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WHNSIM – a soil nitrogen simulation model for Southern Germany

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Abstract

A one-dimensional deterministic soil nitrogen simulation model (WHNSIM) is presented. With the model the leaching of soil nitrate, its uptake by plant roots and the mineralization of soil organic nitrogen can be simulated. Basic elements of WHNSIM are differential equations that describe soil water, soil heat and soil solute transport. The equations are solved with a fully implicit finite difference method for a variety of boundary and initial conditions. With WHNSIM the soil nitrogen behavior of arable fields for one or more consecutive years can be described. The model has been calibrated for typical site conditions in Southern Germany. The main features of WHNSIM are discussed, some simulation results are also presented. For site conditions of Southern Germany the model appears to perform adequately.

Notation

Symbols not explained in the text were used as follows:

C = nitrate concentration in the soil solution (mg l^{-1})
D = apparent diffusion coefficient (cm^2 day^{-1})
H = total potential of soil water (cm)
K = soil hydraulic conductivity (cm day^{-1})
N = soil or crop nitrogen (kg ha^{-1})
S = sink or source for soil nitrate (mg cm^{-3} day^{-1})
U = soil water extraction rate (cm^3 cm^{-3} day^{-1})
V = soil heat extraction rate (J cm^{-3} day^{-1})
c_v = soil volumetric heat capacity (J cm^{-3} °C^{-1})
c_{vw} = volumetric heat capacity of soil water (J cm^{-3} °C^{-1})
h = soil water tension (cm)
t = time (day)
z = soil depth (cm)
γ = psychrometer coefficient (mbar °C^{-1})
Δ = slope of the relation between the temperature and the saturated (water) vapor pressure (mbar °C^{-1})
λ = soil thermal conductivity (J cm^{-1} day^{-1} °C^{-1})
θ = volumetric water content of soil (cm^3 cm^{-3})

Introduction

Soil nitrogen is of interest as a major crop nutrient, but also as a potential environmental pollutant. As a consequence, knowledge about the behavior of soil nitrogen is desirable in order to optimize plant growth and crop yield, with environmental side effects that are as small as possible. Many aspects of soil nitrogen behavior are conveniently discussed with use of the soil nitrogen budget equation. For a defined period of time (for example a growing season, a calendar year or a crop rotation) this equation for a flat area for a soil profile of arbitrary depth can be written as:

$$F + A + O + R = E + P + G + B \tag{1}$$

in which equation the symbols (units $kg\,ha^{-1}$) are used as follows:

F = amount of applied nitrogen fertilizer
A = atmospheric nitrogen deposition
O = nitrogen fixation by soil organisms
R = nitrogen incorporated into the soil with crop residues
E = crop nitrogen uptake that is stored above the soil surface
P = amount of soil nitrogen leached from the soil profile
G = gaseous nitrogen losses into the atmosphere
B = change of amount of nitrogen that is stored in the soil profile under consideration.

In sloped areas it may be necessary to consider also soil nitrogen losses caused by erosion and surface runoff. However, in the present paper the processes of erosion and surface runoff will not be dealt with.

With reference to eq. 1, agricultural management practices should be such that an optimum value of E is obtained for values of F, P and G that are as small as possible. This, however, is not easily achieved since the interrelationships between the various components of the soil nitrogen budget equation are complex and not fully understood. Soil nitrogen simulation models may help to examine such interrelationships and identify gaps in the knowledge about soil nitrogen behavior. At the same time soil nitrogen simulation models can be used to calculate (or estimate) such components of eq. 1 that cannot, or only with great effort, be measured. To this end WHNSIM (Water, Heat and Nitrogen Simulation) was developed. It combines features of the soil water simulation model of [4], the root nitrogen uptake model of [10], the soil nitrogen mineralization model of [14] and the numerical analysis of [6]. Hence, WHNSIM is primarily constructed for the calculation of deep seepage and nitrate leaching. Therefore, the transport of water and solutes in WHNSIM is treated in great detail, whereas nitrate uptake and crop growth are considered of secondary importance. These quantities, however, are preferably used to evaluate the model performance.

