Plant and Soil **190:** 47–60, 1997.

Is low rooting density of faba beans a cause of high residual nitrate content of soil at harvest ?

Henning Kage
*University of Hannover, Institute for Vegetable Crops, Herrenhaeuser Str. 2, D-30419 Hannover, Germany**

Received 30 May 1996. Accepted in revised form 15 January 1997

Key words: model, nitrate uptake, root length density, *Vicia faba*

Abstract

It was the aim of this study was to evaluate the hypothesis that low rooting density of faba beans is the major reason for the comparable low depletion of N_{min}-nitrogen from the rooted soil volume during the vegetation period. Therefore a simulation study was carried out using data from a two-year field experiment with faba beans and the reference crop oats. Since the nitrate dynamics in the soil is closely coupled with the water budget, the model simulated also the water uptake by plants, movement and content in the soil applying a numerical solution of the Richard's equation. The nitrogen budget part of the model includes calculation of vertical nitrate movement in the soil, mineralisation of nitrate from organic matter and nitrate uptake by the crop. Vertical nitrate movement was simulated with the convection-dispersion equation. Mineralisation was computed from a simple first order kinetic approach using only one fraction of mineralisable organic matter. Nitrate uptake was assumed to be determined either by the nitrogen demand of the crop, which was estimated from a logistic growth equation that was fitted to measured data of N-accumulation, or by the maximum nitrate transport rate towards the root surface. The latter was computed from a steady state solution of the diffusion - mass flow equation for cylindrical co-ordinates.

For oats the model calculated a maximum nitrate transport rate towards roots that was quite close to the measured N-uptake of that crop. For faba beans, however, the calculated maximum nitrate transport towards roots was much lower than total N-uptake and lower than for oats. Consequently, simulated N_{min}-contents below faba beans were during the growing season about 20-30 kg N ha^{-1} higher than below oats. This difference matches quite close with the observed differences between the two crops. Therefore it was concluded that low nitrate uptake resulting from low rooting density is the main reason for higher residual nitrate contents below faba beans at harvest time.

Introduction

The amounts of nitrate nitrogen in the rooted soil below the legume crop faba bean at harvest time are usually much higher than below non-leguminous crops, e.g. cereals (Hauser, 1992; Maidl et al., 1991). Due to the higher amounts of nitrogen and much lower C/N ratio of faba bean straw compared to cereal straw, the N_{min}-content of the soil is further growing during autumn. During the leaching period the nitrate concentration of the soil solution below faba beans therefore often exceeds the allowed level for drinking water in Germany and the European Community (BMG, 1986) and the practicability of growing the break crop faba beans in protected water collection areas is sometimes questioned. In this study the reasons for the comparable low depletion of the N_{min}-content in the rooted soil by faba beans are evaluated.

In a preceding paper (Kage, 1995) the hypothesis was examined that nitrogen fixation activity of faba bean root nodules leads to a suppression of the nitrate uptake activity. In that study it was shown that faba beans reduce their nitrogen fixation activity at very low nitrate concentrations. Thus there appears to be only a small influence of nitrogen fixation on nitrate uptake. It seems therefore unlikely that nitrogen fixation seriously decreases nitrate uptake of faba beans.

* FAX No:+49-511-762-3606.
E-mail:kage@gem.uni-hannover.d400.de

In the present study the hypothesis will be examined that the low rooting density and total root length of faba beans, which is about 1-2 km m^{-2} (Müller, 1984; Reid et al., 1984), may limit the transport of nitrate nitrogen from the bulk soil to the roots and thereby the nitrate uptake capacity of this crop.

Nitrate transport in the soil and towards the roots is accomplished by mass flow and diffusion (Barber, 1962). These processes are physically well defined, and the hypothesis formulated above therefore seemed to be provable with a mathematical model.

Material and methods

Since nitrate transport rate to roots is dependent on the nitrate concentration in the soil, the model had to incorporate all quantitatively important processes that influence the nitrate budget of the rooted soil. The model consequently simulated soil water budget including transpiration, evaporation, water uptake of roots as a function of depth and time and the vertical flow of water in the soil. The second main component of the model is the soil nitrogen budget including: vertical nitrate transport, nitrogen uptake of plants, nitrate transport to the roots by mass flow and diffusion and formation of nitrate nitrogen from soil organic matter. Dry and wet deposition and denitrification on the other hand are assumed to be of lower quantitative importance and may almost compensate each other. So these processes are neglected in the model.

The necessary input parameters were taken from a field experiment conducted in 1982 and 1983 on an experimental site near Göttingen, Germany (Meyer, 1984; Müller, 1984; Müller et al., 1985).

Experimental data

The experiment of Müller et al. (1985) was designed to explore the differences in the soil water and soil nitrogen budget between faba beans and oats. It was conducted in 1982 and 1983 on an experimental field with a loamy, loess derived soil (typical hapludalf) under a conventional tillage system (mouldboard plough) near Göttingen, Germany. The crops were sown on March 19 and March 10 in 1982 and 1983, respectively, with a row width of 14.7 cm for oats and 29.4 cm for faba beans. The previous crop was winter wheat in 1982 and summer wheat in 1983. Nitrogen fertilisation was given to oats only at rates of 30 and 40 kg N ha^{-1} on May 10 1982 and May 20 1983, respectively. Rainfall from May to August was 162 mm in 1982 and 205 mm in 1983, both values less than the long-term average of 264 mm.

Measurements of root length density were carried out weekly with the profile wall method and once during the vegetation period with the monolith method (Böhm, 1979). Owing to the underestimation of root length density by the profile wall method (Köpke, 1979), the data were calibrated to the results of the monolith method using empirical regression equations (Müller, 1984). The interpolated Data of Root length density are shown as a function of time and depth in Figure 1. Soil water contents were measured gravimetrically 2-3 times a week down to a depth of 2 m at 10 cm intervals. The data of hydraulic conductivity as a function of soil water tension were taken from earlier measurements for the same field (Ehlers, 1976, 1977; Opara-Nadi, 1979).

