predicted by standard formulations of soil water flow (Richards' equation) and N fate and transport (i.e., advection–dispersion equation with first-order reaction terms, as discussed below), where input parameters were determined either by inverse modeling (dispersivity) or direct measurement in batch experiments (hydraulic properties, NH_3 sorption isotherm, nitrification rates).
- to perform a leaching risk analysis for further clarification of the advantages and limitations of split fertilizer applications.

The numerical simulation model used was Version 2.0 of HYDRUS-1D, a software package for simulating water, heat, and solute movement in one-dimensional variably saturated media on the basis of finite element representation of the governing equations (Šimůnek et al., 1998).

Vertical water movement in isotropic soil is computed by solving Richards' equation subject to the appropriate initial and boundary conditions:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial h}{\partial z} + K(\theta)\right] - S \qquad [1]$$

where θ is the volumetric water content (cm cm^{-3}), h is the pressure head (cm H_2O), K is the unsaturated hydraulic conductivity (cm h^{-1}), z is the vertical coordinate (cm), and S is the root water uptake term (cm^3 cm^{-3} h^{-1}). Root water uptake term was considered only when leaching risk simulations were conducted.

The relationship between h and θ is represented by the following equation (van Genuchten, 1980):

$$\theta = \frac{\theta_s - \theta_r}{[1 + (-\alpha h)^n]^m} + \theta_r \qquad [2]$$

where θ_s is the saturated volumetric water content; θ_r is the residual volumetric water content; α, n, and m are parameters; and $m = 1 - 1/n$. Drying soil water retention data of the two soils obtained by the suction method, pressure plate method, and vapor equilibrium method (Klute, 1986) are shown by symbols in Fig. 4.

The unsaturated hydraulic conductivity is defined as (van Genuchten, 1980)

$$K = K_s\sqrt{S_e}\,[1 - (1 - S_e^{1/m})^m]^2 \qquad [3]$$

where K_s is the saturated hydraulic conductivity (cm h^{-1}) and S_e is the effective saturation. Saturated hydraulic conductivities of the two soils were measured by falling-head method (Klute and Dirksen, 1986).

Since mineralization, denitrification and volatilization rates in both soils were negligibly small (see below), the partial differential equations governing the NH_4–N and NO_3–N transport and transformation in a variably saturated porous media are

$$\frac{\partial\theta c_1}{\partial t} + \frac{\partial\rho s_1}{\partial t} = \frac{\partial}{\partial z}\left(\theta D_1\frac{\partial c_1}{\partial z}\right) - \frac{\partial q c_1}{\partial z} - k_{nit}\theta c_1 - k_{nit}\rho s_1 - Sc_1 \qquad [4]$$

$$\frac{\partial\theta c_2}{\partial t} = \frac{\partial}{\partial z}\left(\theta D_2\frac{\partial c_2}{\partial z}\right) - \frac{\partial q c_2}{\partial z} + k_{nit}\theta c_1 + k_{nit}\rho s_1 - Sc_2 \qquad [5]$$

where c_1 and c_2 are the soluble NH_4–N concentration and the soluble NO_3–N concentration (mg N cm^{-3}), respectively; s_1 is the adsorbed NH_4–N concentration (mg N g^{-1}); ρ is the bulk density (g cm^{-3}); and D_1 and D_2 are the dispersion coefficients (cm^2 h^{-1}) for soluble NH_4–N and NO_3–N, respectively. The first-order nitrification rate constant, k_{nit}, was estimated from the batch tests. Both soluble and adsorbed NH_4–N were assumed to be converted to NO_3–N by nitrification, as described below. Soil water content and temperature during the infiltration experiments were comparable to those during the batch tests. Adsorption isotherms for NH_4–N in sand and Andosol (Fig. 2) were fitted to the Freundlich adsorption equation.

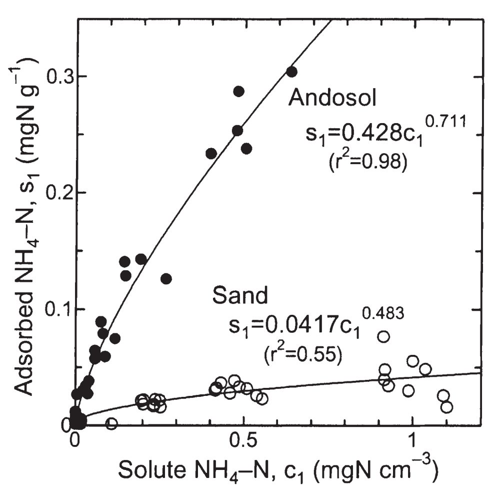

Fig. 2. Ammonium adsorption isotherms for sand and an Andosol. Symbols are measured data from the batch tests. Solid lines are obtained by fitting measured data using the Freundlich type equation. r^2 is the coefficient of determination.

Sorption of NO_3–N was considered to be negligible. The dispersion coefficient of soluble substance, D, is given by

$$\theta D = D_L|q| + \theta D_w \tau \quad [6]$$

where D_L is the longitudinal dispersivity (cm), $|q|$ is the absolute value of the Darcian fluid flux density (cm h^{-1}), D_w is the molecular diffusion coefficient in free water (cm^2 h^{-1}), and τ is a tortuosity factor in the liquid phase (Šimůnek et al., 1998). D_w was 0.064 and 0.069 cm^2 h^{-1} for NH_4–N and NO_3–N, respectively (Ma et al., 1999).

Initial and Boundary Conditions and Spatial Discrimination

For the simulation of the column experiments, initial conditions of volumetric water content, soluble NH_4–N, and NO_3–N were obtained by linear interpolation of measured profile values at the time just before the first fertigation. The soil surface boundary was represented by atmospheric boundary conditions with specified irrigation rates, evaporation rates, and NH_4–N concentration in the applied water. Constant evaporation rates, measured gravimetrically during the experiment, were assigned between irrigation dates. The bottom of the column was represented by a seepage boundary condition—if the lower part of the soil profiles was saturated then the last node was treated as a prescribed pressure head boundary with $h = 0$; if this node was unsaturated, then a prescribed flux boundary with $q = 0$ was specified at the lower boundary (Šimůnek et al., 1998). The vertical discretization of the finite element cells was set to 0.125 cm.

Inverse Solution

Except for the longitudinal dispersion, D_L, all parameters of the flow and transport model were determined independently of the column experiment. However, water retention data and saturated hydraulic conductivities obtained by standard methods in batch experiments needed to be confirmed because soil conditions differed somewhat between the experiments used to measure hydraulic properties and the column irrigation experiments. Therefore, the results of the column study were used to determine D_L but also to obtain an independent estimate of the parameters α, n, and K_s using model optimization (inverse solution).

The inverse solution for these parameters was a two-step process. In the first step, flow simulations were conducted to optimize α, n, and K_s for sand and Andosol. The calibration targets for the flow simulations were the amounts of leachate and the volumetric water content profile at different sampling times, as well as the measured water retention data and saturated hydraulic conductivities obtained by standard methods in batch experiments. In the second step, flow and solute transport simulations were conducted to optimize D_L. The calibration targets for determining D_L were soil solution concentrations of NO_3–N for sand and soil solution concentrations of NH_4–N for Andosol (no leachate data were available). It was assumed that D_L for NH_4–N and NO_3–N was identical. The reason for using NO_3–N data for sand was that NO_3–N in sand behaved as a conservative solute, and that nitrification was negligible, while the calibration against the NH_4–N profile in sand would have to consider measurement errors in the adsorption isotherm.

