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Modelling corn rooting patterns and their effects on water uptake and nitrate leaching

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Abstract

Water and nitrogen absorption by corn (*Zea mays* L.) are partly determined by the region in the soil containing roots and, as a result, rooting patterns could change water availability and leaching of nitrates. A two-dimensional model of corn root growth was developed and linked to a two-dimensional model for water, heat and solute transport in soil. The model was calibrated with root distribution and soil environment data obtained in a Mollisol at Lamberton, MN. Changing the root growth parameters allowed the model to be used to compare water uptake and NO_3 leaching between a shallow, dense root system and a deep, sparse root system. For the rainfall conditions used in model validation, the model predicted a small amount of water absorption from lower in the soil profile with the deep, sparse root system compared with the shallow root system, but that most of the water for transpiration would come from shallow depths directly below the plant. Nitrate leaching was almost identical for both root systems. However, the model predicted reduced downward movement of N when plant uptake of water occurred than with no plant water uptake. The bulk volume of soil explored by the root system may be more important for determining water availability and possible plant water stress during dry periods than for decreasing fertilizer or pesticide leaching. The model should be useful for other examinations of water and chemical movement in the soil by including the effects of the plant in the system. The model also allows at least a preliminary examination of soil management effects on water and nutrient availability.

Introduction

Row crops like corn (*Zea mays* L.) have a two-dimensional rooting pattern when viewed perpendicular to the row, with greater root density beneath the row than beneath the interrow. This rooting pattern translates into a water uptake pattern that corresponds to the root distribution and two-dimensional water movement. Field studies by Timlin et al. (1992) showed water potential gradients perpendicular to the row under soybean (*Glycine max* (L.) Merr.) and corn with drier soil immediately below the plant than in the interrow. The root systems also affected chemical distributions resulting in less leaching of strontium bromide directly below the plants than in the interrows. In addition, row-crop management practices such as ridge tillage and wheel traffic (Benjamin et al., 1990a), or furrow irrigation (Kemper et al., 1975) can induce a two-dimensional pattern of water, heat and/or chemical transport within the soil. Allmaras and Nelson (1971) demonstrated that tillage and crop residue management can affect the two-dimensional distribution of roots for corn and soybeans.

Ground water quality has been reduced by leaching of agricultural chemicals from the root zone. The public desire for improvements of ground water quality provides an incentive to explore the possible reduction of leaching by changing the rooting patterns of crops through genetic manipulation (plant breeding) or through soil management. One-dimensional models (Jones and Kiniry, 1986; United States Department of Agriculture, 1995) are often adequate for such studies. However, two-dimensional models are needed for

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intensive examinations of soil and crop management effects such as band vs. broadcast fertilizer or pesticide applications or wheel traffic and ridge tillage. Two-dimensional models have been used to predict crop management effects on chemical leaching in the root zone in irrigated (Benjamin et al., 1994) and rainfed (Hamlett et al., 1987) agricultural systems, but most modelling efforts have largely ignored the effect of the plant on such movement. Models of different rooting patterns and their effects on water and chemical movement can be convenient and powerful tools for such explorations. The objective of this study was to develop a two-dimensional model of the corn root system and to use the model to show possible effects of change in root distribution and root density on water and nitrate movement in soil.

Model description

The two-dimensional water, heat and chemical transport model, CHAIN-2D (Simunek and van Genuchten, 1994) was used as the soil environment model. It uses finite element solutions of Richards equation for water transport, the convective-dispersion equation for chemical transport, and the thermal conductivity equation for heat transport. The original model used the approach of Chung and Horton (1987) to determine the water-content-dependent thermal properties. We modified the thermal conductivity calculation to use the approach of De Vries (1966) as also used in the Benjamin et al. (1992b) model to simplify the input data required for the determination of thermal properties.

Various submodels were added to the CHAIN-2D model to calculate fluxes for the boundary conditions from more general weather and plant growth data. Total potential evapotranspiration (PET) in mm was calculated as in the Ritchie (1972) model by

$$PET = 1.28((R_s(1 - al))/24.4)(\delta/\delta + 0.68) \quad (1)$$

where R_s, is the daily solar radiation (kJ m^{-2}), al is the albedo, and δ is the slope of the saturation vapor pressure curve at the mean air temperature.