Model description

Transport equations

In the introduction it was mentioned that calibrated soil nitrogen simulation models can be used advantageously to estimate soil nitrate seepage losses. In this respect it is necessary that such models describe the movement of the soil solution. At the same time such models should be able to treat the process of mineralization, which adds nitrate to the soil solution. Since it is well known that soil temperature influences mineralization, it thus is necessary that also soil heat behavior is simulated. For this reason three transport equations build the central part of WHNSIM. They are:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta) \cdot \frac{\partial H}{\partial z}\right] - U \tag{2}$$

for soil water movement,

$$\frac{\partial (c_v \cdot T)}{\partial t} = \frac{\partial}{\partial z}\left(\lambda \cdot \frac{\partial T}{\partial z}\right) - c_{vw} \cdot \frac{\partial (\theta v \cdot T)}{\partial z} - V \tag{3}$$

for soil heat movement, and

$$\frac{\partial (\theta C)}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \cdot \frac{\partial C}{\partial z}\right) - \frac{\partial (\theta v \cdot C)}{\partial z} - S \tag{4}$$

for the movement of nitrate with the soil solution. The used symbols are explained at the beginning of this contribution (Notation).

In eqs. 2–4 the symbols U, V and S are used to denote sinks and sources. In eq. 2 U represents root water uptake, in eq. [3] V denotes (for the sake of completeness) the related uptake of heat. In eq. 4 finally, S symbolizes a sink or a source for nitrate due to mineralization of soil organic matter or manure, immobilization or root nitrogen uptake.

Equations 2, 3 and 4 are solved with a fully implicit finite difference procedure. This procedure requires that the soil profile under consideration is subdivided into a finite number of compartments. The height of the compartments in WHNSIM is kept variable in order that soil profiles of arbitrary depth can be dealt with. The tridiagonal system of linear equations that arises for each of the equations 2–4 are solved with the Thomas algorithm, as described in [13]. With use of a Newton-Raphson procedure [6] a proper water balance is maintained.

Soil parameters

The soil parameters, needed for computational work with eqs. 2–4, can be determined experimentally without exception [9]. However, since the laboratory or field determination of some of these parameters is rather cumbersome, it is sometimes more convenient to estimate such parameters from other soil data. In principle WHNSIM requires original, experimentally determined soil characteristics in tabular form. However, WHNSIM also contains options to derive some of the needed characteristics from other soil parameters. The simulations that were carried out for Southern Germany used measured soil water retention curves and hydraulic conductivities at saturation. The unsaturated hydraulic conductivities, however, were calculated with a method of Millington and Quirk in the modification of Jackson [8]. The volumetric heat capacity c_v and the thermal conductivity λ also were calculated from other soil data, according to formulas described in [3]. Finally, the apparent diffusion coefficient D in WHNSIM was calculated as

$$D = D_m + D_h \tag{5}$$

where D_m is the true diffusion coefficient and D_h is the hydrodynamic dispersion. The parameter D_m was calculated as $D_m = \delta\, D_0$ and the parameter D_h as $D_h = \varepsilon v$, where D_0 is the diffusion coefficient for nitrate in water and v is the pore flow velocity. The quantities δ and ε denote the tortuosity factor and the dispersivity, as discussed in [1] or [17]. The dispersivity ε depends strongly on the degree of aggregation of the soil [17] and can be determined from tracer experiments. The tortuosity δ finally, is calculated in WHNSIM according to

$$\delta = (m/\theta) \cdot e^{n \cdot \theta} \tag{6}$$

where θ is the volumetric water content ($cm^3\, cm^{-3}$) and m and n are constants which, according to [11], can be taken as $m = 0.005$ and $n = 10.0$.