Nitrate contents of the soil were measured in intervals of two weeks down to a depth of 1 m in intervals of 0.2 m. Dry matter production was determined from yields of the above ground biomass in two-week intervals from 0.6 m^2 sub-plots. The nitrogen accumulation then was calculated from the average total nitrogen content of the plant material and the dry matter data.

Model

Soil water balance

Since the soil water balance part of the model is very similar to the models of Feddes et al. (1978) and Duynisveld (1983), only a brief description will be given. For more details the reader is referred to the original papers cited above as well as to Kage (1992).

Vertical water transport in the soil profile is calculated using the water content based formulation of the Richard's equation:

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

where θ s the volumetric water content of the soil, t is the time, z is the depth, $D_w(\theta)$ is the diffusivity of water, k (θ) is the unsaturated hydraulic conductivity and $S(\Psi)$ is the so called sink term which accounts for the water uptake of the roots.

Equation (1) is solved numerically by an implicit finite difference scheme with explicit linearisation (Remson et al., 1971). For this purpose the soil col-

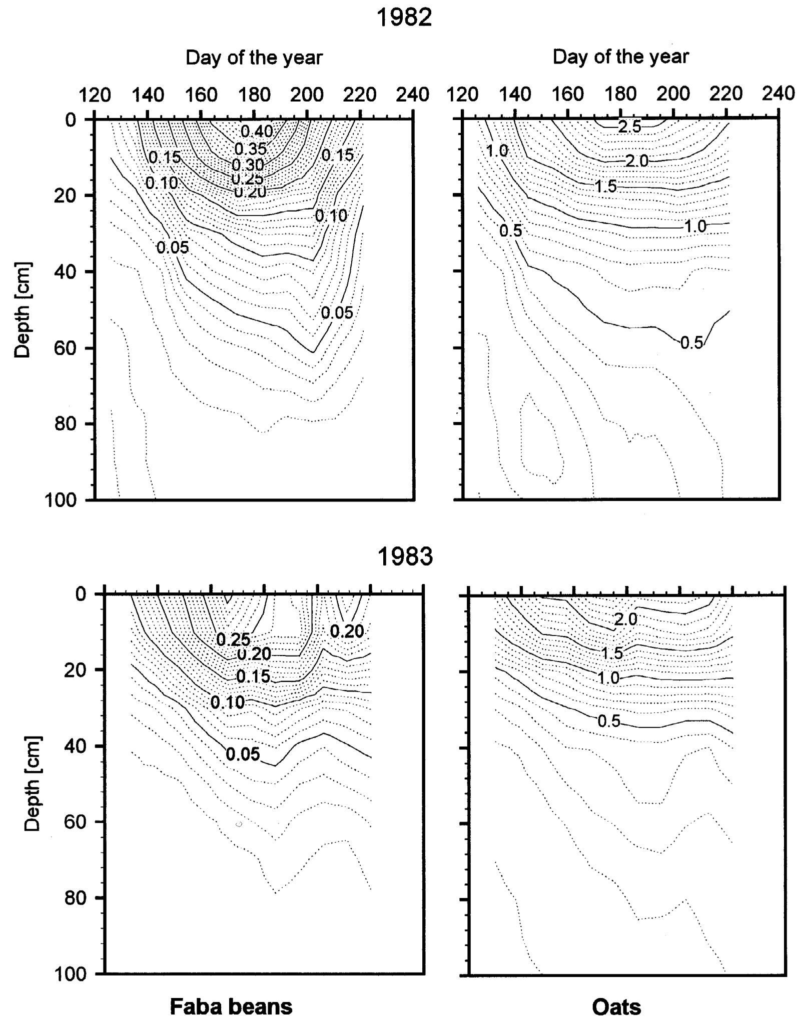

Figure 1. Root length density (cm^3 cm^{-1} of faba beans and oats as a function of depth and time in 1982 and 1983 on Hoffmeisterschlag, Göttingen.

umn was divided into 20 intervals of 10 cm thickness down to a depth of 2 m. For the upper boundary condition of Equation (1) the sum of soil evaporation and precipitation corrected for interception was used. The lower boundary condition was defined through measured or interpolated volumetric water content in 200 cm depth.

The relationships between D_W and θ and k and θ were described using the functions suggested by Van Genuchten (1981) in the revised form of Wösten and Van Genuchten (1988). The necessary parameters for this relationships were estimated with the program RETC (Van Genuchten, unpublished work) using data on hydraulic conductivity vs. soil water tension and soil water content vs. soil water tension (Ehlers, 1976, 1977; Opara-Nadi, 1979) for the different soil layers of the profile (Table 1).

The sink term $S(\Psi)_{,i}$ in the layer i of the finite difference scheme is calculated from a hypothetical maximum sink term $S_{max}(\Psi)_{,i}$ that is defined by the following equation:

$$S_{max,i}(\Psi) = Tr_p \cdot \frac{RD_i^{cf}}{\sum_{i=1}^{i \cdot \Delta z = z_r} RD_i^{cf}} \quad (2)$$

Table 1. Parameters of the Van Genuchten-Mualem equation found by fitting to data on soil water tension vs. soil water content and hydraulic conductivity vs. soil water tension