PET is separated into potential evaporation (PE) and potential transpiration (PT) with the empirical functions presented by Villalobos and Feneres (1990)

$$PE = PET exp(-0.41 LAI) \quad (2)$$

$$PT = 1.07 PET(1 - exp(-.52 LAI) \quad (3)$$

where LAI is the leaf area index. Evaporation and heat fluxes on the soil surface are then calculated from the energy balance model of van Bavel and Hillel (1976). To solve for the surface soil temperature needed in the energy balance model, we used the method of Bristow (1987) which employs a Newton iteration scheme. The surface boundary condition also requires an estimate of LAI. We used the empirical approach of Flesch and Dale (1987) to determine aerial growth of the corn plant through the growing season. They based the aerial development of the corn canopy on a normalized thermal crop calendar (NC), which is set at 0 for planting, 0.5 for silking, and 1.0 for physiological maturity. During the growing season, NC is determined from the modifed growing degree days (MGGD) for the hybrid as

$$NC = \Sigma MGDD_t / \Sigma MGDD_m \quad (4)$$

where $\Sigma MGDD_t$ is the cumulative MGDD at time t and $\Sigma MGDD_m$ is the cumulative MGDD at maturity. Seasonal growth of the corn crop is divided into three growth stages, stage 1 from planting to silking (NC from 0 to 0.5), stage 2 from silking to start of rapid senescence (NC from 0.5 to 0.9), and stage 3 rapid senescence (NC > 0.9). The following equations were used by Flesch and Dale (1987) to describe leaf area index (LAI) through the growing season. The LAI during growth stage 1 is calculated by

$$LAI = LA_{max}(POP/10)/\{1 + [(LA_{max}/0.01)exp[-HYB_b NC)\} \quad (5)$$

where LA_{max} is the maximum leaf area per plant for the hybrid, POP is the plant population (thousands of plants ha^{-1}), and HYB_b is an empirical growth coefficient. LA_{max} is calculated from the plant population and a hybrid-dependant growth factor, HYB_L by

$$LA_{max} = -0.0019 POP + HYB_L \quad (6)$$

The decline of LAI during stage 2 is calculated by

$$LAI = LAI_1 - HYB_{DEC}(NC - 0.5) \quad (7)$$

where LAI_1 is the LAI at the end of stage 1 and HYB_{DEC} is a decline factor. A rapid decline of LAI as the plant reaches stage 3 is calculated by

$$LAI = LAI_2 - 0.15D \quad (8)$$

where LAI_2 is the LAI at the end of stage 2 and D is the number of days since the start of stage 3.

We developed a simple root growth model to determine the soil volume from which the root system can extract water and chemicals. Our interpretation of photographs (Foth, 1962; Miller, 1916) and line drawings (Kiesselbach, 1949; Weaver, 1926; Weihing, 1935) of corn root systems during the growing season was that, as the root system develops, there is a change from a primarily horizontal growth direction early in the life cycle to a primarily vertical growth direction for later stages in the life cycle. We generalized these data to delineate a region to the left and right, as viewed along the center of the plant row, and downward in which root growth may potentially occur. The size of the region is defined by the extension rate of the root system (γ) and the growth angle (ϕ) from the horizontal. The horizontal extension of the root region is assumed to progress by

$$X - X_p + \gamma cos(\phi)\Delta t \qquad (9)$$

where X is the new horizontal limit of the root zone (m), X_p is the previous horizontal limit of the root zone (m), and Δt is the time increment (d). The zones of potential root growth are assumed to be symmetric to the left and right of the plant. The vertical extension of the root system is assumed to progress by

$$Z = Z_p + \gamma sin(\phi)\Delta t \qquad (10)$$

where Z is the new vertical limit of the root zone (m) and Z_p is the previous vertical limit of the root zone (m). Values for the coefficients γ (m/d) and ϕ (degrees) are dependent on the corn hybrid and the age of the plant. Equations 9 and 10 define an expanding zone under the row in which root growth can occur and roots can extract water and nutrients. As the zone enlarges, it will encompass an inceasing number of nodes in the finite element mesh used for the CHAIN-2D model.