Boundary and initial conditions

Before simulations with eqs. 2–4 can be carried out, boundary and initial conditions must be specified. Theoretically, both conditions can be obtained from field measurements. Frequently, however, the required information is incomplete and substitutes are necessary. This is true for the upper boundary of the soil column under consideration (soil surface) as well as for the lower boundary (some arbitrary depth, usually well below the main rooting zone). The simplest boundary at the lower end of the soil column is encountered when this boundary coincides with a groundwater table at constant depth, with constant temperature and constant nitrate concentration. Usually, however, conditions are not as simple and some judgement has to be made. WHNSIM contains a number of options that deal with this lower boundary as it may occur in the field. It can handle Dirichlet (specification of boundary condition in terms of hydraulic head), Neumann (flux) as well as Cauchy (mixed head and flux) conditions.

The boundary conditions at the soil surface (with respect to eqs. 2–4) usually are not simple either. Especially the condition with respect to soil water movement can be rather complex and is neither easily measured nor formulated. This condition will be dealt with in some detail. First, however, the boundary conditions at the soil surface for heat and solute (nitrate) movement will be discussed briefly. So far, they have been treated rather simply in WHNSIM. As far as heat transport is concerned, either the mean daily temperature of the air above the soil has been used, or a cosine curve is constructed from the maximum and minimum daily temperature. To describe the boundary condition at the soil surface for nitrate transport, also a simple approach has been used so far. For periods without precipitation no nitrate flux is crossing the soil surface. For periods with precipitation (rain), measured nitrate concentrations in the influent are used to define the solute flux. In case of mineral fertilizer application, an equivalent nitrate concentration in subsequent rainwater is calculated. Manure is treated as organic matter, which is subject to mineralization after having been incorporated into the soil.

For the simulation of water movement through the soil, a flux condition at the soil surface is formulated. In this respect WHNSIM follows a previous work as described in [4]. Either infiltration or evaporation occurs. The infiltration rate is calculated from the precipitation rate from which the rate of interception is subtracted. The rate of evaporation, in turn, is calculated as described in [2] and depends on the potential evaporation and on the dryness of the soil near the surface. The potential evaporation E_p is calculated from weather and crop data. Its calculation will be discussed in the next section.

Sinks and sources

In eq. 2 the sink term U denotes root water uptake. In WHNSIM this uptake is considered to be a function of the evaporative demand of the atmosphere, the fine root distribution and the soil dryness in the rooting zone. The daily evaporative demand ET_p of the atmosphere in WHNSIM is estimated with a modified Priestley and Taylor equation [12], which can be given as

$$ET_p = \alpha \cdot \frac{\Delta/\gamma}{\Delta/\gamma + 1} \cdot R_n^* \tag{7}$$

where α is a constant (in WHNSIM $\alpha = 0.860$ for grassland and $\alpha = 0.935$ for other crops), Δ/γ is a temperature-dependent coefficient, see [5], and R_n^* is the equivalent net radiation, in WHNSIM calculated as

$$R_n^* = (1 - \phi) \cdot R_s \tag{8}$$

where ϕ is the albedo of the evaporating surface and R_s is the global radiation. Eq. 7 yields for summer days values for ET_p that are nearly identical with such, calculated with the original Priestley and Taylor equation. For winter days, where some evaporation is observed, the original Priestley and Taylor equation provides frequently negative values for ET_p. With Eq. 7, however, also for such days a positive value for the daily evaporation is calculated. From ET_p of eq. 7 the potential daily transpiration T_p is calculated according to [4] as

$$T_p = ET_p - E_p \tag{9}$$

where E_p is the potential daily evaporation. This potential evaporation E_p in turn is calculated as

$$E_p = (1 - S_C)(ET_p - E_I)\,, \tag{10}$$

with S_C being the soil cover and E_I the eventual evaporation of crop intercepted precipitation. The amount of intercepted precipitation finally is estimated with relations given by [4] as

$$E_I = 0.55 \cdot S_C \cdot P^{0.53-0.0085\cdot(P-5)} \tag{11}$$

for a precipitation rate $P \leqq 17$ mm per day, and by

$$E_I = 1.85 \cdot S_C \tag{12}$$

for $P > 17$ mm per day.