Depth (cm)	θr ($cm^3\ cm^{-3}$)	θs ($cm^3\ cm^{-3}$)	α (cm^{-1})	n	l ($m\ d^{-1}$)	K_s
0-10	0.0	0.4918	0.0440	1.2635	-4.185	5.76
10-20	0.0	0.4341	0.0130	1.2574	-3.848	1.52
20-30	0.0	0.4292	0.0112	1.2668	-3.780	1.13
30-40	0.0	0.3718	0.0138	1.2453	-2.107	6.54
40-50	0.0	0.3913	0.0161	1.2524	-0.378	22.18
50-70	0.0	0.3917	0.0220	1.2254	-0.202	45.83
70-90	0.0	0.3835	0.0139	1.1494	1.161	68.92
90-110	0.0	0.3822	0.0086	1.1410	2.085	37.30
110-130	0.0	0.4170	0.0290	1.1367	-3.507	76.68
130-160	0.0	0.4192	0.0209	1.1677	-5.578	3.36
160-190	0.0	0.3930	0.0094	1.2205	-3.516	1.00
190-200	0.0	0.3944	0.0053	1.2886	-2.896	0.35

where T_{rp} is the potential transpiration rate, RD_i is the rooting density in the layer i, z_r is the maximum rooting depth, Δz is the thickness of the layers and cf is an empirical factor that accounts for root competition. This factor is set to a value of 0.5 according to the results of Ehlers et al. (1991).

The maximum sink term $S_{max}(\Psi)_{,i}$ is converted to the actual sink term $S(\Psi)_{,i}$ by multiplication with an empirical reduction factor $\alpha(\Psi)$ as described by (Feddes et al., 1978). This factor declines from a value of one at matrix potentials $\geq$ -800 hPa down to zero at 20000 hPa.

Potential evapotranspiration, the sum of interception, potential evaporation and potential transpiration, is calculated according to Van Bavel (1966). The interception rate was determined following an empirical approach (Hoyningen-Huene, 1983), as a function of leaf area index and rainfall intensity. Potential evaporation was calculated from the relationship suggested by Ritchie (1972) and Duynisveld (1983), actual evaporation was determined from an empirical function using potential evaporation and the water potential in 10 cm depth as input parameters (Beese et al., 1978). The potential transpiration at least is then calculated as the remaining part of the potential evapotranspiration after subtracting potential evaporation and interception and taking also into account an empirical crop resistance.

Soil nitrogen balance

Since in well aerated soils the concentration of ammonium compared to the concentration of nitrate is usually very low, only nitrate and organic nitrogen are considered for in the model.

Vertical nitrate transport

Vertical nitrate transport in the soil profile is described by the convection-dispersion equation (Addiscott and Wagenet, 1985):

$$\frac{\partial(\theta C_l)}{\partial t} = \frac{\partial}{\partial z}\left(\theta \cdot D_s \frac{\partial C_l}{\partial z}\right) - \frac{\partial F_w \cdot C_l}{\partial z} - S(z,t) + P_m \quad (3)$$

where C_l is the nitrate concentration of the soil solution, D_s is the apparent dispersion coefficient, F_w is the water flow rate, S(z,t) is the nitrate uptake rate of the roots and P_m is the production rate of nitrate nitrogen from organic matter.

The term D_s is the sum of the dispersion coefficient $D_h(v)$, which is a function of pore water velocity, v, and the effective diffusion coefficient, $D_e(\theta)$, which is a function of the volumetric soil water content (Beese and Wierenga, 1980):

$$D_s = D_h(v) + D_e(\theta) \quad (4)$$

The value of the apparent dispersion coefficient was assumed to be identical with the pore water velocity, v, calculated from volumetric water content, θ, and water flow rate, Fw:

$$D_h = v = \frac{F_w}{\theta} \quad (5)$$

Equation (3) is solved numerically using the Crank-Nicholson procedure (Remson et al., 1971). The same discretisation as Equation (1) is used. The upper boundary condition of Equation (3) is a zero flow rate, for the lower boundary condition a zero gradient in 200 cm depth was assumed. The initial condition was the measured nitrate concentration from 0 to 100 cm. Since no N_{min}-measurements were available for depths below 100 cm, all layers from 100 to 200 cm were initialised with the measured N_{min}-content of the layer 90-100 cm depth.

Nitrate uptake by plant roots

It is assumed that the nitrate uptake by the plant roots UR_{act} is determined either by the nitrogen demand of

Table 2. Parameters Npl_{max} (maximum N-content), Npl_0 (N-content at sowing) and r_g (growth rate parameter) of logistic growth functions estimated from measured data of N-accumulation of Faba beans and oats on Hoffmeisterschlag in 1982 and 1983

Crop	Year	Npl_{max} (kg N ha^{-1})	Npl_0 (kg N ha^{-1})	r_g (d^{-1})
Faba bean	1982	313.03	0.089	0.0880
Faba bean	1983	283.26	0.097	0.0767
Oats	1982	138.62	0.815	0.0700
Oats	1983	154.32	0.382	0.0615

the plants N_{dem} or the maximum nitrate transport rate to the root system UR_{max}:

$$\begin{aligned} UR_{max} < N_{dem}: &\quad UR_{act} = UR_{max} \\ UR_{max} > N_{dem}: &\quad UR_{act} = N_{dem} \end{aligned} \tag{6}$$

Nitrogen demand of plants is derived in a simple empirical way through fitting a logistic growth function (Thornley and Johnson, 1990) to measured data of nitrogen content of the plants at different times:

$$Npl_{(t)} = \frac{Npl_{max} \cdot Npl_o}{Npl_o + (Npl_{max} - Npl_0)e^{-r_g t}} \tag{7}$$

where Npl_{max}, is the maximum N-content accumulated in the plants, Npl_0, the nitrogen content at sowing and r_g is a growth rate parameter. The parameter values found for faba bean and oats in 1982 and 1983 are shown in Table 2.

The derivative of Equation (7) versus time is used as a quantification of the nitrogen demand N_{dem}. In addition, a nitrogen deficit defined in Equation (9) is thought to influence nitrogen demand. Thus:

$$N_{dem} = r_g \cdot Npl(t) \cdot \left(1 - \frac{Npl(t)}{Npl_{max}}\right) + N_{def} \tag{8}$$

The nitrogen deficit term N_{def} is the sum of the positive differences between N_{dem} and UR_{max}:

$$N_{def} = \sum_{t=0}^{t=t_{act}} max\,\{(N_{dem} - UR_{max}) \cdot \Delta t, 0\} \tag{9}$$

This simply means that unfulfilled nitrogen demand from previous time steps is added to the actual demand until it can be met by the nitrate uptake rate.