We assumed that root growth followed characteristics of first order population dynamics (Boyce and DiPrima, 1977). The change in root density for a given position in the root zone is determined by

$$dR_d/dt = \epsilon R_d - \sigma R_d^2 \qquad (11)$$

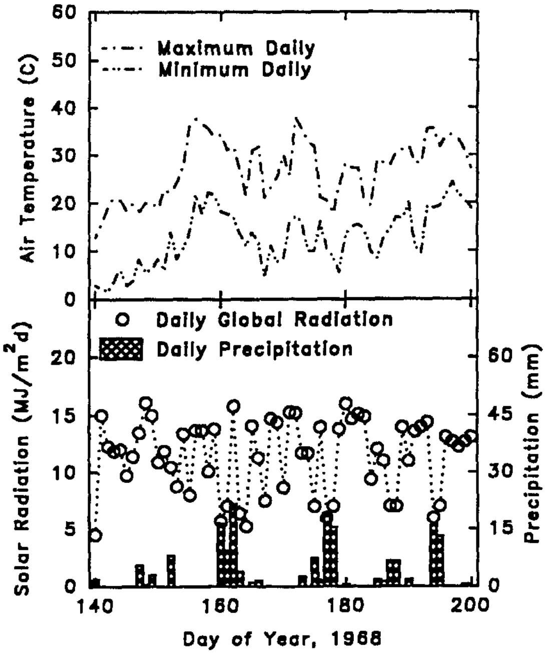

Figure 1. Weather condiions during 60 d period for corn root growth at Lamberton, MN, 1968.

where R_d is the root density at a given time, ϵ is the proliferation rate, and σ is the root death rate. The first term on the right side of Equation 11 is similar to the expression used by Bar-Yosef and Lambert (1981) to describe the total length of roots for corn and cotton early in the plant life cycle. The second term on the right side of 11 is included to characterize root death. The ϵ is estimated from the proliferation rate for non-limiting soil conditions, ϵ_o, and limitations to proliferation caused by the soil environment. Mengel and Barber (1974) found that the corn root density increased rapidly during the vegetative growth period, was relatively constant for about a 2-week period after tasseling, and then decreased rapidly as the plant approached scenesence. In our model, ϵ_o is equated to the maximum root proliferation rate during vegetative growth, ϵ_{max}, until silking and decreases linearly to 0 at maturity. We translated the root proliferation pattern to the NC of vegetative growth as:

$$\begin{aligned} \epsilon_o &= \epsilon_{max} for NC < 0.5 \qquad (12)\\ \epsilon_o &= \epsilon_{max} - (NC - 0.5)(\epsilon_{max}/0.4)\\ &\quad for 0.5 < NC < 0.9\\ \epsilon_o &= 0 for NC > 0.9 \end{aligned}$$

Soil environment effects on root density

An approach similar to that employed by Jones et al. (1991) is used to approximate the response of root proliferation to the soil environment. They described a method to calculate the relative suitability for root growth in soil layers. We extended this concept for a