After T_p thus is estimated, the potential daily root water uptake rate U_p at depth z is calculated as

$$U_p = \frac{w}{\int_0^L w \cdot dz} \cdot T_p \tag{13}$$

in which expression $w = w(z, t)$ is the root length density at depth z and L is the maximum rooting depth. From U_p of eq. 13, the actual root water uptake rate U at depth z finally is calculated according to [16] as

$$U = f_1 \cdot U_p \,, \tag{14}$$

where f_1 at depth z is a reduction factor, which depends on the soil water tension h at depth z. The general shape of f_1 as a function of h is shown in Fig. 1. Typical values for $lg\,h_1$, $lg\,h_2$, $lg\,h_3$ and $lg\,h_4$ are 0, 1, 3 and 4.2. However, the used values for h_1, h_2, h_3 and h_4 for different sites and different crops showed a considerable variation. The sinks and sources denoted with S in eq. 4 are not as easily calculated. In WHNSIM five sinks and sources are treated (S_1, S_2 and S_3 for mineralization, S_4 for immobilization and S_5 for root nitrogen uptake. Since in soils from Southern Germany usually little ammonium is found, it is assumed that the process of nitrification is much faster than the process of ammonification. Therefore, WHNSIM does not consider ammonium in the soil solution. Thus the sources S_1, S_2 etc. denote nitrate. The sources S_1, S_2 and S_3 are calculated from the different fractions of soil organic material (very easily mineralized, easily mineralized and not easily mineralized) as recognized by [14]. Mineralization as well as immobilization in WHNSIM is described as a first-order reaction. Hence, if the three fractions of organic matter are denoted as N_1, N_2 and N_3, the change of nitrate concentration in the soil solution due to mineralization can be calculated from

$$\frac{dN_i}{dt} = -k_i \cdot N_i \,, \quad i = 1, 2, 3 \tag{15}$$

where k_i are coefficients, which depend on soil water tension and soil temperature. Similarly, the immobilization rate dN_2/dt is calculated as

$$\frac{dN_2}{dt} = k_4 \cdot (\theta C) \tag{16}$$

Hence, the fraction N_2 at depth z increases (immobilization) whenever $k_4 \cdot (\theta C)$ is larger than $k_2 N_2$. This happens, for example, when large amounts of mineral fertilizer are applied.

WHNSIM calculates the coefficients k_i as function of soil water tension h and temperature T according to [14] and [18] as

$$k_i = f_2 \cdot g_i(T) \,, \quad i = 1, 2, \ldots 4 \tag{17}$$

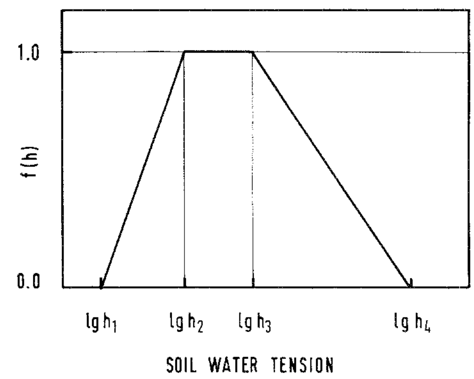

Fig. 1. A schematic representation of the function $f(h)$, used in eqs. 14 and 17.

where f_2, like f_1, is a reduction factor. The general shape of f_2 as a function of h, is also shown in Fig. 1. Typical values for $lg\,h_1$, $lg\,h_2$, $lg\,h_3$ and $lg\,h_4$ in this case are 1, 2, 2.7 and 3.5, but also here the used values for different sites varied considerably. The functions $g_i(T)$ were not considered to be site-specific. In WHNSIM they have the form

$$g_i(T) = K_0^Q \cdot K_{20}^{(1-Q)} \tag{18}$$

in which expression K_0 and K_{20} are reaction coefficients at 0 and 20°C [14]. Table 1 shows the values of K_0 and K_{20} that WHNSIM uses for Southern Germany. It is remarked that g_1 refers to most easily mineralized organic matter, g_2 and g_3 to easily and not easily mineralized organic matter, and g_4 to immobilization with respect to easily mineralized organic matter (fraction N_2). The values of K_0 and K_{20} for g_2 and g_3 are taken from [14], those for g_4 from [15]. The values for K_0 and K_{20} pertaining to g_1 were set (somewhat arbitrarily) five times as high as those for g_2.