Leaching Risk Simulations

Simulations were conducted to investigate the long-term effects of split fertilizer application on seepage solute fluxes under actual weather and representative cropping conditions in the study region. While farmers on Japanese upland soils are increasingly growing greenhouse crops, our focus here is on the N-leaching risk under actual (field) precipitation conditions. Significant rainfall during the growing season is a key hydrological characteristic in Japan.

The simulation scenarios assumed that two crops, watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai var. *lanatus*] and tomato (*Lycopersicon esculentum* Mill.) are grown during each calendar year. Typical growing seasons for these crops were used, lasting from 1 March (60 d) through 29 June (180 d) for the first crop and from 30 June (181 d) through 28 October (301 d) for the second crop. Nitrogen fertilizer was assumed to be applied as NH_4–N. In all simulation scenarios, the first and second crop each received a total of 240 and 60 kg N ha^{-1}, respectively. Four fertilizer management scenarios, a single lumped application and three variations of split applications (2, 3, and 6 splits), were simulated (Table 2).

Weather data were obtained from the weather station nearest the soil sampling site at Yonago in the Tottori Prefecture, Japan. These included daily mean air temperature, daily mean relative humidity, day length, total solar radiation, daily mean wind speed, and daily total precipitation for the 9 yr from January 1992 to December 2000. Actual daily crop evapotranspiration during the 9 yr was calculated as the product of potential evapotranspiration and crop coefficient (Allen et al., 2001). Potential evapotranspiration was calculated using the Penman method (Snyder and Pruitt, 1989). Crop coefficients used were those provided by UCCE (1987). For the simulations, actual crop evapotranspiration, ET, was partitioned into an evaporation component (boundary condition at the soil surface) and a root water uptake component (transpiration). Crop transpiration rates, T, were derived from (Campbell, 1985)

$$T/\mathrm{ET} = 1 - \exp(-0.82\mathrm{LAI}) \quad [7]$$

where LAI is the leaf area index (defined as the total one-sided leaf area per unit ground area). Average annual precipitation and actual crop ET during 1992 through 2000 were 174.8 and 88.4 cm, respectively.

Crop uptake of NH_4–N and NO_3–N was assumed to be by passive transport since no quantitative crop uptake curves for the target crops were available. Under field conditions, NH_4–N and NO_3–N uptake characteristics are known to depend on soil water solution composition and the growth stage of the crop (Olson and Kurtz, 1982). However, under irrigated conditions with negligible water stress in the root zone, passive N uptake has been shown to be a reasonable approximation

Table 2. Applied NH_4–N amount (mg N ha^{-1}) for hypothetical simulations. S-1 to S-6 represent scenarios for sand, and A-1 to A-6 represent scenarios for Andosol. Dates are the number of days since 1 January.

		First crop						Second crop					
Scenario		60 d	78 d	96 d	114 d	132 d	150 d	181 d	201 d	221 d	241 d	261 d	281 d
S-1 and A-1	Lumped	240	0	0	0	0	0	60	0	0	0	0	0
S-2 and A-2	two-split	120	0	0	120	0	0	30	0	0	30	0	0
S-3 and A-3	three-split	80	0	80	0	80	0	20	0	20	0	20	0
S-6 and A-6	six-split	40	40	40	40	40	40	10	10	10	10	10	10

when simulating soil water and solute transport dynamics in the root zone (Hopmans and Bristow, 2002).

Since HYDRUS does not include an irrigation management model, two simplified irrigation scenarios, spanning much of the observed irrigation practices in the study area, were selected for estimating the effect of split applications on N leaching:

Model A: Minimal Water Leaching Rate (Best Case Scenario)

In this case, the farmer was assumed to have perfect foresight of the weather for the 6 d following the next irrigation. Only the amount of irrigation water necessary to grow the crop to the next (known) rain was applied. Crop water needs were met from both precipitation and irrigation. The amount and timing of irrigation were designed by performing trial-and-error flow simulations. Rules to develop the irrigation schedules (one for sand and one for Andosol, separate irrigation schedules for each of 9 yr) were as follows:

1. During the growing season, irrigation was scheduled on the day when the soil water content in the root zone became less than the maximum allowable depletion of moisture content for optimum growth, which was assumed to occur at a soil water tension of −100 cm for sand and −1000 cm for Andosol. Calculations were repeated until the root zone water content did not drop below the depletion limit at any time during the growing season.
2. The amount of applied water at any time was the sum of crop evapotranspiration minus precipitation during the 6 d following the irrigation, divided by irrigation efficiency, which was assumed to be 0.8. If this value was negative (because of high precipitation), the amount of applied water was the sum of crop evapotranspiration before the next precipitation event.
3. For the NH_3 applications (as dissolved solute in the upper boundary water flux), additional irrigation was applied on the fertigation dates as needed such that the net water flux across the boundary into the soil (precipitation + irrigation − evaporation) was at least 0.1 mm on the day of NH_3 application.

In Model A, the value of LAI was assumed to be 2.0; that is, the crop transpiration constituted 80% of the actual crop evapotranspiration, with the remainder being soil evaporation. The root zone was set to be 30 cm deep with uniform root distribution during the entire two growing seasons of each year. The constant, near-maximum LAI and maximum rooting depth throughout the growing season provide an upper bound for the actual water and nutrient uptake, thereby providing an estimate of the lower bound for the N leaching risk.

Model B: High Water Leaching Rate (Worst Case Scenario)

Under the Model B irrigation schedule, it was assumed that none of the precipitation is effective (i.e., available to meet crop ET). All crop water needs were met by irrigation only, which leads to maximum possible water leaching rates. The amount of irrigation water and the irrigation frequency were determined based on soil moisture and based on the actual daily crop evapotranspiration rates during the growing season. For the study area, the amount of irrigation water applied per irrigation and the frequency of irrigation were calculated depending on the growth stages of the two crops (Table 3). Temporal changes in the LAI were estimated by assuming that the LAI was proportional to the crop coefficient. Maximum values of the LAI for watermelon (2.2) and tomato (3.8) were reported by Toyama and Takeuchi (1980) and Scholberg et al. (2000), respectively.

Table 3. Applied amount of water applied in one irrigation (IW) and the interval of irrigation (ID) in Model B of hypothetical simulations. Dates are the number of days since 1 January.

	The first crop				The second crop			
	60–126 d		127–180 d		181–238 d		239–301 d	
	IW	ID	IW	ID	IW	ID	IW	ID
	cm	d	cm	d	cm	d	cm	d
Sand	0.64	4	1.72	4	1.47	3	1.68	3
Andosol	0.80	5	2.15	5	1.47	4	1.68	4

Transient boundary conditions were discretized into 1-d stress periods. Spatial discretization and bottom boundary conditions were the same as in the simulations of the soil column experiments. The hydraulic parameters and solute properties of Exp.1 were adopted for these simulations. The simulated soil profile was 30 cm long. Nitrification properties of deeper soils were not known and may be different from the top soil. For the two crops of interest, the main effects of the fertilization management occur in the top 30 cm because of the shallow rooting depth (<30 cm).

