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Modelling of nitrogen dynamics in the subsurface environment

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Abstract This paper presents a physically-based model (RISK-N) to simulate nitrogen cycling in soils, and nitrate transport and fate in soils and groundwater. The soil is separated into upper-root, lower-root, sub-drainfield, and intermediate vadose zones, each with uniform properties. Transport in each soil zone is modelled on the basis of complete mixing, by spatially averaging the related partial differential equation. Transport in the aquifer, however, is modelled using a two-dimensional advection-dispersion equation.

INTRODUCTION

Models describing nitrogen cycling within the soil environment are both numerous and diverse, ranging from simple leaching equations to complex mechanistic models. However, there have been few attempts at linking the unsaturated and saturated zones in N modelling (Canter, 1997). Models that have been developed to simulate the complete system are numerically-based, and require a large amount input data.

This paper describes a physically-based, analytical nitrate transport model which simulates both the vadose and groundwater zones, with fewer input parameters and greater ease-of-use than any currently available models simulating the complete system. This is the first development of a physically-based model having the capability of simulating both irrigated agriculture and septic tank systems underlying turfgrass areas. The latter is especially important because no physically-based nitrogen cycling models have been developed to simulate the combined effect of septic tanks and turfgrass found in suburban settings. This new nitrogen cycling and nitrate transport model, known as RISK-N, is based on the pesticide fate and transport model described by Hantush & Mariño (1996).

MODEL DEVELOPMENT

In simulating N processes, the RISK-N model separates the unsaturated soil into the upper-root, lower-root, sub-drainfield, and intermediate-vadose zones (Fig. 1). Volatilization, mineralization/immobilization, and nitrification occur predominantly in the top 0.3 m of soil, while roots may extend much deeper, so the root depth is divided