Nitrogen transport to roots

The maximum nitrogen transport rate to roots is calculated using the single root model approach (Gardner, 1960). The nitrate transport to a single root located in the centre of a cylindrical flow domain may be described by the following partial differential equation (Nye and Spiers, 1964):

$$\frac{\partial C_l}{\partial t}\theta = \frac{1}{r}\cdot\frac{\partial}{\partial r}\left(r\cdot D_l\cdot f(\theta)\cdot\theta\cdot\frac{\partial c_l}{\partial r} + r\cdot J_w\cdot C_l\right) \tag{10}$$

where r is the distance to the root centre, D_l is the diffusion coefficient of nitrate in water, f (θ) is the tortuosity factor and J_w is the water flux density.

Baldwin et al. (1973) developed an analytical solution of Equation (10) assuming steady state conditions. In this solution the authors used a term called root absorbing power, α, which is simply:

$$\alpha = \frac{I}{2\cdot\pi\cdot a\cdot c_{la}} \tag{11}$$

where I is the actual nutrient influx rate (uptake rate per unit root length), a is the root diameter and C_{la} is the nutrient concentration at the root surface.

Substituting this relationship for α into equation (viii) of Baldwin et al. (1973) and solving for I, the maximum influx rate, I_{nmax}, can be calculated which is attained when the concentration at the root surface, C_{la}, reaches a definable low value, C_{lmin}:

$$\begin{aligned} I_{nmax} &= \frac{\bar{C}_l 2\pi a J_{wa} - C_{lmin}\cdot 2\pi a J_{wa}\cdot\Omega}{1-\Omega} \\ \Omega &= \frac{\frac{2}{2-\frac{aJ_{wa}}{Db}}\left[\left(\frac{x}{a}\right)^{2-\frac{aJ_{wa}}{Db}} - 1\right]}{\left(\frac{x}{a}\right)^2 - 1} \end{aligned} \tag{12}$$

where $\bar{C}_l$ is the average nitrate concentration in the soil solution, a is the root radius, J_{wa} is the water flux density at the root surface, and x is the half mean distance between the roots in a given soil layer.

The minimum concentration C_{lmin} is defined as the lowest concentration where nitrate uptake matches transport to roots (De Willigen and Van Noordwijk, 1987). Since faba beans (Kage, 1995) are like most other plant species (Peuke and Kaiser, 1996) very efficient in nitrate uptake, this value will be usually very low (< 10^{-7} mol cm^{-3}), which is equivalent to less than 1 kg N in a 30 cm soil layer a volumetric water content of 30%. Therefore the exact value of this parameter is not very important. It can set to zero, as it was done in this study, in order to calculate the calculate maximum uptake rate which is only transport limited.

The half mean distance between roots, x, is computed from the root length density RD by (Nye and Tinker, 1977):

$$x = \frac{1}{\sqrt{\pi \cdot RD_i}} \tag{13}$$

The term Db in Equation (12) is the product of the effective diffusion coefficient D_e and the buffer power b. Since for nitrate the buffer power is identical with the volumetric water content θ, the following equation holds (Van Rees et al., 1990):

$$Db = D_l \cdot \theta \cdot f \tag{14}$$

where f in Equation (14) stands for the impedance factor which accounts for the tortuosity of the diffusion pathway in the soil. This parameter is a function of the soil water content θ. In the model the empirical relationship:

$$f = 3.35 \cdot \theta^2 \tag{15}$$

derived from experimental data of Barraclough and Tinker (1981) was used.

For each rooted soil layer i the maximum nitrate uptake rate $AR_{max,i}$ is computed from the maximum nitrate influx rate $I_{nmax,i}$ and the root length in that particular layer $L_{r,i}$:

$$AR_{max,i} = I_{nmax,i} L_{r,i} \tag{16}$$

The sink term of Equation (10) then is computed either from the nitrogen demand and the proportion of the maximum nitrate uptake rate to the sum of the maximum uptake rate in all rooted soil layers:

$$S_i = N_{dem} \cdot \frac{AR_{max,i}}{\sum_{i=1}^{i \cdot \Delta z = z_r} AR_{max,i}} \tag{17}$$

or if the sum of the maximum uptake rates is smaller than the nitrogen demand the sink term is simply the maximum uptake rate itself:

$$S_i = AR_{max,i} \tag{18}$$

Mineralisation

For modelling the mineralisation of nitrate-nitrogen from organic matter a simple approach is used. It is assumed that mineralisation follows first order kinetics and there exists only one fraction of potentially mineralisable organic matter, N_{pm}.

$$\frac{dN_{pm}}{dt} = N_{pm} \cdot k \cdot f_{min}(T, \theta) = P_m \tag{19}$$

The influence of soil water content and soil temperature is accounted for by a reduction factor $f_{min}(T, \theta)$ as described by Groot (1987). The soil temperature which is needed for the computation of the reduction parameter is calculated from the measured average air temperature in 2 m height (Groot, 1987).

The two parameters N_{pm} and k of Equation (19) were estimated by fitting the calculated N_{min}-content below oats at harvest to the measured N_{min}-content at harvest (see Figure 8). The assumption is made that the mineralisation rate of the soil below faba beans is the same as below oats. Therefore the parameter values found for oats: 390 and 490 kg N ha^{-1} for Npm and 0.0045 and 0.005 d^{-1} for k in 1982 and 1983 respectively, are also used for faba beans.