The function Q in eq. 18 is derived from data

Table 1. The reaction coefficents K_0 and K_{20} for the description of mineralization and immobilization (see eq. 18)

Function	Reaction coefficients (day^{-1}) K_0	K_{20}
g_1	$7.196 \cdot 10^{-3}$	$8.342 \cdot 10^{-2}$
g_2	$1.439 \cdot 10^{-3}$	$1.668 \cdot 10^{-2}$
g_3	$1.734 \cdot 10^{-4}$	$1.417 \cdot 10^{-3}$
g_4	$3.122 \cdot 10^{-3}$	$2.550 \cdot 10^{-2}$

given by [14]. In WHNSIM Q is expressed as

$$Q = 3999.45/(T + 273) - 13.65 \tag{19}$$

where T is the soil temperature in degrees Celsius at depth z.

To conclude the section on the sources and the sinks that occur in eqs. 2–4, the sink term S_5 (root nitrogen uptake) must be discussed. In WHNSIM root nitrogen uptake is calculated according to a procedure, described by [10], which we slightly modified. The daily uptake of nitrogen (or the change in the amount of nitrogen stored in the crop, expressed in kg ha^{-1} day^{-1}) is denoted as $(dN/dt)_{act}$. It is the sum of convective and diffusive uptake and hence can be written as

$$\left(\frac{dN}{dt}\right)_{act} = \left(\frac{dN}{dt}\right)_{con} + \left(\frac{dN}{dt}\right)_{dif} \tag{20}$$

In WHNSIM care is taken that $(dN/dt)_{act}$ is equal to or less than the potential daily nitrogen uptake $(dN/dt)_{pot}$, defined as

$$\left(\frac{dN}{dt}\right)_{pot} = b \cdot W \cdot Z \cdot (Z_{max} - Z) \tag{21}$$

In eq. 21 the quantity $b \cdot Z \cdot (Z_{max} - Z)$ is a crop-specific time-variable coefficient (units kg nitrogen per kg dry matter of canopy). The quantities Z and Z_{max} (numbers without units) are assigned values that correspond to the instantaneous amount of nitrogen N (kg ha^{-1}) in the canopy and the potential amount of nitrogen N_{max} (kg ha^{-1}), stored in the canopy at the time of harvest. The quantity W in eq. 21 (kg ha^{-1} day^{-1}) denotes the rate of dry matter accumulation and is calculated according to the Bierhuizen and Slatyer procedure as described in [4]. First, the actual amount of daily transpiration T_a is calculated as

$$T_a = \int_0^L U \cdot dz \tag{22}$$

Next, the quantity W is calculated as

$$W = a \cdot \frac{T_a}{\Delta e} \tag{23}$$

where Δe is the mean daily pressure deficit of the air above the canopy and a is another crop-specific constant.

After $(dN/dt)_{pot}$ thus has been estimated, the convective nitrogen uptake (eq. 20) is calculated from

$$\left(\frac{dN}{dt}\right)_{con} = \int_0^L U \cdot C\,dz \tag{24}$$

In case $(dN/dt)_{con}$, as determined with eq. 24, is larger than $(dN/dt)_{pot}$ (eq. 21), $(dN/dt)_{con}$ is reduced and put equal to $(dN/dt)_{pot}$. In this case $(dN/dt)_{dif}$ of eq. 20 is set to zero. In case $(dN/dt)_{con}$ is smaller than $(dN/dt)_{pot}$, a quantity $(dN/dt)_{difpot}$ is calculated as

$$\left(\frac{dN}{dt}\right)_{difpot} = \left(\frac{dN}{dt}\right)_{pot} - \left(\frac{dN}{dt}\right)_{con} \tag{25}$$

