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Two–Dimensional Analysis of Nitrate Nitrogen Movement under Drip Irrigation

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The objective of this paper was to clarify the temporal and spatial two–dimensional variations of volumetric water content and NO_3–N concentration in soil under drip irrigation. A numerical model was used for estimating temporal and spatial movements of water and NO_3–N in soil. Laboratory experiments were conducted to estimate the physical properties such as soil water retentivity and conductivity. A field observation was conducted to evaluate the model accuracy. The temporal and spatial changes of volumetric water content and NO_3–N concentration in soil were measured in a 1 m×1 m×1 m lysimeter where NH_4NO_3 solution was supplied in a row. The results of simulation calculated by the model agreed well with observed data. By using the model, temporal and spatial variations of soil water content and NO_3–N concentration were calculated. The results described simultaneous movements of water and NO_3–N spreading in a soil profile. The numerical model introduced here can be effective to estimate variations of water and NO_3–N in soil.

INTRODUCTION

Drip irrigation is a method that saves water and fertilizer by allowing water to drip slowly onto the soil surface or directly to the root zone. In this irrigation system, fertigation, the application of dissolved fertilizers with water, has been used. A variety of chemicals are dissolved in the water. NO_3–N, which is one of the common chemicals of fertilizers, can easily leach to the ground water table because it is eluvial at moderate pH (Jury and Horton, 2006). NO_3–N in drinking water can cause low oxygen levels in the blood of infants, which is a potentially fatal condition (Bernard *et al.*, 1997). Clarifying simultaneous transport of water and NO_3–N in soil is important and the proposition of effective irrigation methods is necessary to prevent NO_3–N from reaching the ground water table.

Numerous studies have been conducted to estimate the movements of NO_3–N in soil. Nakamura *et al.* (2004) studied temporal and vertical variations of NO_3–N and NH_4–N concentrations including nitrification in root zone. Some models describing temporal and spatial multidimensional movement of solute, such as HYDRUS (2D/3D) (Šimůnek *et al.*, 2008), have been developed. However, there have been few papers published on the investigation of two–dimensional changes of water and NO_3–N in soil under drip irrigation.

The goal of the current study was to clarify temporal and spatial two–dimensional variations of volumetric water content and NO_3–N concentration in soil under drip irrigation by using a combination of experiments and modeling.

METHODLOGY

Governing equation of water and NO_3–N transfer in soil

A numerical model describing water flow and NO_3–N transport in soil was used to predict the temporal and spatial variations of NO_3–N concentration with water flow.

Two–dimensional water movement in isotropic soil can be computed by solving Richards' equation as follows:

$$C_w \frac{\partial \phi_m}{\partial t} = \frac{\partial}{\partial x}\left(k_w \frac{\partial \phi_m}{\partial x}\right) + \frac{\partial}{\partial z}\left(k_w \frac{\partial \phi_m}{\partial z}\right) + \frac{\partial k_w}{\partial z} \qquad (1)$$

where ϕ_m is the pressure head (cmH_2O), C_w is the water capacity function (cm^{-1}), k_w is the unsaturated hydraulic conductivity (cm s^{-1}), t is the time (s), x is the horizontal coordinate (cm), and z is the vertical coordinate (cm).

The relationship between the volumetric water content, θ (cm^3 cm^{-3}) and ϕ_m is represented by the following equation (van–Genuchten, 1980):

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

where θ_s is the saturated volumetric water content (cm^3 cm^{-3}), θ_r is the residual volumetric water content (cm^3 cm^{-3}), and α and n are parameters.

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

$$k_w(\phi_m) = k_{ws}\left[\frac{1}{1+(-\alpha\phi_m)^n}\right]^{\frac{n-1}{2n}}\left[1-\left\{1-\frac{1}{1+(-\alpha\phi_m)^n}\right\}^{\frac{n-1}{n}}\right]^2 \qquad (3)$$

where k_{ws} is the saturated hydraulic conductivity (cm s^{-1}).