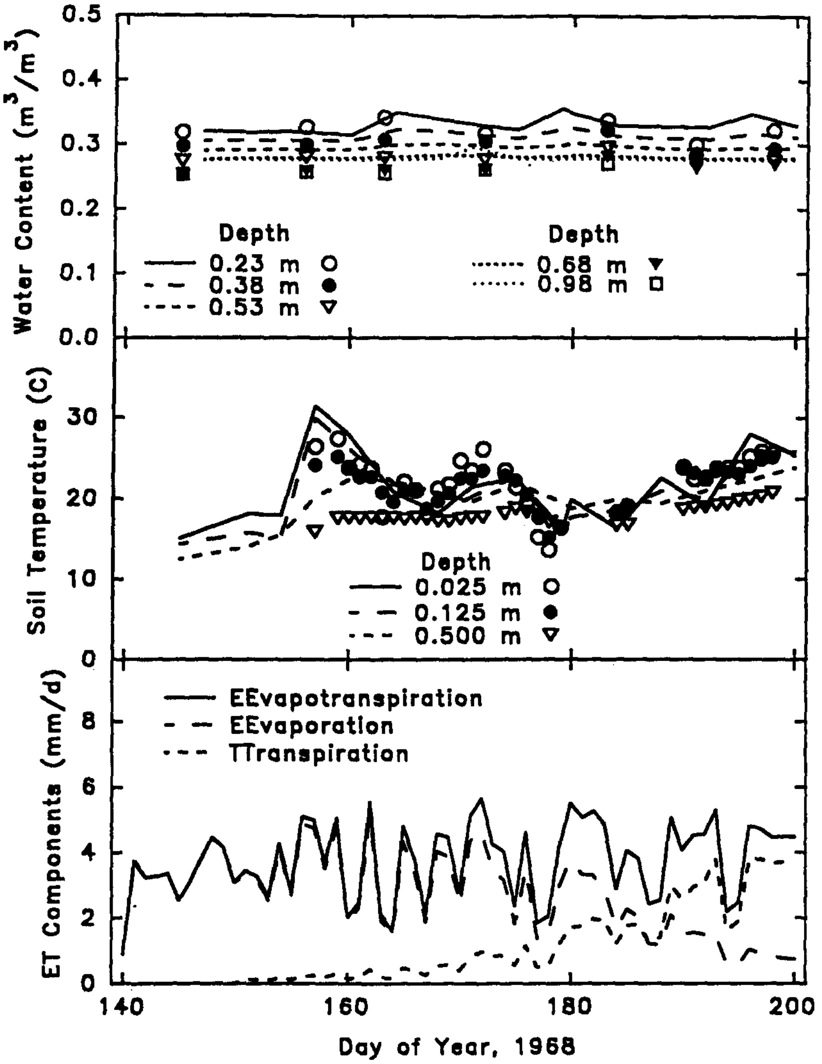

Figure 2. Measured (symbol) and predicted (line) water contents, temperatures, and predicted evapotranspiration components during the 60 d period for corn root growth at Lamberton, MN, 1968.

two-dimensional soil region. Restrictions to root proliferation are calculated from the positional soil temperature, water content and bulk density.

The limitation of soil temperature on root growth, R_T, is determined by

$$R_T = \sin \pi/2(T - T_{min})/(T_{opt} - T_{min}) \qquad (13)$$

where T is the positional soil temperature, T_{min} is the minimum temperature for root growth, and T_{opt} is the optimum temperature for maximum root growth. For this model T_{opt} is set at 25°C and T_{min} is set at 10°C.

As in the Jones et al. (1991) model, bulk density (ρ_b) and water content (θ) are combined to estimate the root restrictions caused by water and soil strength. The optimum bulk density for root growth and the bulk density that limits root growth are determined from the volumetric sand content of the soil. Restriction of root proliferation caused by θ is determined from a linear difference between the drained upper limit water content defined as θ at -10 kPa ψ and the lower limit water content defined as θ at -1500 kPa ψ with ψ being the soil water matric potential. The total restriction of root proliferation, R_{wp}, caused by θ and ρ_b is

$$R_{wp} = R_w^{1/2} R_{\rho b} \qquad (14)$$

with R_w being the restriction to rooting caused by water content and $R_{\rho b}$ being the root restriction caused by

Table 1. Positional bulk density (ρ_p), van Genuchten coefficients of the water retention (α, n), saturated hydraulic conductivity (K_s), and residual water content (Θ_r used in the simulation of corn root growth[a]

Depth (m)	ρ_b (Mg m^{-3})	α (1 mm^{-1})	n -	K_s (mm d^{-1})	Θ_r (m^3 m^{-3})
0-0.3	1.38	0.01	1.15	240	0.05
0.3-0.6	1.48	0.01	1.17	240	0.05
0.6-0.9	1.57	0.01	1.17	240	0.05
0.9-2.0	1.70	0.01	1.13	240	0.05

[a] Corn root growth in a Normania clay loam (fine loamy, mixed, mesic, aquic Haplustols) located near Lamberton, MN (44.2°, 95.8° W), 1968. The soil was formerly classified as a Nicollet clay loam (fine loamy, mixed mesic, aquic Hapludols).