This quantity denotes the potential daily nitrogen uptake by diffusion and is considered to be the upper limit for the actual daily nitrogen uptake $(dN/dt)_{dif}$ of eq. 20. This last quantity is calculated in WHNSIM as

$$\left(\frac{dN}{dt}\right)_{\mathrm{dif}} = \int_0^L S_{dif} \cdot dz \tag{26}$$

in which expression S_{dif} is the nitrogen uptake per unit volume of soil. This quantity in turn is calculated as

$$S_{dif} = M(z) \cdot D_m \cdot \frac{C - C_r}{d} \tag{27}$$

with C being the nitrogen (nitrate) concentration in the bulk solution and C_r the concentration at the root surface. The symbol d ($d = 0.1$ mm) represents a characteristic length, which is described by [10]. The quantity $M(z)$ in eq. 27 denotes the total root surface density at depth z, and D_m is the molecular diffusion coefficient for nitrate, that was discussed previously (eq. 5). For $C_r = 0$ a maximum value for S_{dif}, and correspondingly for $(dN/dt)_{dif}$, is calculated. In case $(dN/dt)_{dif}$ is smaller than or equal to $(dN/dt)_{difpot}$ of eq. 25, $(dN/dt)_{dif}$ represents the actual daily nitrogen uptake by diffusion. If, however, $(dN/dt)_{dif}$ is larger than $(dN/dt)_{difpot}$, a new value for C_r is calculated according to

$$C_r = C \cdot (1 - \tau) \quad (28)$$

with τ given as

$$\tau = \frac{\left(\frac{dN}{dt}\right)_{difpot}}{\int_0^L S_{difm} \cdot dz} \quad (29)$$

in which expression S_{difm} represents S_{dif} from eq. 26, calculated for $C_r = 0$. In this respect it is noted that WHNSIM calculates L, w (eq. 13) and M (eq. 27) as functions of the cumulative dry matter production. However, during the growing season these quantities should be measured once or twice so that a calibration is possible. These and other measurements are required in order that meaningful simulations with WHNSIM can be carried out. They will be discussed briefly in the next section.

Some results and data requirements

The model WHNSIM was tested and calibrated with field data collected at Hohenheim and Renningen between 1984 and 1987. At Renningen the soil nitrogen dynamics of a crop rotation (winter wheat, sugar beet, winter wheat, corn) was investigated. At Hohenheim the soil nitrogen behavior of extensively used grassland was studied. Materials and methods are described in detail in Huwe and Van der Ploeg [7]. Among others, soil matric potential, soil temperature and soil nitrate in the soil profile were determined weekly. During the growing season dry matter accumulation, root distribution and nitrogen uptake were determined a number of times. Dates of fertilization and amounts of N-fertilizer were recorded and also the atmospheric input of nitrate (wet deposition) was measured. At Hohenheim as well as at Renningen, an agroclimatic weather station collected regularly a variety of parameters needed in WHNSIM.

Besides the field work at Hohenheim and Renningen, additional soil nitrogen studies were conducted at Öhringen and at Bruchsal. Here, however, the measuring programs were less comprehensive. For example, neither at Öhringen nor at Bruchsal a weather station was located at the research site. Nevertheless, the data collected at Öhringen (1984–1987) and Bruchsal (1988–1989) were also used to evaluate the performance of WHNSIM.

As far as weather data are concerned, WHNSIM is able to process data from the German Weather Bureau, like mean daily temperature, mean daily air humidity, daily hours with bright sunshine and daily sums for global radiation. In case the Weather Bureau cannot provide radiation data, these data can be estimated from other weather data with a method described in [19].