Two–dimensional soluble NO_3–N movement in isotropic soil can be computed by solving convection–diffusion equation described below:

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$$\frac{\partial}{\partial t}(\theta C) = \frac{\partial}{\partial x}\left(\theta D_{cx}\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial z}\left(\theta D_{cz}\frac{\partial C}{\partial z}\right)$$

$$- \frac{\partial}{\partial x}(q_{wx}C) - \frac{\partial}{\partial z}(q_{wz}C) \quad (4)$$

where C is the soluble NO_3–N concentration (mgN cm^{-3}), D_c is the dispersion coefficient (cm^2 s^{-1}), and q_w is the water flux (cm^3 s^{-1}). Sorption of NO_3–N was negligible. The dispersion coefficient of soluble substance can be estimated as follows:

$$\theta D_c = D_0 a \exp(b\theta) + \lambda |q_w| \quad (5)$$

where D_0 is the molecular diffusion coefficient in free water (cm^2 s^{-1}), λ is the longitudinal dispersivity (cm), and a and b are the parameters.

Initial and Boundary Conditions

For the simulation of the field experiment described in the following section, initial conditions of volumetric water content and soluble NO_3–N were obtained by linear interpolation of measured profile values just prior to irrigation. The boundary condition of water movement at soil surface was given by specified irrigation rates $q_{w\,irri}$, and a constant evaporation rate $q_{w\,eva}$. The boundary condition of NO_3–N at soil surface was given by the NO_3–N flux $q_{c\,irri}$ with irrigation. Boundary conditions at the walls and the bottom were set as fluxes equal to zero in both water and NO_3–N simulation.

Model Description

To solve the governing equations shown in eqs.(1) and (4), the finite–differential method was used. The numerical model for estimating water and NO_3–N movements are shown in Fig. 1 with the boundary conditions. The 1 m×1 m domain was divided into 60×60 grids. The time step was 0.05 second during irrigation and 1 second after the irrigation.

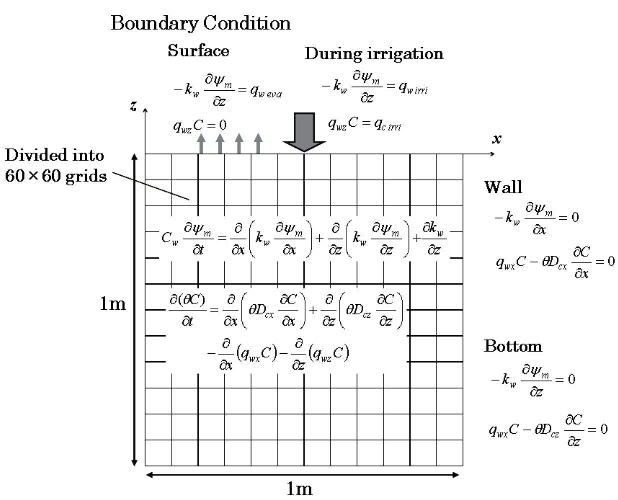

Fig. 1. Numerical model for predicting the movement of water and NO_3–N in soil.

EXPERIMENTS

Laboratory Experiments

Laboratory experiments were conducted to determine some soil physical properties, including the soil water retentivity and conductivity, to apply the numerical model shown in Fig. 1. Granite soil was used in the experiments; this was also used in the field observation

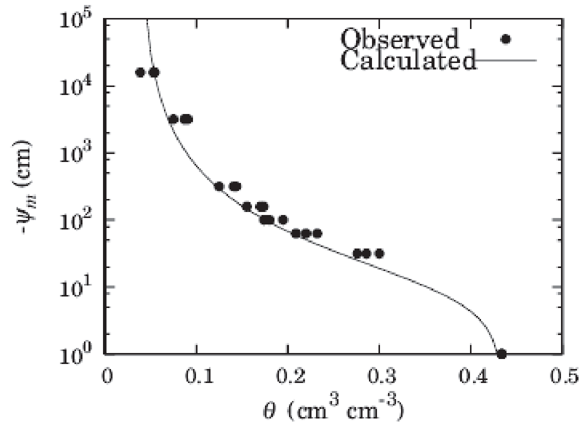

Fig. 2. Water retention curve.