Table 2. Coefficients used in the corn root growth model and designated to change during the growing season[a]

NC	γ (mm/d^{-1})	ϕ (degrees)	ϵ_o	σ
0-0.1	20	20	0.20	0.02
0.1-0.25	20	45	0.20	0.02
0.25-0.4	20	70	0.20	0.02
0.4-0.5	20	90	0.20	0.02
0.5-0.9	0	90	see Eq. 4	0.02
0.9-1.0	0	90	0.0	0.02

[a] NC denotes the normalized thermal crop calender (0.0 = planting, 0.5 = skiing, 1.0 = physiological maturity); γ ϕ ϵ_o and σ are defined in Equations 9, 10, and 11.

bulk density. For each position in the soil, ϵ is determined from ϵ_o and the most restrictive soil environmental condition by

$$\epsilon = \epsilon_o \min(R_T, R_{wp}) \qquad (15)$$

Root water and chemical uptake

Water uptake from the root zone is dependent upon the transpiration demand, the soil water status, and the root density within the soil. The finite element mesh constructed for the CHAIN-2D model defines a succession of soil volumes defined by the elements (assuming unit width) and surrounding nodes. No water extraction will occur from elements not included within the root zone. Once a node within the potential root zone is occupied by roots the model assumes water uptake can occur from the elements associated with that node.

The nodes within the root zone are treated as a distribution of point sinks for the finite element solution of Richards equation. Water extraction by the root system is based on an extension of the single root model (Feddes et al., 1974). In an individual element the water extraction is determined by

$$S_e = -2\pi LK(\psi)(\psi_p + d - \psi_s)/ln(r_s/r_r) \qquad (16)$$

where S_e is the elemental water sink, L is the root length in the element, K(ψ) is the elemental hydraulic conductivity, ψ_p is the water potential at the base of the plant, d is the distance from the center of the element to the base of the plant, ψ_s is the elemental soil water potential, r_s is the distance between roots (assuming a uniform root distribution in the element) and r_r is the radius of the individual roots. The elemental water extraction is equally partitioned to the nodes associated with the element. An iterative scheme is used to find the ψ_p such that

$$T = \Sigma S_e \qquad (17)$$

where T is the transpiration demand. The minimum ψ_p is set at −1500 kPa. If Σ S_e is less than T for the minimum ψ_p then T is set to Σ S_e and the plant is under water stress. While some studies (Tardieu,

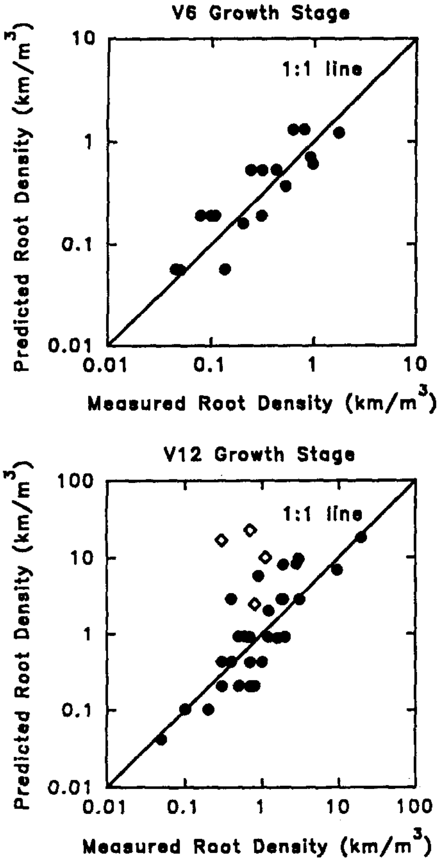

Figure 3. Measured vs. predicted positional root density for the CK treatment (Allmaras et al., 1987) at the V6 and V12 growth stages. The solid line is the 1:1 relationship. The open diamonds for the V12 stage indicate the 0.1 to 0.2 m soil layer and the closed circles indicate all other soil layers.

1988a, b) have shown a spatial variability of the root distribution within a small distance, no generalization of the distribution is attempted here and the roots are assumed to be uniformly distributed within a volume element. As a first approximation of nutrient uptake by the plant, a simple mass flow routine was included to simulate nitrogen uptake. The total nitrate uptake was calculated by

$$T_N = \Sigma C_n S_e \tag{18}$$

where T_N is the total nitrate removed from the soil by the plant and C_n in the nitrate concentration in the soil water.

Model use

The model was used to simulate root growth as presented in the study by Allmaras et al. (1987). The data from the check (CK) tillage treatment in 1968 was selected. A soil region 0.8 m wide and 1.5 m deep was divided into a uniform rectangular grid (431 nodes and 430 elements) with a 25 mm node spacing. The initial water potential was set at -10 kPa and the initial temperature was set at 15°C. The boundary conditions were set as zero flux conditions on the vertical axes, a constant -10 kPa water potential and a constant 15°C temperature on the bottom boundary, and a flux boundary condition on the top boundary with the fluxes across the top boundary controlled by atmospheric conditions.