The simulation started at the first N_{min} sampling date after N-fertilisation (May 24) and ended at August 1th. The time step size was variable, using a water content change of 0.005 cm^3 cm^{-3} during a time step as a target value for the time step length. Maximum time step length, however, was restricted to 2 hours.

Scenario calculation

In order to give a more systematic view on the possible limitations of low root length densities on soil nitrate depletion, a simulation study for simplified conditions was carried out were root length density was varied over a range found for faba beans and oats in the subsoil. The depletion of a N_{min}-nitrogen amount of 30 kg N ha^{-1} situated in an isolated soil layer of 30 cm thickness through a root system acting as a zero sink was studied during a 30 days simulation period. A volumetric water content of 0.2 cm^3 cm^{-3} (D_e = 2.57·10^{-6} cm^2 s^{-1}) was assumed and mass flow was either neglected or considered according to a water uptake rate of

1 mm d^{-1} from that layer. The calculation was done through a simple numerical integration of the nitrate uptake using Equation (12) for calculation the maximum uptake during each time step.

Results

Soil water contents

The simulated soil water contents below oats and faba beans agree quite well with measured values for faba beans (Figure 2) and oats (Figure 3) in 1982. The same is true for 1983 (data not shown). Discrepancies between measured and simulated soil water contents occurred on July 30 in the soil depth of 90-120 cm. It appears possible that this is due to a methodological problem. Soil water contents were measured gravimetrically with two augers differing in diameter. The thicker was used for 0-100 cm, the second one then was introduced into the same bore hole down to a depth of 2 m. This procedure made it likely that drier soil material from the upper layers contaminated the probes in the first layers of the second auger.

Nitrate uptake rates

Calculated actual nitrate uptake rates for faba beans are about 1 to 2 kg N ha^{-1} d^{-1} and therefore much lower than the N-demand calculated from measured N-accumulation,which had peak values up to 6 kg N ha^{-1} d^{-1} (Figure 4). Actual nitrate uptake rate of faba beans is consequently during almost all the simulation time identical with the maximum possible nitrate uptake rate, limited by the transport of nitrate to the roots. The N-content of faba beans at the start of simulation plus the integration of the calculated nitrate uptake rate over the simulation period gave values of 113 kg N ha^{-1} in 1982 and 124 kg N ha^{-1} in 1983 compared to a measured total N-accumulation of 308 kg in 1982 and 274 kg in 1983 (Table 3). This indicates that the predominant part of the measured N-accumulation of faba beans is therefore contributed by N_2-fixation, being about 63% 20 of total N-accumulation in 1982 and 55% in 1983.

The actual nitrate uptake rate of oats is contrary to the situation with faba beans in almost full accordance with the nitrogen demand which was derived from measured N-accumulation data (Figure 5). This was mainly due to the much lower total N-uptake of oats being 134 kg ha^{-1} in 1982 and 140 kg ha^{-1} in 1983, which resulted in a calculated N-demand lower than 2.5 kg N ha^{-1} d^{-1} (Figure 5). Maximum N demand was about two weeks later in 1983 compared to 1982.

Table 3. Calculated components of the nitrogen budget of faba bean and oats on Hoffmeisterschlag 1982 and 1983

	Faba beans		Oats	
	1982	1983	1982	1983
N content of plants				
Begin of simulation	34	31	57	29
End of simulation	308	274	134	140
Nitrate uptake	79	93	77	111
Mineralisation	38	69	43	68
Nitrate inflow (at 100 cm depth)	6	7	4	7
N_{min}-content of soil				
Begin of simulation	60	53	41	53
End of simulation	25	36	11	17

In both years shortly after the N demand reached its maximum value the calculated nitrate uptake rate was lower than the N demand (Figure 5). This indicates that the maximum uptake rate UR_{max} was in both years not substantially higher than the actual nitrate uptake rate. This seems to be a quite realistic outcome of the calculations, since oats received in both years only small amounts of nitrogen and it is likely that oats absorbed nitrate from the soil at or close to the maximum rate.

Mineralisation of nitrate from soil organic matter and net flow of nitrate into the rooting zone

The very simple approach of simulating the mineralisation from organic matter calculated a cumulative mineralisation during the simulation period of 68 days of 38 and 69 kg N ha^{-1} for faba beans in 1982 and 1983 respectively and of 43 and 68 kg N ha^{-1} for oats in 1982 and 1983 (Table 3). Despite the fact that similar amounts of potential mineralisable organic matter and the same reaction constant was assumed for the two crops, there was a small difference in calculated mineralisation. This is caused by small differences in the water content of the upper soil layers, which resulted in different values of the reduction factors in Equation (19).

Due to the negative water balance of the soil during the simulation period and the resulting upward flow of