Table 1. Parameters for van–Genuchten equation

θ_s (cm^3 cm^{-3})	θ_r (cm^3 cm^{-3})	α	n	$k_{ws\,(cm\,s^{-1})}$
0.434	0.039	0.110	1.438	1.72×10^{-3}

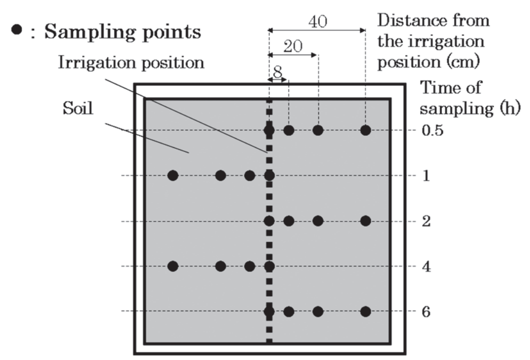

Fig. 3. Plan view of the lysimeter.

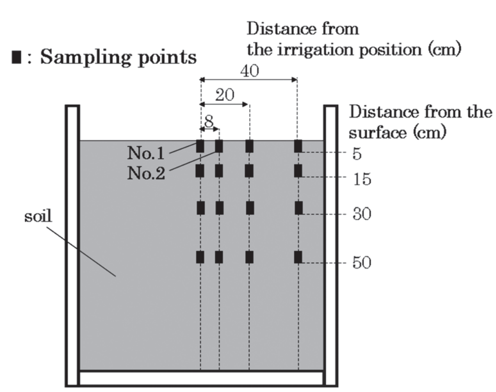

Fig. 4. Soil sampling profile of the lysimeter.

described below. The saturated water conductivity, k_{ws}, in eq.(3), was obtained by the falling head method. The water retention curve was obtained by the hanging water column method and the centrifuge method. The residual volumetric water content, θ_r and the parameters, α and n in eqs.(2) and (3), were determined by the least squares method for the data. The retention curve calculated by eq.(2) and observed values are represented in Fig. 2. The values used in eqs.(2) and (3) are represented in Table 1.

Field Observation

The accuracy of the numerical model for estimating water flow and NO_3–N transport in soil was verified by a field observation using 1 m×1 m×1 m lysimeters. The lysimeters were filled with the granite soil. To simulate a condition of drip irrigation with dissolved fertilizer, 1 L of NH_4NO_3 solution with a concentration of 500 mgN L^{-1} was supplied at the center row of the lysimeter (Fig. 3). Irrigation intensity was 6.2 mm h^{-1}. Soil samplings were conducted at the points shown in Fig. 4 to investigate the volumetric water content and the NO_3–N concentration at 0, 0.5, 1, 2, 4, and 6 hours after the irrigation.

RESULTS AND DISCUSSION

Model Validation

Simulated and observed values of volumetric water content and NO_3–N concentration in soil are shown in Figs. 5 and 6, respectively. The sampling points of Figs. 5 and 6 are shown in Fig. 4. The simulated values have relatively good agreement with the observed values. The results indicate that the model is valid. Differences between the simulated and the observed values might be caused by non–uniformity of soil physical characteristics and initial distribution of water and NO_3–N.

Spatial distributions of water and NO_3–N concentration in soil

The temporal and spatial variations of the soil water content and NO_3–N concentration simulated by the use of the numerical model are shown in Figs. 7 and 8. The assumed conditions in this simulation are represented in Table 2. The soil properties in the simulation are the same as those in the laboratory experiments above. As shown in Figs. 7 and 8, NO_3–N is transferred with soil water by convection. The area of NO_3–N distribution is larger than the area of water distribution because the dispersivity λ used in the simulation is relatively large (Jury and Horton, 2004) and diffusion also occurs even if there is no water flow.