To account for non-zero N initial conditions within the soil profile, each climate year was simulated twice. In the first run, initial water content was set to be 50% saturation and initial NH_4–N and NO_3–N concentrations to be zero. In the second run, initial water content and N concentrations were set to be the values at the end of the first annual run. The final water content and N profiles of the second run were generally the same as those of the first run, indicating a long-term quasi-steady state was obtained. The results for the second run are reported here. This procedure makes each year's results independent from residual effects of the previous climate year. Not counting trial-and-error simulations to set up the Model A irrigation schedule, a total of 288 transient simulation runs (365 d each) were completed (two irrigation scenarios × two soils × four fertilizer application practices × nine years × two runs per year).

RESULTS AND DISCUSSION

First-Order Rate Constant for Nitrification

For sand, the decrease in the total NH_4–N was small (Fig. 3a). Corresponding increases in NO_3–N were small as well (Fig. 3b). Mineralization, nitrification, and denitrification in the sand soil are therefore considered negligible. In contrast, the Andosol experiments resulted in a significant NH_4–N decrease and an accompanying increase of NO_3–N (Fig. 3c and 3d), clearly indicating nitrification. Soluble and adsorbed NH_4–N concentrations decreased proportional to the total amount of NH_4–N. Ammonia volatilization appears to be negligible for both sand and Andosol because soils were not alkaline. Soil pH values at the start of incubation were 6.1 and 6.5 for sand and Andosol, respectively (Table 1). The pH of applied $(NH_4)_2SO_4$ solution was 7.2. Also, we did not observe a decrease of total NH_4–N concentration immediately after the start of incubation, which would have been characteristic for volatilization (Fig. 3a and 3c). Concentrations of NO_2–N in the soil solution were zero for sand and <1.2 mg N kg^{-1} for Andosol.

Changes in total inorganic N were small except for one unexplained outlier during the initial 5 d of the 500 mg

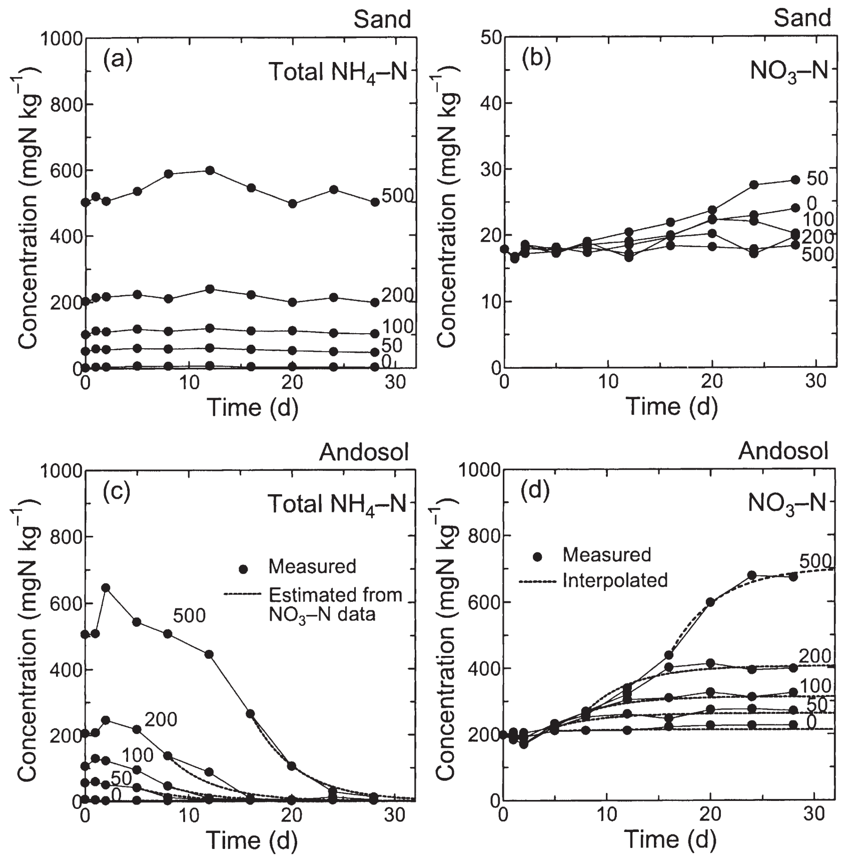

Fig. 3. Temporal changes in the concentrations of (a) total NH_4–N and (b) NO_3–N in sand batch tests and (c) total NH_4–N and (d) NO_3–N in Andosol batch tests. Values in figures represent applied NH_4–N concentration (mg N kg^{-1}). Dotted lines are fitted by using a first-order rate reaction formula for nitrification.

N kg^{-1} treatment. A net zero change of total inorganic N implies either that the mineralization rate is equal to the denitrification rate or that both the mineralization rate and the denitrification rate are zero. While neither rate had been measured directly, it seemed unlikely that the two rates incidentally balanced each other, in particular because conditions during the experiment were aerobic, thus favoring mineralization over denitrification. Both, mineralization and denitrification were therefore considered negligible.

The first-order rate constants k_{nit} for the Andosol were estimated from the rate of NO_3–N increase. The estimation did not consider the early period immediately after incubation, which may have been influenced by nonlinear effects due to nitrifying bacteria population growth and mineralization. The estimated nitrification rate, k_{nit}, was 0.00933 h^{-1}. It is impossible to specify exactly whether soluble NH_4–N only, adsorbed NH_4–N only, or both forms of NH_4–N were converted to NO_3–N in the process of nitrification. We estimated k_{nit} under the assumption that either only soluble or only adsorbed NH_4–N was nitrified. Neither one of these estimates could reproduce measured NO_3–N data adequately. Therefore, for purposes of the fertigation simulations, both forms of NH_4–N were considered to be simultaneously converted to NO_3–N at the same rate, k_{nit}.

Parameter Calibration

Calibrated parameters are shown in Table 4, and optimized soil water retention curves for both soils are shown in Fig. 4 together with measured retention data. The optimized water retention for sand apparently underestimated the measured drying curve. This is possibly the result of the hysteresis effect: the water flow process was under wetting conditions soon after solution applications, while the retention curve measurement was made under drying conditions. In contrast, the optimized water retention curve of Andosol compared well with the measured retention curve (no hysteretic effect). Optimized saturated hydraulic conductivities of sand and Andosol were close to the measured values, indicat-

Table 4. Optimized parameters using HYDRUS-1D.

	α	*n*	K_s	D_L
			cm h^{-1}	dm
		Sand		
Exp. 1	0.0982	1.93	79.5	1.42
Exp. 2	0.0860	2.02	79.5	0.655
Measured	0.0673†	1.61†	79.2‡	–
		Andosol		
Exp. 1	0.199	1.19	39.5	1.05
Exp. 2	0.202	1.20	39.8	1.41
Measured	0.152†	1.19†	39.6‡	–

† Interpolated from measured soil water retention data.
‡ Measured K_s by falling head method.