Weather conditions for the portion of the 1968 growing season used in the model, i.e. the maximum and minimum air temperatures, daily global radiation, and precipitation, are shown in Figure 1. Soil bulk densities for soil layers were measured during the experiment and hydraulic characteristics for different soil layers were derived from paired tensiometer-volumetric water content measurements also measured during the experiment (Table 1). MGGD_m, estimated from the plant growth relationship to MGDD in Allmaras et al. (1987), was set at 1300. Other vegetative plant parameters were unknown for the hybrid (Trojan TXS 102[1]) used so the plant characteristics were set at nominal values in the Flesch and Dale (1987) study as $\mathrm{HYB}_L = 0.88$, $\mathrm{HYB}_b = 5.86$ and $\mathrm{HYB}_{DEC} = 0.67$. The plant population was 45600 plant ha^{-1}. Root growth parameters (Table 2) are based on photographs (Foth, 1962; Miller, 1916) and line drawings (Kiesselbach, 1949; Weaver, 1926; Weihing, 1935) of corn root systems during the growing season that show a change from a primarily horizontal growth direction early in the life cycle to a primarily vertical growth direction for later stages in the life cycle. We estimated ϕ early in the growing season (20 to 30 days after planting) to be from 20° (Weaver, 1926) to 30° (Foth, 1962). Later in the growing season (30 to 60 days after planting), we estimated ϕ to be from 60° (Weaver, 1926) to 75° (Miller, 1916). After silking, we estimated ϕ to be 90° (Foth, 1962; Miller, 1916; Weaver, 1926). Based on the change in root extent from one sampling to the next in the Weaver (1926), Foth (1962) and Miller (1916) studies, we interpreted γ to be approximately 20 to 30 mm d^{-1} for several environmental conditions.

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[1] Trade names do not indicate endorsement by the USDA over similar products and are included for clarity only.

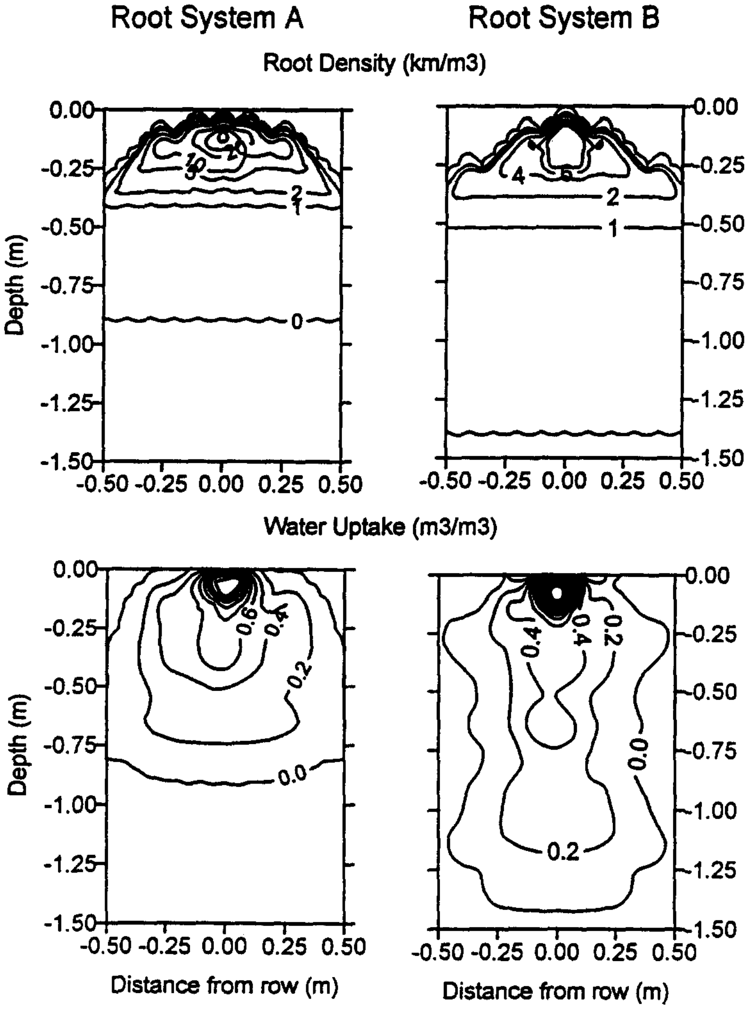

Figure 4. Predicted root distribution and total water uptake after 60 d simulation. Root System A is the root system predicted from the calibration study and Root System B is the deeper, sparser root system.