Table 2. Initial and boundary conditions

Initial volumetric water content ($cm^3\ cm^{-3}$)	0.089
Initial NO_3–N concentration (mgN cm^{-3})	0
Water flux of irrigation (cm s^{-1})	0.00139
NO_3–N concentration of irrigation water (mgN cm^{-3})	0.25
Evaporation rate (cm s^{-1})	0
Dispersivity (cm)	5

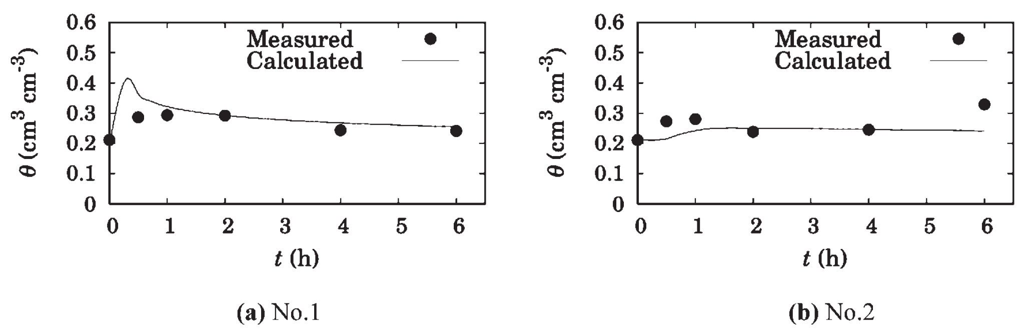

Fig. 5. Calculated and measured values of volumetric water content θ in soil.

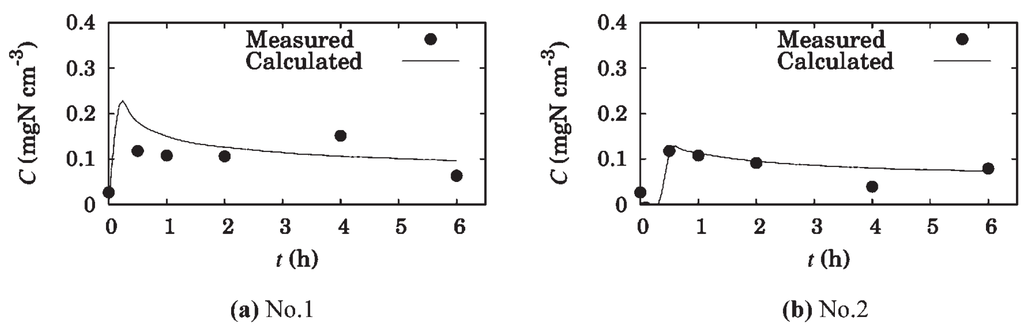

Fig. 6. Calculated and measured values of NO_3–N concentration C in soil.