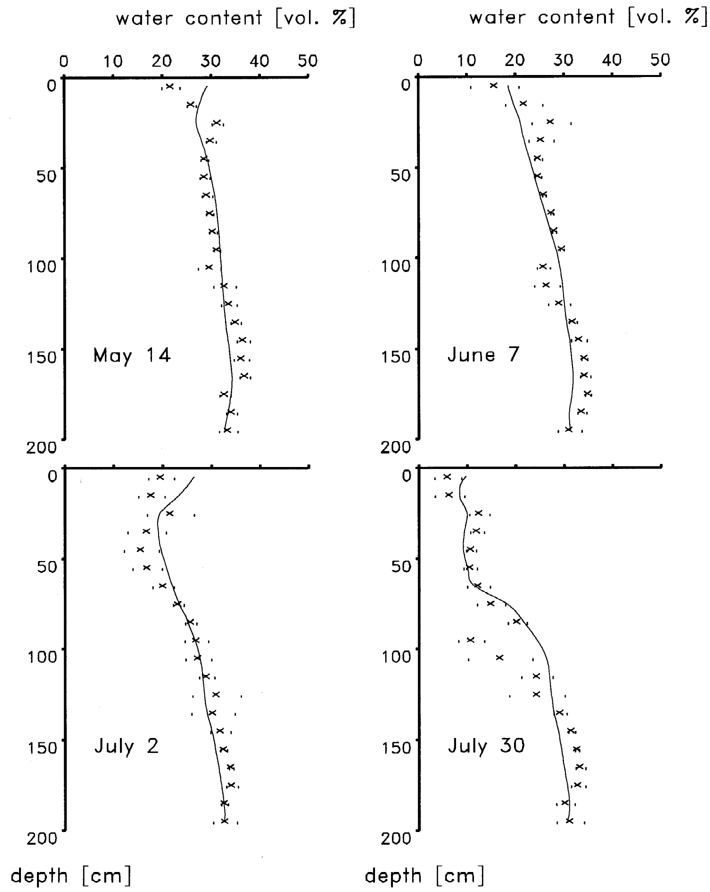

Figure 2. Simulated (——) and measured (x) volumetric water contents (±standard deviation (|)) as a function of soil depth on faba beans plots for 4 different times in 1982 on Hoffmeisterschlag in 1982.

water also the flow of nitrate at 100 cm depth was in both years and for both crops mainly upward directed. Integration over the simulation period resulted in a net inflow of nitrate into the rooting zone of 4 to 7 kg N ha^{-1} (Table 3).

Nitrate content of soil

In 1983 both crops started with the same level of soil nitrate content, whereas in 1982 oats had already taken up about 20 kg N ha^{-1} more than faba beans (Figure 6). Despite the high N demand of faba beans the soil nitrate content below faba beans does not decrease in the same amount as it does below oats. The difference being in both years about 20-30 kg N ha^{-1}. The model was able to reproduce this different reaction mainly as a consequence of the low nitrate uptake capacity of the faba bean root system (Figure 4, Table 3).

The highest nitrate content under faba bean was found at the soil depths of 0 - 20 cm and 80 - 100 cm of the soil profile (Figure 7). This distribution pattern of mineral nitrogen is also simulated by the model. For the soil layer 0-20 cm the reason for a high mineral N-content is probably the ongoing mineralisation of nitrate and the low soil water content at the end of the growing season (Figure 4). Under these conditions the simulated diffusion flow decreases more than the mineralisation rate.

There was almost no depletion of nitrate nitrogen in the layers 80-100 cm. Also in the soil depth from 20 to 80 cm depth faba beans are obviously not able to extract mineral nitrogen in the same amount as oats (Figure 8).

In oats the depletion of the N_{min}-nitrogen is simulated too high for the soil layers from 20 down to 60

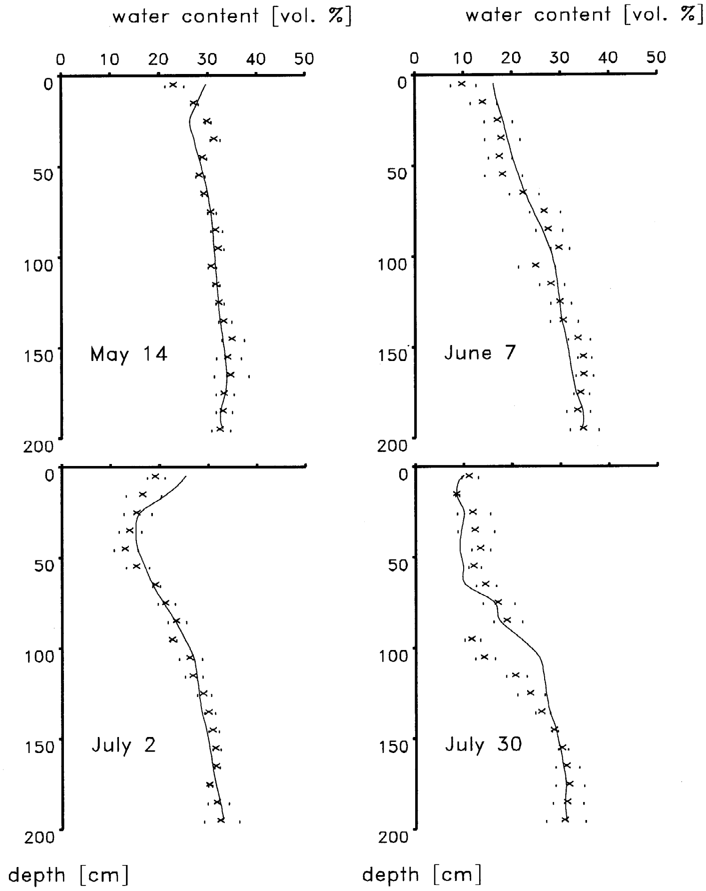

Figure 3. Simulated (——) and measured (x) volumetric water contents (±standard deviation (|)) as a function of soil depth on oats plots for 4 different times in 1982 on Hoffmeisterschlag in 1982.

cm depth (Figure 8). Below that depth, the calculated N uptake is lower than measured uptake.

Scenario calculation

A root length density of 0.2 cm cm^{-3} is under the conditions assumed obviously sufficient to exhaust the assumed N_{min}-nitrogen pool of 30 kg N ha^{-1} in a soil layer of 30 cm thickness almost completely during 30 days (Figure 9).Thereby it seems to be without much importance if mass flow was considered in the calculations or not. For a root length density of 0.1 cm cm^{-3} and with mass flow, however, there was a remaining nitrate amount of 8 kg N ha^{-1} calculated, without mass flow the value was 10.8 kg N ha^{-1}. Reducing the root length density further to 0.06 or 0.03 cm cm^{-3} increases the amount of not available nitrate more than proportional and the importance of mass flow increases as root length density decreases (Figure 9).

Discussion

A necessary condition for the soil nitrogen part of the model is a correct estimate of the water content of the different soil layers as well as rates of water uptake and water movement between the soil layers because the effective diffusion coefficient is a function of the soil water content and the water uptake rate determines the mass flow to the roots. Water uptake rates of roots and the water flow between the soil layers are not measurable in a direct way, but the quite good agreement between measured and simulated water contents (Figures 2 and 3) indicates that these parameters are correctly estimated by the model.