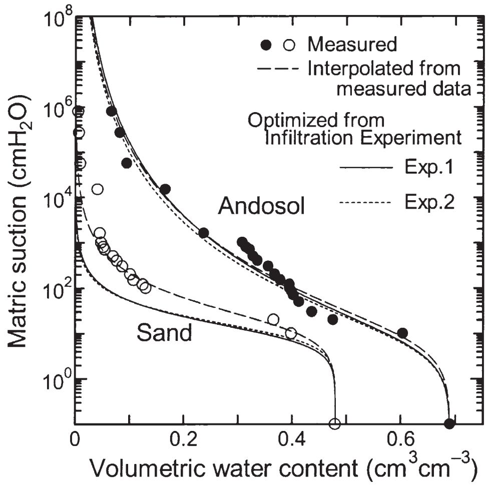

Fig. 4. Water retention curves of sand and the Andosol. Symbols represent measured data for drying; dashed lines are interpolated from measured data. Solid and dotted lines were optimized using HYDRUS-1D for Exp. 1 and 2, respectively.

ing that the falling head method (Klute and Dirksen, 1986) provided adequate parameter values for modeling purposes. Calibrated longitudinal dispersivities (Table 4) compared favorably with values reported in the literature (e.g., 0.3–4.0 cm for loamy sand, Persson and Berndtsson, 1999). The differences between Exp. 1 and Exp. 2 were likely attributable to differences in initial water content, applied water amount, and solute concentration gradients (Hillel, 1998).

Column Profiles: Water Content, Ammonium, and Nitrate

In sand, the peak of the NO_3–N and the soluble NH_4–N profiles moved deeper in Exp. 1 (lumped application) when compared with Exp. 2 (split application) (Fig. 5), indicating that the lumped fertilizer application resulted in increased downward transport of soluble NO_3–N and NH_4–N relative to the split applications. Nitrate-N transport appeared to be faster than NH_4–N transport because of the sorption of the latter. In the Andosol, differences in profile concentrations between the dispersivity of Exp. 1 and 2 were much less pronounced.

Simulated volumetric water content, NH_4–N, and NO_3–N profiles and simulated temporal dynamics agreed well with measured profiles (Fig. 5). Simulations showed that small differences of NO_3–N between sand Exp.1 and sand Exp.2 were caused by the differences in initial NO_3 concentrations, longitudinal dispersivities, applied water amounts, and evaporation rates (Fig. 5a, bottom). Simulations captured the profile differences observed between Exp. 1 and 2 (Fig. 5b, bottom). Only the simulated soluble NH_4–N concentrations at the upper part of the soil columns were significantly underestimated (Fig. 5b, center). Similar results were obtained for soil profiles of total NH_4–N (data not shown). The error may be due to neglecting NH_4–N sorption dynamics during infiltration, when NH_4–N sorption may effectively be rate-limited. The model assumed instantaneous sorption. Another reason that may have contributed to the discrepancy is that the nitrification rates k_{nit} of soluble and adsorbed NH_4–N, which were assumed to be identical in the model, were in fact not the same.

Seepage Face Fluxes (Breakthrough Curves)

Figure 6 (top) shows measured and simulated cumulative seepage water flux. Seepage fluxes were limited to short periods of time immediately following the irrigation. The difference between measured and simulated cumulative seepage fluxes was small and can be explained by water storage in glass beads and hose pipes that were connected to the flask collecting the leachate (≈0.4 cm). Associated temporal changes in cumulative NH_4–N and NO_3–N fluxes at the bottom of the columns are obtained via simulation (Fig. 6, bottom). In sand, Exp. 1 (lumped application) produced higher seepage solute flux than Exp. 2 (split application). This was due to both higher NH_4–N and NO_3–N concentrations in the lower profile (Fig. 5a, center and Fig. 5a, bottom) and due to increased amounts of leachate (Fig. 6, top). In the Andosol, the difference between Exp. 1 and 2 was significantly less pronounced than in the sand because of higher adsorption of NH_4–N and high water retention capacity.

Leaching Risk Simulations

The column experiments considered neither long-term conditions nor plant water uptake, which are experimentally more difficult to implement under highly controlled conditions. But the experiments provided significant confidence in the ability of the flow and transport model to appropriately capture soil–water–nutrient dynamics. As an extension of the experiments, simulations were used to further evaluate the effect of split application under more realistic crop growing conditions.

Simulated N leaching past the 30-cm profile depth and root N uptake varied from year to year due to interannual variability in weather patterns, in particular the timing and amount of precipitation relative to fertigation and plant uptake dynamics. Despite the variability, N leaching followed a consistent soil and fertigation-dependent pattern (shown for scenario A in Fig. 7 and Fig. 8) explored here in more detail.

In the sand, N fluxes consisted entirely of NH_4–N because of the lack of nitrification. In the Andosol, most of the NH_3 was nitrified, and N seepage was primarily in form of NO_3–N. Negligible (<1%) N was stored in the 0- the 30-cm zone from year to year; that is, all of the annually applied N was subject either to root N uptake or N leaching from the root zone.

Fertilizer N leaching beyond the 30-cm profile began 40 to 70 d after the initial application of the year. With the lumped application, N losses were higher in the early season than in the late part of the growing season. Most of the losses occurred during the first of the two annual crop growing season because of the much higher fertigation rate (Table 2). For the split applications, early losses were smaller, and losses were more evenly distributed throughout the season. Throughout the simulation pe-