Primary crop data required by WHNSIM are day of emergence and day of harvest. Also crop specific constants, like b and Z_{max} (eq. 21) or a (eq. 23), have to be known. Table 2 shows values for these variables as used by WHNSIM for Southern Germany. Other data, like soil cover and root distribution, are considered as functions of the total amount of dry matter, see also [4]. It is recommended, though, that occassionally during the growing season for which soil nitrogen simulation studies are planned, relevant crop parameters are measured directly.

Substitutes for not directly determined soil parameters were discussed previously. For all sites in Southern Germany for which simulations with WHNSIM were carried out, at least the moisture retention curves and the hydraulic con-

Table 2. Crop-specific constants for Southern Germany, as used in WHNSIM

Crop	Crop constants a $(kg \cdot mbar \cdot mm^{-1} \cdot ha^{-1})$	b –	N_{max} $(kg \cdot ha^{-1})$
Winter wheat	$0.28 \cdot 10^3$	$0.16 \cdot 10^{-5}$	350
Sugar beet	$0.50 \cdot 10^3$	$0.96 \cdot 10^{-6}$	290
Corn	$0.49 \cdot 10^3$	$0.18 \cdot 10^{-5}$	225
Grass	$0.26 \cdot 10^3$	$0.54 \cdot 10^{-5}$	200

ductivities (at saturation) were determined experimentally. Also the organic matter and the nonorganic matter content (especially the quartz content) were determined without exception. It was tried occasionally to determine the various soil organic matter fractions (N_1, N_2 and N_3) from incubation experiments. Usually, however, they were estimated with use of preliminary test runs. To give an impression about the performance of the model, a few comparisons of measured and calculated data will be made. They are shown in Fig. 2 (above-ground dry matter production), Fig. 3 (the corresponding cumulative nitrogen uptake), Fig. 4 (soil temperature) and Fig. 5 (nitrate concentration in the soil solution). To save space, no further comparisons will be presented here. An interested reader may find additional information in [7]. That bulletin, as well as a documented copy of WHNSIM, can be obtained from the senior author on request.

Conclusions

A soil nitrogen model was developed with which the nitrate seepage, the crop nitrogen uptake as

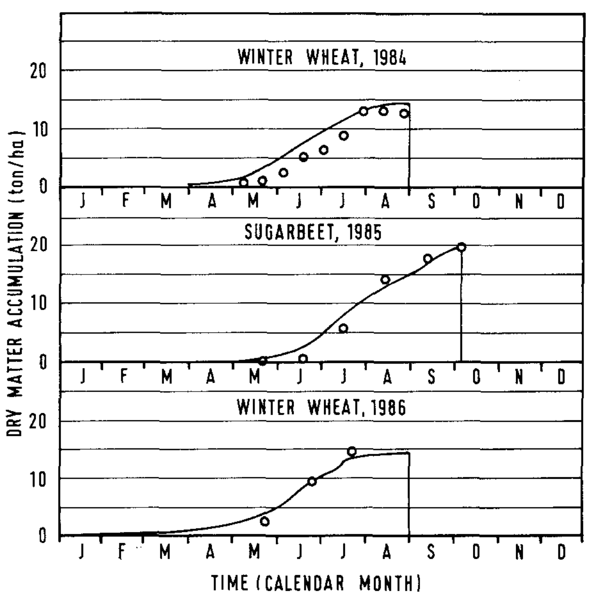

Fig. 2. A comparison of calculated (solid lines) and measured dry matter values for crops in Southern Germany (Renningen): winter wheat (1984), sugar beet (1985) and winter wheat (1986).