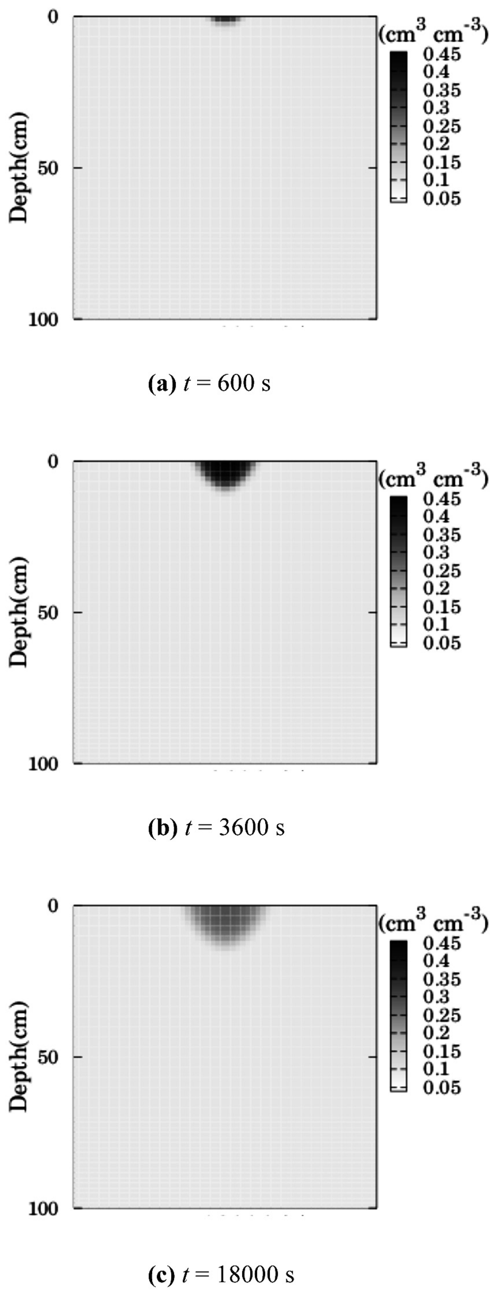

Fig. 7. Temporal and spatial variations of volumetric water content in soil.

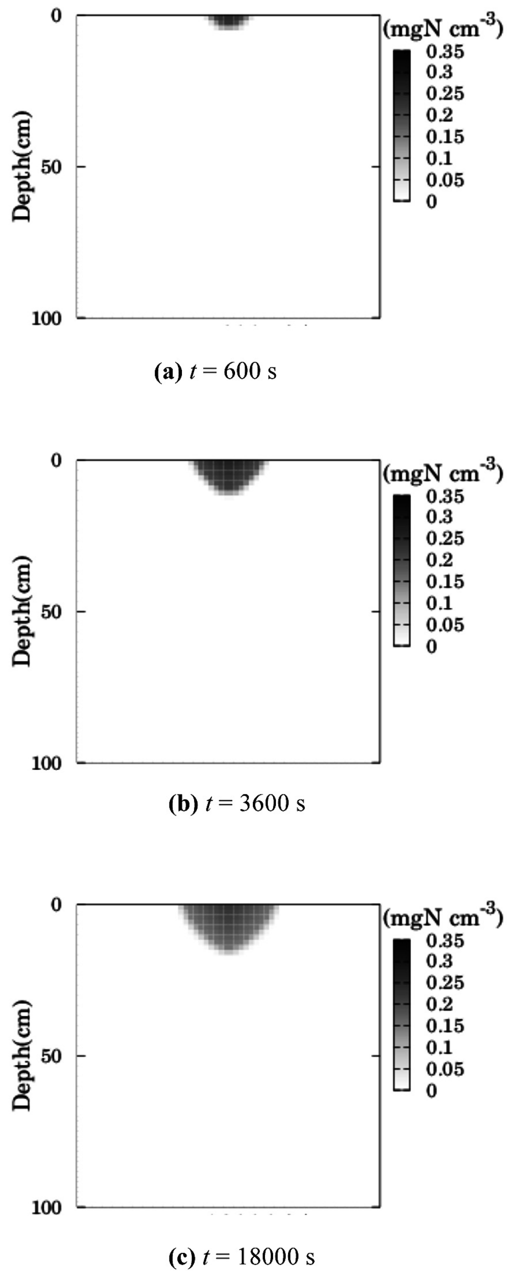

Fig. 8. Temporal and spatial variations of NO_3-N concentration in soil.

CONCLUSIONS

To clarify temporal and spatial two–dimensional variations of volumetric water content and NO_3–N concentration in soil under drip irrigation, a numerical model for estimating temporal and spatial movements of water and NO_3–N in soil was used. Laboratory experiments were conducted to estimate the physical properties including soil water retentivity and conductivity. A field observation was conducted to verify the model accuracy. The temporal and spatial changes of volumetric water content and NO_3–N concentration in soil were measured in a 1 m×1 m×1 m lysimeter where NH_4NO_3 solution was supplied in a row. The results of simulation calculated by the model had good agreement with observed data. By using the model, temporal and spatial variations of soil water content and NO_3–N concentration were calculated. The results described the simultaneous movement of water and NO_3–N spreading in a soil profile. The numerical model introduced here can be effective to estimate the variations of water and NO_3–N in soil. This model can contribute to the prevention of groundwater contamination by NO_3–N, and to plan proper fertilizer application in drip irrigation fields.

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