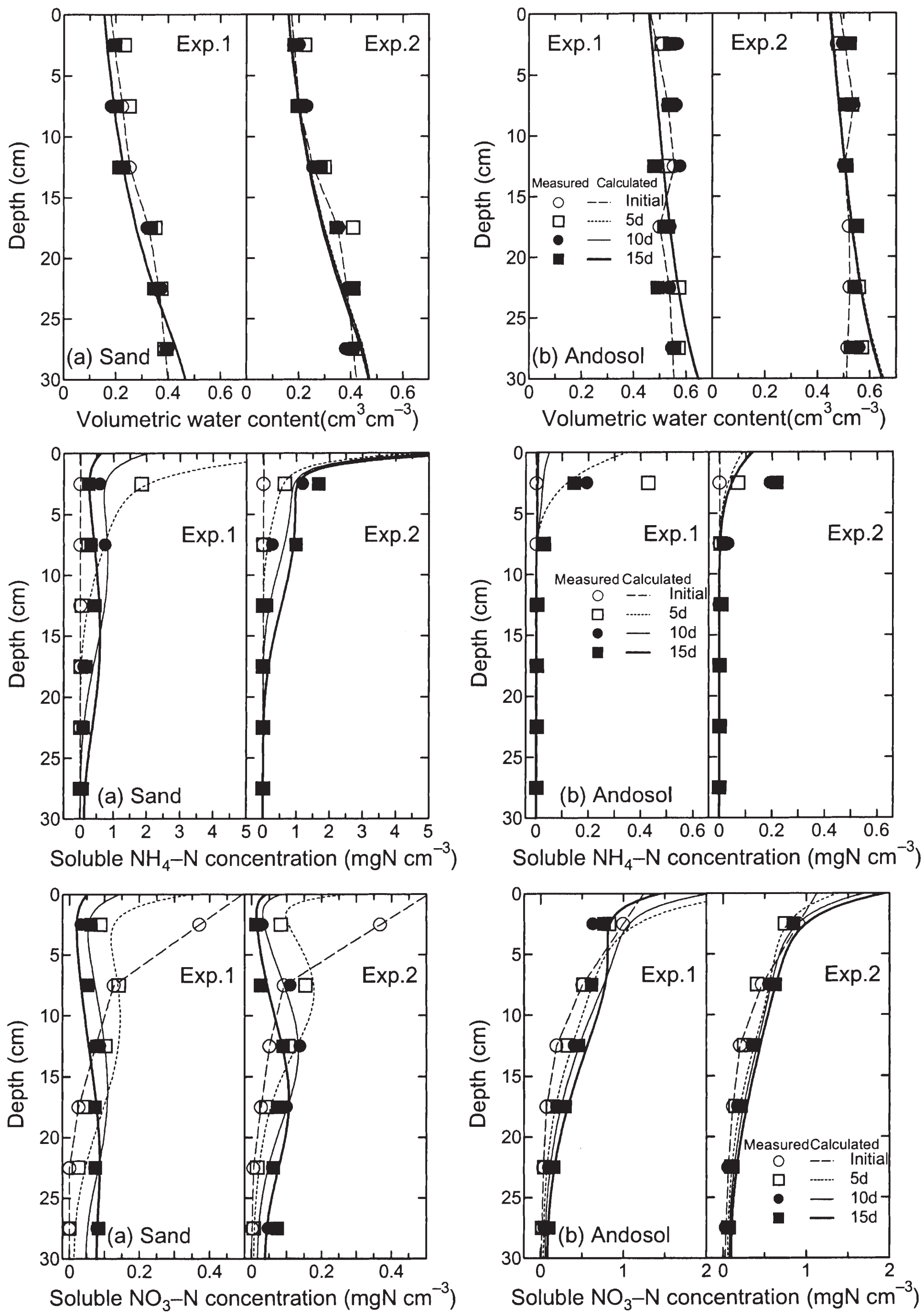

Fig. 5. Measured (symbols) and calculated (lines) changes in the volumetric water content (top), NH_4–N (center), and NO_3–N (bottom) profiles in (a) sand and (b) Andosol columns in the case of Exp. 1 and 2 at the time points just before each solution application and at the end of experiments.

riod, the split application schemes lead to significantly less leaching losses than the lumped application method. The simulations indicate that scheduling the fertilizer applications close to the beginning of the main growth period was critical to avoid unnecessary leaching losses. As in the column experiments, leaching losses in both soils occur step-wise in response to individual precipitation and irrigation events. Between rainfall or precipitation events, drainage and hence N leaching, quickly terminated. The shallow thickness of the root zone in both, the Andosol and the sand provided little buffering against the transient nature of precipitation.

Under optimal irrigation conditions (Scenario A) and lumped fertilizer applications, the N leaching fraction, defined as the ratio of total N annually leached from the root zone to total N annually applied, averaged 72% in sand and 60% in Andosol. The corresponding nutrient uptake efficiency, defined as the ratio of total N annually used by the crop to total N annually applied, varied from 28% in sand to 40% in Andosol. Splitting fertilizer

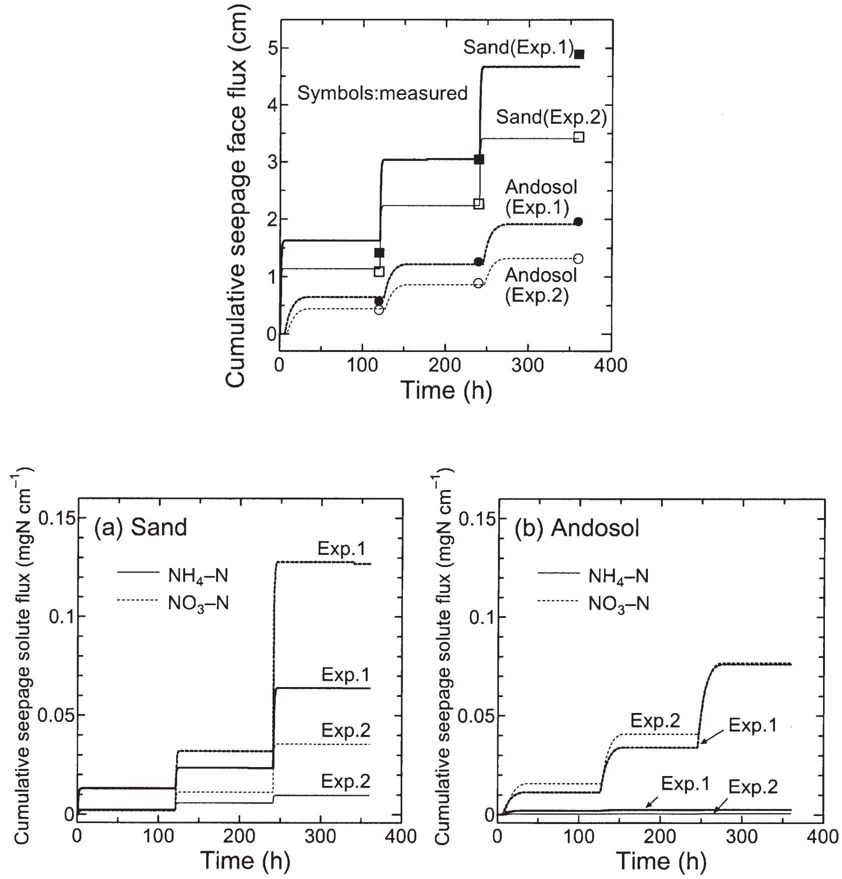

Fig. 6. (top) Measured and calculated temporal changes in the cumulative seepage flux for sand and the Andosol in the case of Exp. 1 and 2. Solid lines represent calculated changes for sand and dotted lines calculated changes for Andosol. Square and circular symbols are measured values for sand and Andosol, respectively. (bottom) Calculated temporal changes in the cumulative seepage NH_4–N and NO_3–N fluxes for (a) sand and (b) Andosol in the case of Exp. 1 and 2. Solid lines represent NH_4–N and dotted lines NO_3–N.

applications just once, into two applications, drastically lowered the total N leachate concentrations in sand (on average from 72 to 48%) and in Andosol (on average from 60 to 40%) with corresponding drastic increases in N use efficiency. In the heavier Andosol, the three-split and six-split applications produced little additional benefit when compared with the two-split application. In the sand, a three-split regime lowered leaching fractions to levels comparable to those achieved in Andosol (near 40%), but little or no leaching risk reduction was achieved by increasing the application method in sand from three to six split applications (Fig. 9, top).