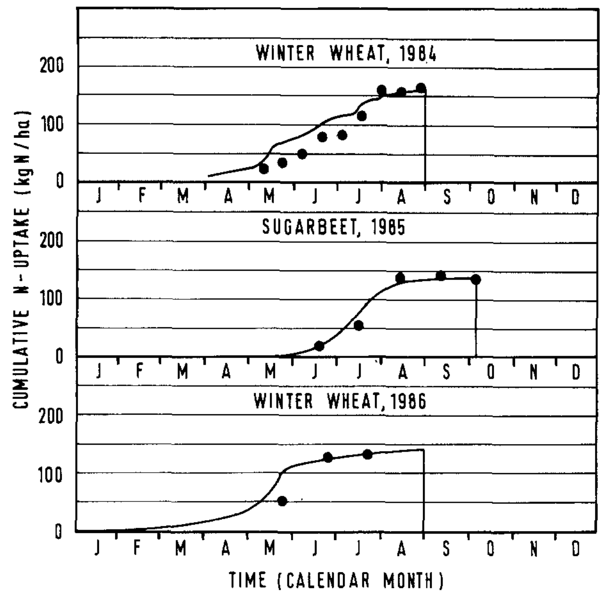

Fig. 3. A comparison of calculated (solid lines) and measured amounts of cumulative nitrogen uptake for the crops dealt with in Fig. 2.

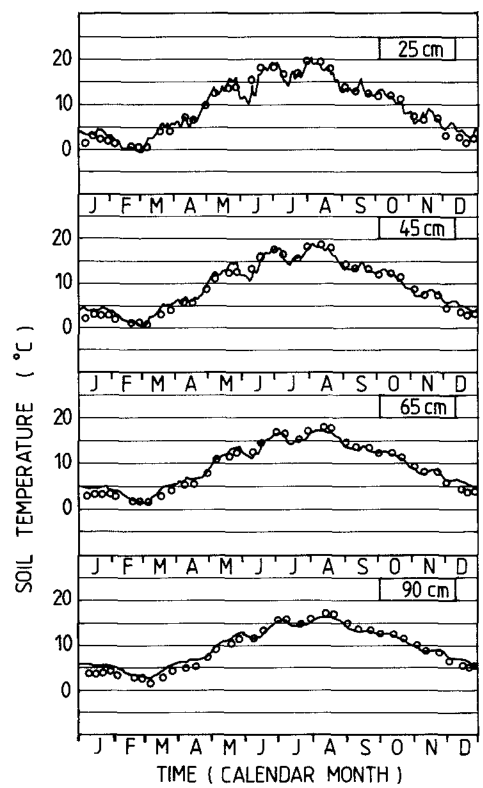

Fig. 4. A comparison of calculated (solid lines) and meassured soil temperatures under grassland (Hohenheim) in 1986.

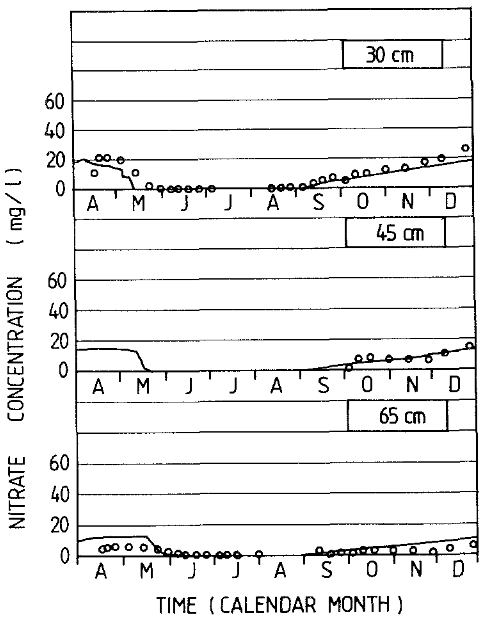

Fig. 5. A comparison of calculated (solid lines) and measured nitrate concentrations in the soil solution under winter wheat in 1984 (Renningen).

well as the mineralization of soil organic matter under field conditions can be simulated. For a number of crops and years, model results were compared with measured data for various sites in Southern Germany. After calibration, which involved mainly the reduction factors for water uptake and mineralization, a fair agreement between measured and simulated data was obtained. Therefore, it is concluded that the model is a valuable tool to describe soil nitrogen behavior of agricultural fields.

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