The model predicted water contents within 0.03 $m^3 m^{-3}$ and soil temperatures within 2 °C of the measurements (Fig. 2). The soil environment for the root growth predictions was similar to the environment used for measured root growth. No direct evaporation or transpiration measurements were taken in the field experiment. The model predicted a change of the partitioning of latent energy between evaporation and transpiration as the crop canopy developed. All of the latent energy was used for evaporation until about day 150, but by the end of the simulation approximately 80% of the latent energy was used for transpiration.

Root length density comparisons between the predicted root density and the measured root density at the same position (depth and lateral distance from the row) relative to the plant row at the V6 and V12 growth stages (Ritchie and Hanway, 1982) are shown in Figure 3. The data were plotted on a log-log scale to expand the scale at the low root densities. At V6 the slope of the regression of log predictions vs. log measurements was 0.85 and the regression coefficient (r^2) was 0.77. At V12, there was a much greater root density predicted in the 0.1 to 0.2 m soil layer (open diamonds) than was observed in the field. Most of the other predicted positional root densities (closed circles) agreed well with the observed values. The low root densities in the 0.1 to 0.2 m layer could have been caused by disease or insect activity that the model does not consider. If all the data are used, the slope of the log-log regression was 1.04 and r^2 was 0.59. If the data from the 0.1 to 0.2

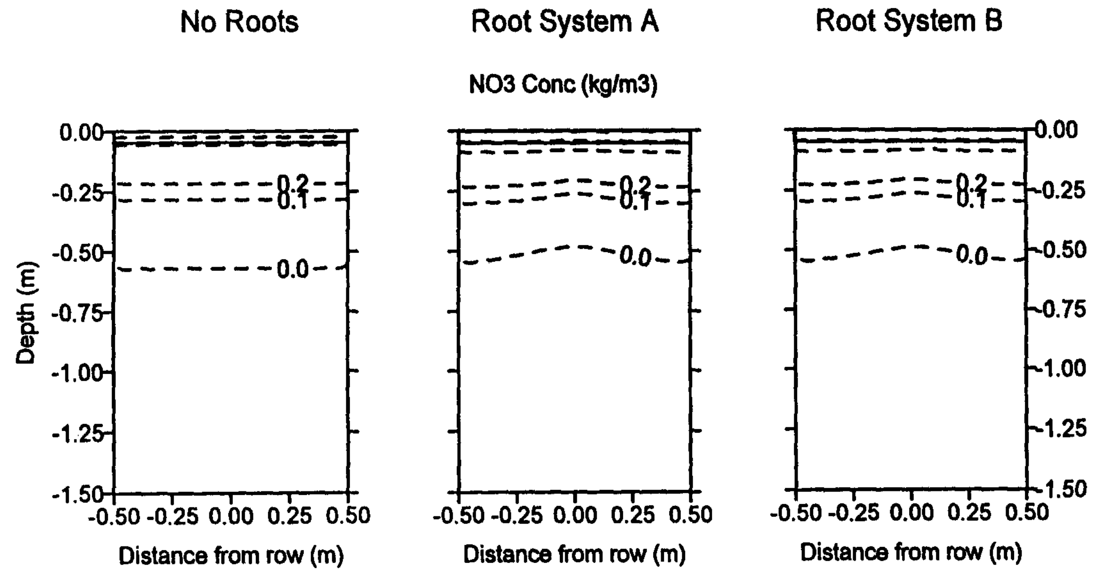

Figure 5. Predicted NO_3^- distribution 60 d after broadcast N fertilizer and planting for 3 cases: corn not planted (no roots), Root System A and Root System B. The initial fertilizer position is shown by the solid line at −0.05 m.