Under less efficient irrigation conditions (Scenario B), N leaching fractions were significantly higher. For the lumped application, for example, they averaged 92% in sand and 90% in Andosol. The two-split application lowered the leaching fraction to 59% in sand and 62% in Andosol (Fig. 9, bottom). On average, annual cumulative N leaching under Scenario B exceeded that of Scenario A by 30% in sand and by 40% in Andosol, regardless of the fertilizer application method. This indicates that adjustments to irrigation efficiency and proper irrigation timing (relative to precipitation) were more effective for NO_3 leaching control in the finer textured soils.

At the same time, the *relative* decrease in N leaching fractions between lumped and split application schemes did not significantly change between irrigation scenarios. Also, under both irrigation scenarios, proper irrigation management lead to more drastic NO_3 leaching reductions in the coarser soil than in the finer textured soil. This suggests that for both Andosol and sand, split applications would be the preferred application method, regardless of the irrigation schedule.

Scenario A and B differed not only in the irrigation timing, but also in the setup of LAI and root growth. To better discern the contribution of (more realistic) variable LAI and root growth modeling and to test the sensitivity of the NO_3 leaching to LAI and root growth behavior, we compared scenario B results for 2000 with simulations under the same irrigation scheme, but constant LAI and constant root depth (as in Scenario A). For the lumped application, neglecting temporally variable LAI and root depth overestimated NO_3 leaching by 19% in sand and by 13% in the Andosol. The increased leaching occurred during the late part of each of the two growing seasons, when the average (constant) LAI is smaller than the actual (temporally variable) LAI, reducing root water uptake. For the split applications, the differences between the two LAI and root depth scenarios were <5% in both soils. Hence, knowledge of LAI and root depth variations through time are less critical in the N leaching evaluation of split application than in the evaluation of lumped applications.

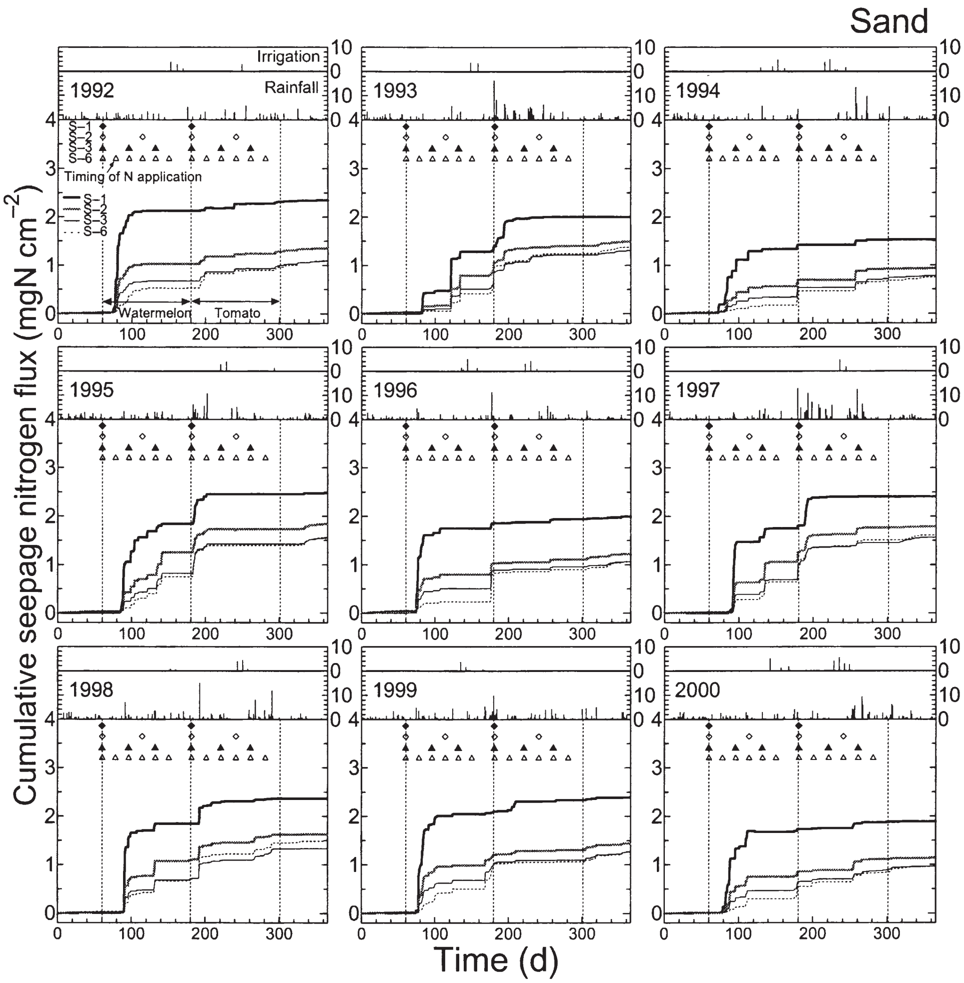

Fig. 7. Temporal changes in the precipitation and irrigation (cm d^{-1}) and simulated temporal changes in the cumulative seepage N fluxes for sand in Model A. Heavy solid, heavy gray solid, thin solid, and thin dotted lines represent the case of lumped (S-1), two-split (S-2), three-split (S-3), and six-split (S-6) applications, respectively. Symbols represent the timing of NH_4–N applications for each scenario. See Table 2 for scenario numbers.

The simulations did not directly consider the effects of plant stress (or toxicity) due to water or nutrient deficiency (e.g., from leaching losses after lumped N applications, Pang and Letey, 1998). This is justified because we considered irrigated, commercial crops that are generally grown under conditions of minimal water and nutrient stress. The dynamics of the root zone water fluxes were therefore properly captured by using unstressed ET data as boundary conditions. Furthermore, within the observed concentration range of NH_3, sorption and nitrification were nearly linear functions of the amount of N applied (Fig. 2). Therefore, NH_3 and NO_3 leaching varied more or less linearly with the total simulated N application rate. Hence, computed N leaching fractions and N use efficiencies were nearly independent of the simulated total amount of N applied (only the application pattern was critical).

While Fig. 7 and 8 compare N leaching between fertilization methods for a specified equal amount of total N input, fields are typically managed to achieve a specified crop yield (i.e., a specified N uptake). Based on the simulated N leaching efficiencies, equal crop production (equal N uptake) will only be achieved by applying from 50% (Andosol, Scenario A) to 500% (sand, Scenario B) more N in the lumped application when compared with the best split application method. Under realistic conditions, then, nearly double to more than quadruple the amount of N leaching occurs under lumped applications than what is shown in Fig. 7 and 8.