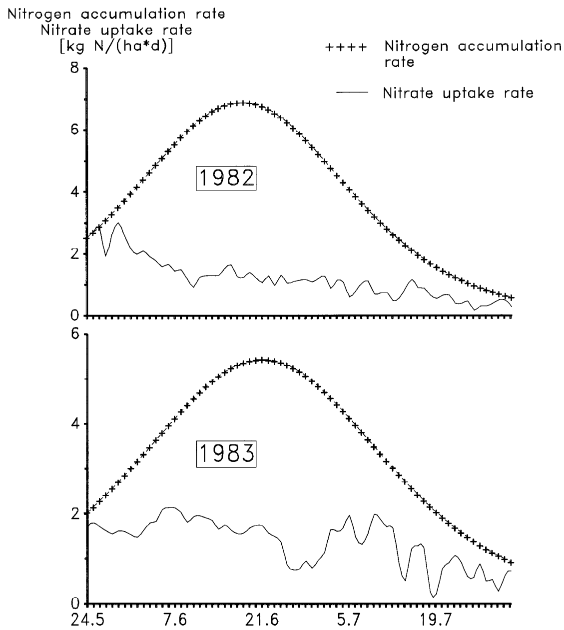

Figure 4. Nitrogen accumulation rate of faba beans (++++) derived from fitting a logistic growth function to measured nitrogen amounts in faba bean shoots and calculated nitrate uptake rates (——) of faba beans for the years 1982 and 1983 on Hoffmeisterschlag, Göttingen.

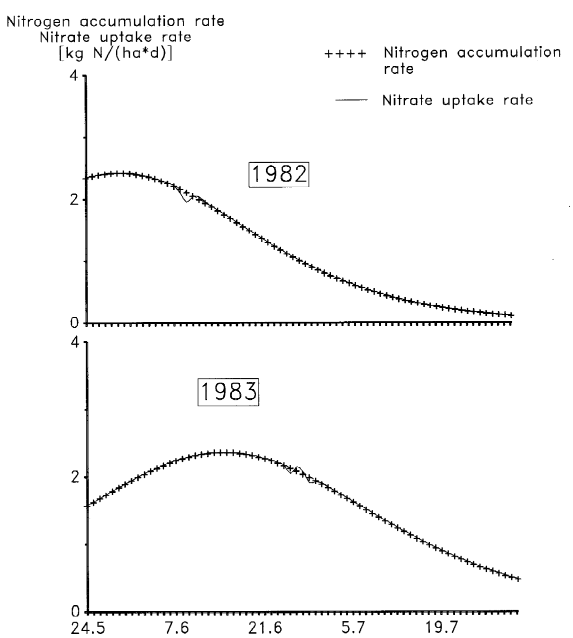

Figure 5. Nitrogen accumulation rate of oats (++++) derived from fitting a logistic growth function to measured nitrogen amounts in oats shoots and calculated nitrate uptake rates (——) of Oats for the years 1982 and 1983 on Hoffmeisterschlag, Göttingen.

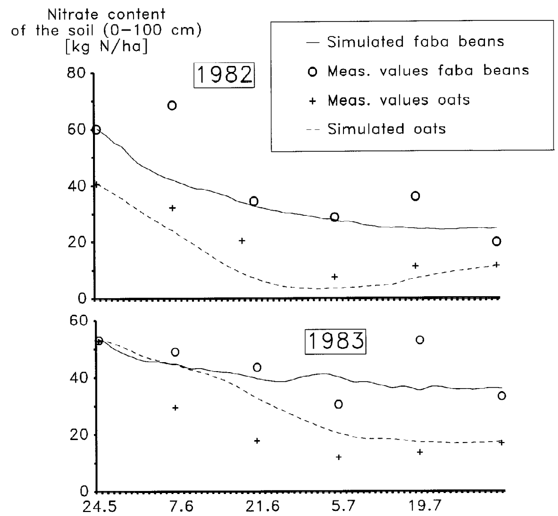

Figure 6. Measured and calculated nitrate content of the soil below faba beans and oats in 1982 and 1983, Göttingen, Hoffmeisterschlag.

It is, however, necessary to be noticed that this good agreement was partly achieved by fitting the crop resistance parameter needed in the calculation of the potential transpiration rate. Without doing this and using the value for the crop resistance reported by Duynisveld (1986) the model already gave an acceptable prediction of the water balance (data not shown). In this study the water balance part of the model was used more to interpolate between measured values and to estimate not measured values rather than really to predict the water balance of the two crops in both years.

The model was able to calculate the differences in soil nitrate depletion between oats and faba beans sufficiently well (Figures 6, 7 and 8). There are at least some problematic points which need to be discussed. The simulation of too high mineral nitrogen content in the soil depth 80 to 100 cm for oats is probably a consequence of the lacking root length density data for soil depths larger than 100 cm. Therefore no nitrate uptake was calculated below 100 cm. This resulted in high nitrate concentrations in the soil depth below 100 cm and consequently a quite high vertical nitrate inflow of 4-7 kg N ha^{-1} during the simulation period into the 90-100 cm soil layer from the underlying soil layers (data not shown). Because of the low rooting density of oats in that soil depth (< 0.2 cm cm^{-3}, Figure 1), the maximum uptake rates for nitrate uptake were quite small, not significantly exceeding the nitrate inflow in the soil layer (see Figure 9 and Table 3). Consequently