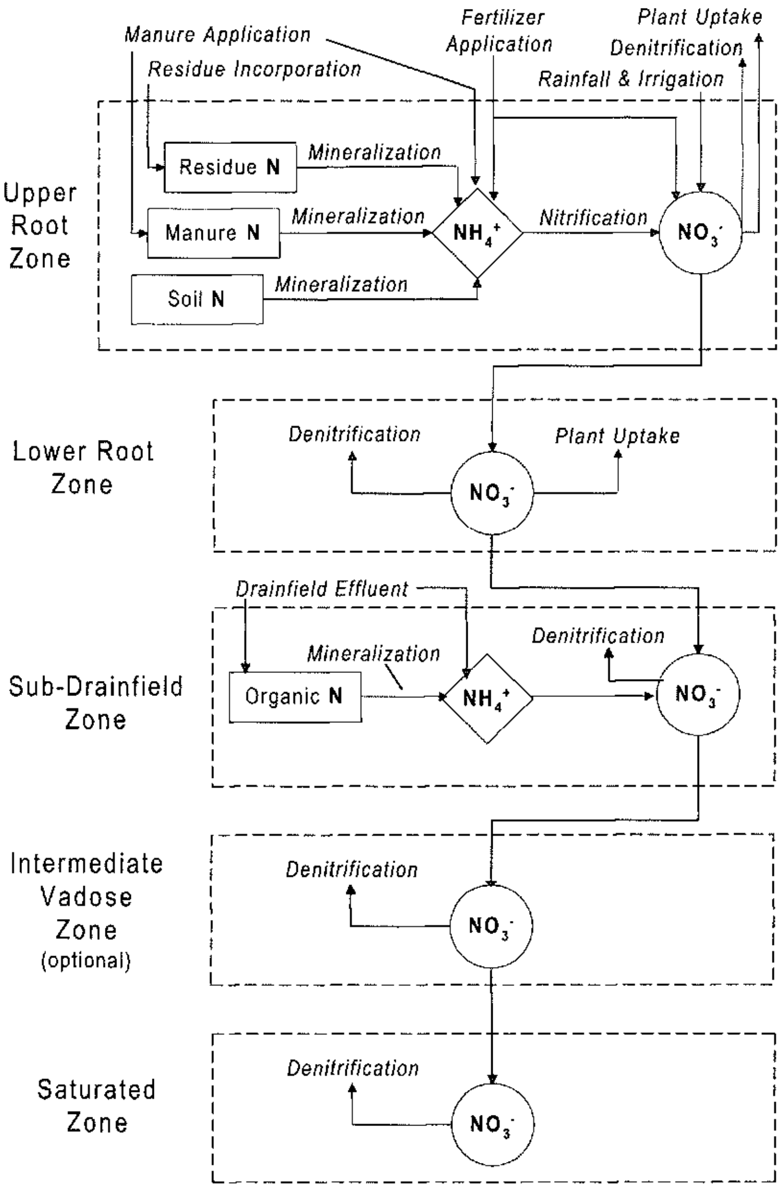

Fig. 1 RISK-N model schematic showing unsaturated and saturated zones.

into the upper- and lower-root zones. The sub-drainfield zone is an optional soil compartment used in modelling N additions from septic system drainfields.

Transport in the unsaturated soil zones is based on complete mixing of N concentrations, which is accomplished by averaging the N convective-dispersive partial differential equations. Nitrogen processes simulated by the RISK-N model include mineralization of three types of organic N, ammonium adsorption (linear, instantaneous equilibrium isotherm), ammonia volatilization, nitrification, denitrification, plant uptake, and leaching. Nitrogen additions to the soil may be in the form of crop residue, manure, mineral fertilizer, or septic system effluent. Nitrogen may also be contributed through rainfall, irrigation, or dry deposition.

For nitrate transport in groundwater, the assumption of complete mixing is not used. Instead, the two-dimensional convective-dispersive equation is solved analytically (Hantush *et al.*, 1996). Nitrate fate and transport in the saturated zone is also affected by diffusion, dispersion, and denitrification.

Soil organic N

In the RISK-N model, soil organic N is conceptually divided into active and passive fractions (Rauschkolb & Hornsby, 1994). The active fraction includes organic N undergoing mineralization, and is divided into slow and rapid mineralization fractions. Recent additions of manure and residue containing organic N comprise the rapidly-mineralized N fraction. The slow fraction is made up of resident soil N still mineralizing, as well as the remaining organic N from past manure and residue applications.

Nitrogen additions

For agricultural applications, the RISK-N model allows the user to specify additions of manure, crop residue, and chemical fertilizer. When manure is applied, RISK-N assumes that it contains 50% urea and 50% organic N (Bouldin *et al.*, 1984). Following Dendooven *et al.* (1990) for crop residue inputs, 50% of the residue N is placed into the rapidly-mineralized fraction, and 45% into the slow fraction; the remaining 5% is not mineralizable.

When chemical fertilizers are applied, the user inputs the amounts of ammonium, nitrate, and urea applied to the soil/crop system. Fertilizer mass is applied instantaneously to the soil, using a Dirac-delta function, with no allowance made for the dissolution of solid fertilizer (Lafolie, 1991). In RISK-N, fertilizer used on turfgrass is applied in the same manner as agricultural fertilizer applications. Nitrogen added through septic tank systems is calculated by the model given user-supplied inputs of per capita septic tank flow, average lot size, and the number of persons per household.

Mineralization

According to Stanford & Epstein (1973), the rate of soil N mineralization is proportional to the availability of potentially-mineralizable soil N. In other words, mineralization is well-described by a first-order rate equation. Most models use first-order rates (de Willigen, 1991), and the RISK-N model uses the same approach. Mineralization rates for the rapid and slow organic N fractions are calculated by the model as a function of user-supplied values for field capacity and seasonal soil temperature and water content data.

Nitrification

A first-order rate is used in the RISK-N model to simulate nitrification. Unless the user supplies seasonal values for the nitrification rate constant, the model uses a default value of $k = 1$ day^{-1}, which is an average of rates found in the literature (e.g. Lafolie, 1991).

Denitrification

The reduction of nitrate to dinitrogen (N_2) gas by a variety of heterotrophic bacteria is known as denitrification, and is one of the main mechanisms (plant uptake is the other) in reducing the nitrate available for leaching. Once nitrate moves below the root zone, denitrification is the only major loss mechanism For the RISK-N model, rates of denitrification may either be calculated by the model or supplied by the user. The method for determining the seasonal denitrification rate coefficients in the unsaturated zones is taken from the CropSyst model, as described in Marchetti *et al.* (1997).