The modeling results confirm past experimental findings with split N application methods. Rathier and Frink (1989) investigated lumped vs. split applications for various N fertilizers and irrigation methods. Splitting applications on container grown conifers significantly reduced N leaching of slow-release fertilizer, which was directly measured in the leachate. Consistent with our simulation results, splitting the application had a more pronounced effect than differences between irrigation methods. Less significant effects from application splitting were observed in a similar study by Colangelo and Brand (1997). However, the lack of control achieved by split applications there was likely due to the large irrigation volumes used. Vos (1999), who estimated leaching losses from N application, N uptake, and zero application controls, found that split applications provided slightly better uptake efficiency (less leaching) than

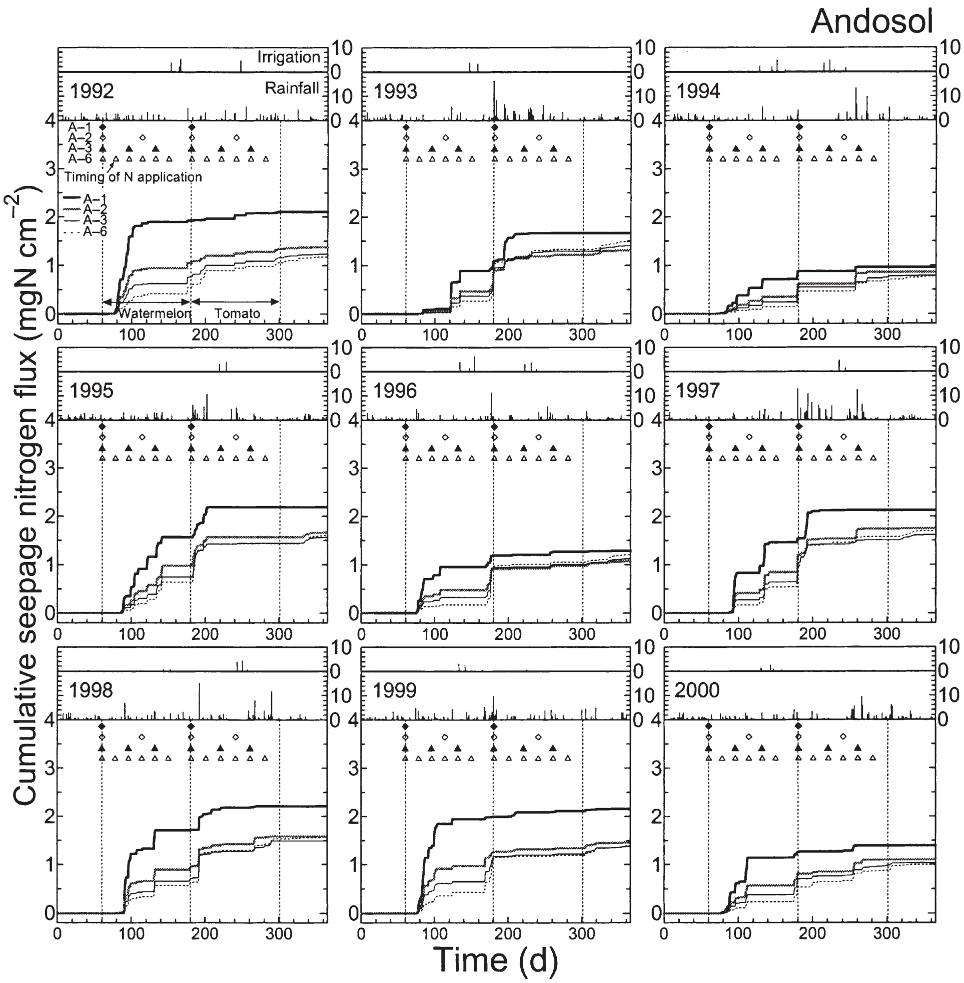

Fig. 8. Temporal changes in the precipitation and irrigation (cm d^{-1}) and simulated temporal changes in the cumulative seepage N fluxes for the Andosol in Model A. Heavy solid, heavy gray solid, thin solid, and thin dotted lines represent the case of lumped (A-1), two-split (A-2), three-split (A-3), and six-split (A-6) applications, respectively. Symbols represent the timing of NH_4–N applications for each scenario. See Table 2 for scenario numbers.

lumped applications. Since their field trial on potato (*Solanum tuberosum* L.) was performed under nonirrigated conditions, leaching losses strongly depended on the timing and amount of precipitation. Their observed N uptake efficiencies were similar to those observed in our simulations.

Field trials have also suggested that the leaching risk reduction achieved by split applications vanishes in soils that are finer textured than those considered here. For example, in field experiments with onion (*Allium cepa* L.) on nonirrigated clay soils in the Netherlands (Visser, 1998), N splitting did not affect the N losses during the growing season. However, since N losses were computed as closure to a mass balance, their results were subject to significant uncertainty. Furthermore, the authors of that study noted that the particular scheduling method used resulted in overapplication of N (with any application method) and that a more precise tuning of N applications and N uptake would likely have resulted in a more pronounced effect of the application method (lumped vs. split) on leaching rates.

Our simulations demonstrate that leaching fractions (and root N uptake) varied considerably from year to year due to the randomness of the rainfall distribution. Yet, the leaching fraction was only weakly correlated with the total amount of precipitation during the growing season. The correlation was more pronounced for the split applications than for the lumped application. Highest correlation coefficients were obtained for the six-split applications (Fig. 10). The highest leaching fractions occurred in the wettest years. This is consistent with Schröder (1999), for example, who reported that split applications of cattle slurry or mineral fertilizer N on sandy soils were a strategy superior to the conventional no-split applications only in very wet years.

The complex dynamics between soil properties and rainfall patterns are also reflected by the differences in year-to-year leaching pattern between the sand and the Andosol. In the sand, the change in fertilizer application method achieved the least leaching reductions in 1993, 1995, and 1997, while the least reductions in the Andosol occurred in 1994, 1996, and 1997. Azevedo et al. (1997) used a similar simulation approach to evaluate N leaching under various management methods, including split and lumped applications. Their results confirmed that split applications do not always result in lower leaching