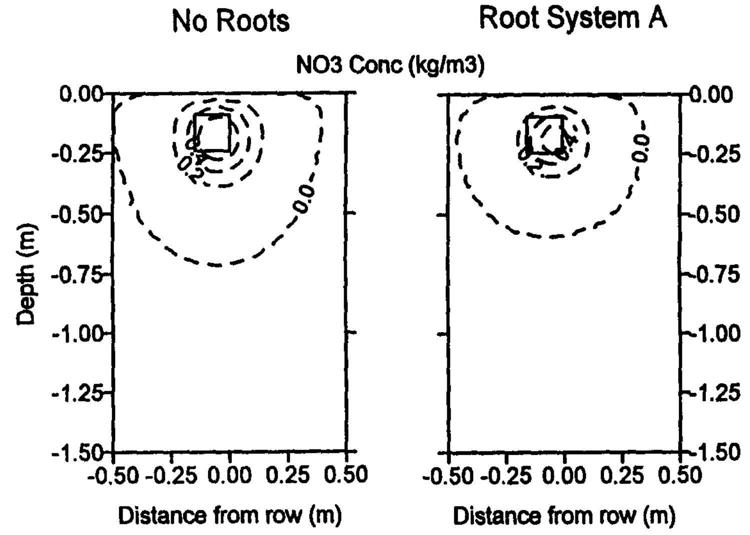

Figure 6. Predicted NO_3^- distribution 60 d after a band-applied N fertilizer for 2 cases: no roots and Root System A. The initial position of the fertilizer is shown by the box at X=−0.1 to 0.0 m and Z = −0.1 to −0.2 m.

m depth are ignored, the slope of the regression was 1.06 and r^2 was 0.78. The maximum root proliferation rate, ϵ_{max}, for this study was 0.2, which was similar to but slightly smaller than the proliferation rate, 0.28, of Bar-Yosef and Lambert (1981) for total corn root systems under non-restrictive soil conditions.

Numerical experiments

The model was used to examine the effects of water uptake by the plant on NO_3^- leaching and by changes of root system depth and density on water uptake and NO_3^- leaching. All initial and boundary conditions such as initial water content and temperature and weather conditions were the same as for the calibration study. Root system A used the same parameters for root growth as in Table 2. A deeper, sparser root system (Root system B) was introduced by changing the extension rate (γ) from 20 to 30 mm d^{-1}, the initial growth angle (ϕ) from 20 to 30°, and the proliferation rate (ϵ_o) from 0.20 to 0.15. Fertilizer in the simulations was set at 630 kg ha^{-1} NO_3^--N (150 kg ha^{-1} N) and was positioned as a broadcast application or in a row band at the start of the simulations. Nitrate in the soil was examined after 60 d.

Root System A (Fig. 4) extended to −0.9 m and had a maximum root density of 45 km m^{-3}. By changing the root growth parameters, Root System B extended to −1.4 m and had a maximum root density of 12 km m^{-3}. For the relatively wet conditions used for the model simulations, the model predicted that Root System B extracted water from deeper depths than Root System A (Fig. 4) but in both cases a large proportion of the water came from directly beneath the plant within the 0-0.2 m depth.

Predicted NO_3^- leaching was less with the plant than without the plant for the broadcast (Fig. 5) and band applications (Fig. 6) caused by increased water extraction from under the plant row and by removal of the NO_3^- from the system. The greatest effects occured near the row. The different water uptake patterns between Root System A and Root System B had little effect on NO_3^- leaching. This effect was consistent when the fertilizer was broadcast (Fig. 5) or band applied (not shown).

Conclusions

The model developed in this paper should be useful for investigating the effects of plant water uptake on water and nitrate movement in the soil. Model predictions showed that water extraction from the soil varied with the extent of root depth and root density and that a large portion of the water needed for transpiration came from a shallow depth directly beneath the plant. The weather conditions used for the simulations were the relatively wet and the possible benefits for a deeper root system may only be apparent for drier conditions or with longer periods between rains. Field experiments in which the soil environment together with the root system resulting from that soil environment would add considerably to our understanding of the plant-soil interaction. Predicted NO_3^- leaching was less when water extraction by the plant was considered than if no plant was included in the soil system. Changing root distributions had less effect on predicted NO_3^- leaching than on the positional water uptake, but, again, this was for wet conditions and could vary under drier conditions.

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