Plant nitrogen uptake

Our primary concern in developing the RISK-N model is the leaching of nitrate over a season, not the specific mechanisms of N uptake, root and shoot N dynamics, and plant growth. As a result, RISK-N is not designed to predict N uptake rates. Instead, the user must supply crop N uptake data or use data found in the literature (e.g. Power & Broadbent, 1989; Rauschkolb & Hornsby, 1994). Broadbent (1984) found that rates of N uptake ranged from 0.5 to 2.0 kg ha^{-1} day^{-1} for numerous combinations of crops, soil types, and locations.

Nitrate transport in groundwater

According to Kelly *et al.* (1991), there have been few applications of analytical dispersion models to nonpoint sources. The RISK-N model uses the convective-dispersive equation with one main groundwater flow direction and two-dimensional hydrodynamic dispersion. Denitrification is the only loss mechanism for nitrate in the saturated zone, while dispersion and diffusion act to spread the nitrate mass entering from the unsaturated soil. Input to the RISK-N model includes the average Darcy velocity of the groundwater, the first-order denitrification rate, dispersivities and diffusion constant, and the depth of nitrate mixing in the aquifer.

MODEL APPLICATIONS

Two example problems were used to demonstrate and validate the use of the RISK-N model: (a) an irrigated and fertilized corn plot, and (b) a suburban area with septic tank systems and fertilized turfgrass. Model results for the two example problems are not provided herein due to space limitations, but are available from the authors.

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REFERENCES

Bouldin, D. R., Klausner, S. D. & Reid, W. S. (1984) Use of nitrogen from manure. In: *Nitrogen in Crop Production* (ed. by R. D. Hauck), 221–245. Soil Sci. Soc. Am., Madison, Wisconsin, USA.

Broadbent, F. E. (1984) Plant use of soil nitrogen. In: *Nitrogen in Crop Production* (ed. by R. D. Hauck), 171 182. Soil Sci. Soc. Am., Madison, Wisconsin, USA.

Canter, L. W. (1997) *Nitrates in Groundwater*. CRC Press, Boca Raton, Florida, USA.

Dendooven, L., Vanlauwe, B., Merckx, R. & Vlassak, K. (1990) Simulation of N-mineralization from crop-residues. In: *Fertilization and the Environment* (ed. by R. Merckx), 60–71. Leuven University Press, Leuven, Belgium.

De Willigen, P. (1991) Nitrogen turnover in the soil-crop system:.

comparison of fourteen simulation models. *Fertilizer Res.* **27**, 141–149.

Hantush, M. M. & Mariño, M. A. (1996) An analytical model for the assessment of pesticide exposure levels in soils and groundwater. *Environ. Modelling and Assessment* **1**, 263 276.

Hantush, M. M., Mariño, M. A. & Shumway, R. H. (1996) Modeling and stochastic analysis of contaminant transport in soils and aquifers. Technical Completion Report. Water Resources Center Project W-832. Univ. California, Davis, California, USA.

Kelly, W. E., Curtis, B. & Adelman, D. (1991) Nitrate ground-water modeling for agricultural and other nonpoint sources. In: *Nitrate Contamination* (ed. by I. Bogárdi & R. D. Kuzelka), 181–198. Springer-Verlag, Berlin, Germany.

Lafolie, F. (1991) Modelling water flow, nitrogen transport and root uptake including physical non-equilibrium and optimization of the root water potential. *Fertilizer Res.* **27**, 215–231.

Marchetti, R., Donatelli, M. & Spallacci, P. (1997) Testing denitrification functions of dynamic crop models. *J. Environ. Qual.* **26**, 394–401.

Power, J. F. & Broadbent, F. E. (1989) Proper accounting for N in cropping systems. In: *Nitrogen Management and Ground Water Protection* (ed. by R. F. Follet), 159–181. Elsevier, New York, USA.

Rauschkolb, R. S. & Hornsby, A. G. (1994) *Nitrogen Management in Irrigated Agriculture*. Oxford University Press, New York, USA.

Stanford, G. & Epstein, E. (1973) Nitrogen mineralization-water relations in soils. *Soil Sci. Soc. Am. Proc.* **38**, 103–106.