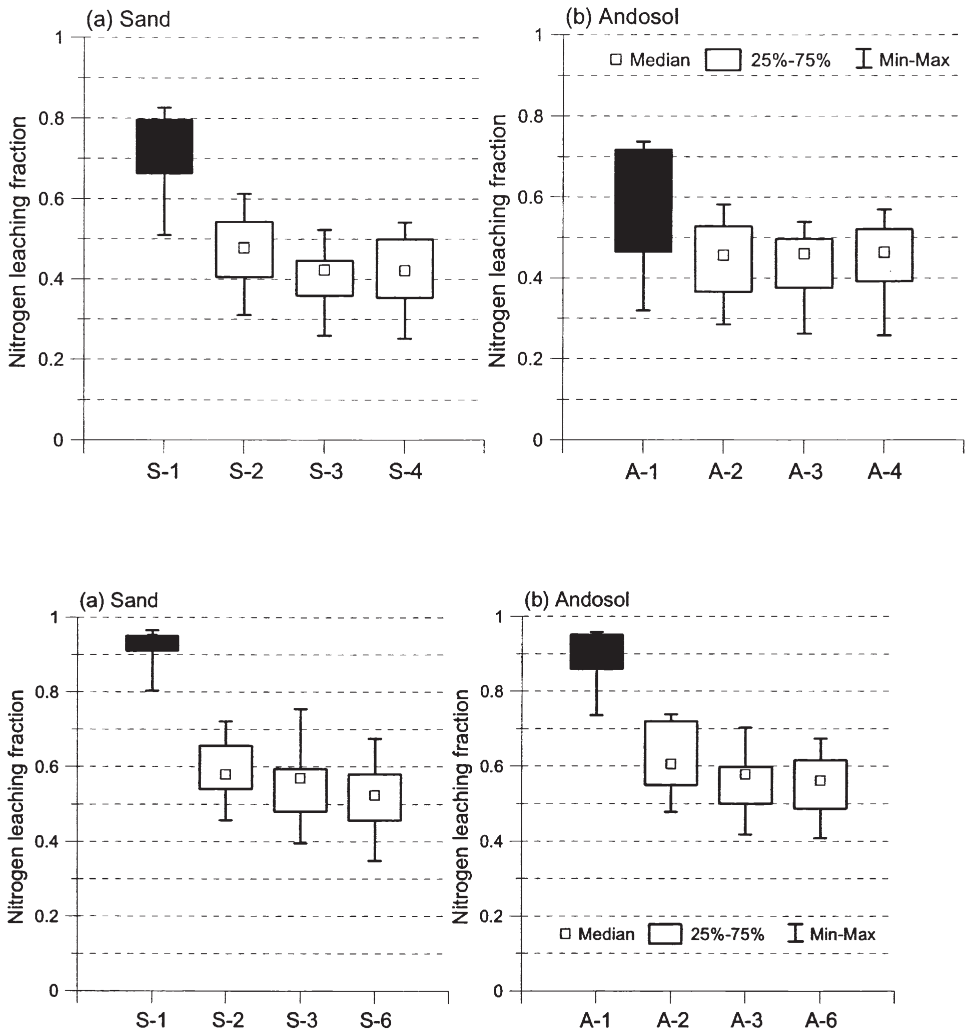

Fig. 9. Grouped quartiles of N leaching fraction computed from nine samples (1992–2000) for (a) sand and (b) Andosol in Model A (top) and Model B (bottom). Scenarios represent lumped (S-1, A-1), two-split (S-2, A-2), three-split (S-3, A-3), and six-split (S-6, A-6) applications.

rates and that the effect of splitting applications is largely dependent on the rainfall regime relative to fertilizer application. This and the fact that the leaching fraction is not more strongly correlated to the total precipitation amount suggests that the efficiency of split applications depends complexly on the timing of fertilizer applications relative to precipitation or irrigation events. This justifies the use of risk simulation models such as the one developed here, to bracket the potential benefits of alternative nutrient management practices.

CONCLUSIONS

Batch experiments for NH_3 sorption and nitrification rate estimation together with standard soil hydraulic measurements provided sufficiently accurate parameter data for simulating water and N management scenarios and evaluating N leaching risk on sand and Andosol soils in Japan. The comparison of column experiment and modeling results demonstrated that the independently determined parameters are able to closely simulate the behavior in the experimental soil columns. Differences between lab measured parameters and those obtained from calibrating against the column experiment were relatively minor.

The experiments as well as the leaching risk simulations demonstrated that fertilizer management significantly controls the leaching of NH_4 in sand and NO_3 in Andosol. Split applications increase N root uptake and lower the amount of soluble N in the deeper soil profile. For the specific Japanese soils and climate conditions simulated, two-split fertilizer applications provided an effective means for lowering the risk of groundwater contamination. In sandy soils, a three-split application appeared to provide the best N use efficiency in practice. In fertigation, where it is easy to control the amount and frequency of water and fertilizer, split fertilizer application should therefore be implemented to the maximum extent possible. This will also reduce the risk of leaching losses due to unforeseen rainfall events. In conventional broadcast application of fertilizer, it is recommended to split the necessary amount of fertilizer into at least two applications to lower the risk of N leaching to groundwater.

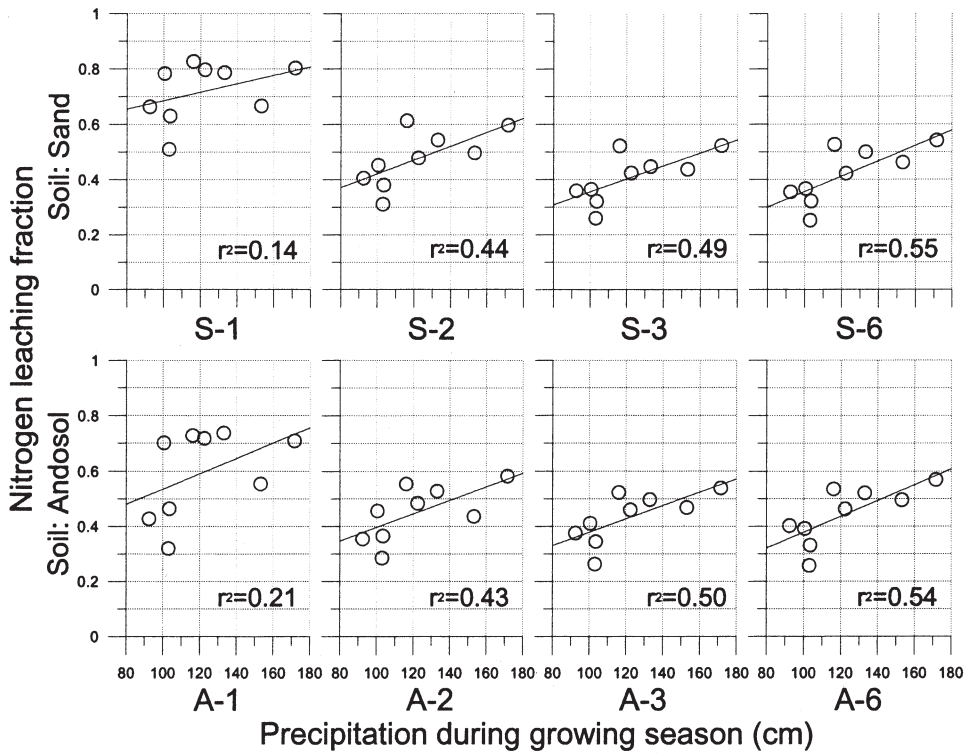

Fig. 10. Relationship between the N leaching fraction and the total amount of precipitation during the growing season obtained by nine samples (1992–2000) for each scenario in Model A. Solid lines represent the linear regression curve. r^2 is the coefficient of determination. Scenarios represent lumped (S-1, A-1), two-split (S-2, A-2), three-split (S-3, A-3), and six-split (S-6, A-6) applications.

Annual differences in precipitation patterns have a significant influence on the amount of N leaching out of the root zone, especially under the split application regimes. Timing of rainfall or irrigation relative to fertilizer application is as critical as the total amount of precipitation or irrigation during the growing season. The large amount of interannual variability in N leaching observed in the leaching risk simulations explains the difficulties encountered in field experiments to establish definite benefits based on only 1 to 3 yr of experimental data, particularly if the water regime is strongly controlled by precipitation.

In the future, more realistic simulation models than the one employed here should include active plant N uptake dynamics, water and nutrient-stress dynamics (e.g., Pang and Letey, 1998), and irrigation scheduling. However, such models come with additional data requirements, particularly for the nutrient uptake dynamics, which are often unavailable. Until such data are available, simplified models and sensitivity analyses such as the one implemented here can provide a significant scientific basis for the evaluation of alternative nutrient management methods.

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