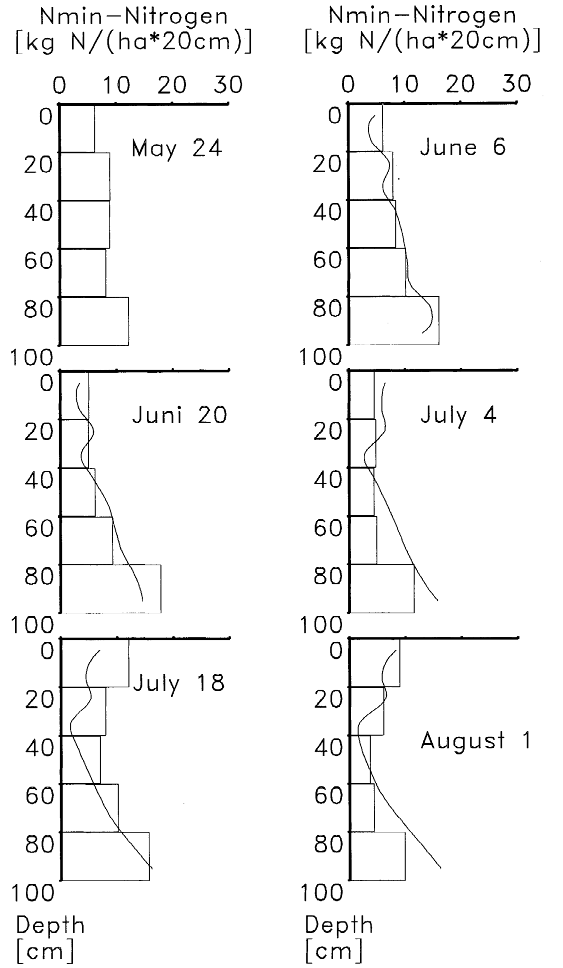

Figure 7. Simulated (Bars) and simulated soil N_{min} -content (——) as a function of soil depth and time for faba beans on Hoffmeisterschlag in 1983.

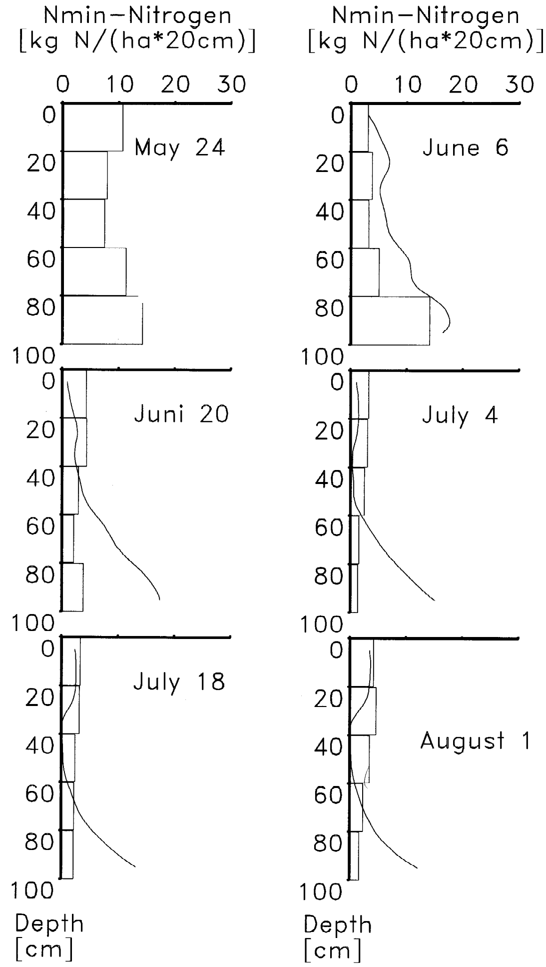

Figure 8. Measured (Bars) and simulated (——) soil N_{min}-content as a function of soil depth and time for oats on Hoffmeisterschlag in 1983.

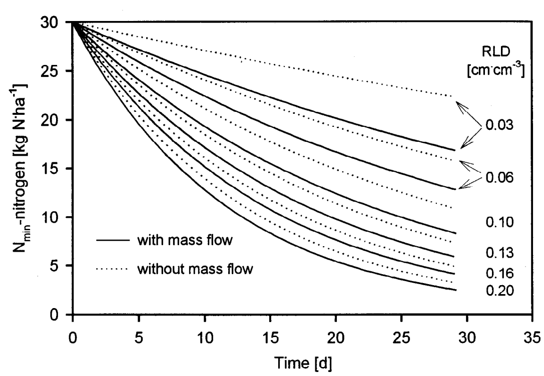

Figure 9. Simulated depletion of the N_{min}-content of an isolated soil layer of 30 cm thickness for different root length densities and without and with mass flow (assumed water uptake rate of 1 mm d^{-1}). Roots are assumed to act as zero sinks, other parameters: vol. water content 0.20 cm cm^{-3}, root radius 0.02 cm.

no full depletion of the nitrogen amounts in that depth was calculated.

For faba beans, however, the simulated high nitrate content in the soil depth from 60 to 100 cm seems to be no artefact. In that depth the rooting density of faba beans is in both years very low, reaching from a value of 0.03 cm cm^{-3} to almost zero (Figure 1). The simulation study shown in Figure 9 showed that a rooting system with a root length density of 0.03 cm cm^{-3}, as it is found for faba beans in the subsoil, is only able to extract quite small amounts of nitrate nitrogen. It therefore seems likely that indeed nitrate transport to roots because of the low rooting density restricted nitrate uptake of faba beans.

One of the most serious errors influencing the reliability of the calculations may be seen in the large error root length density measurements normally have. But it has to be noticed that the difference in root length density between faba beans and oats are in the order of one magnitude. A calculation where rooting density values of faba beans were simply doubled in their value (data not shown), resulted in only slightly reduced residual nitrate contents of the soil. This was to some extent due to the fact that rooting depth was not altered.

On the other hand the assumptions of an evenly root distribution in every soil layer made in the model is obviously not true, especially for faba beans. This can lead to a serious overestimation of the real nitrate uptake capacity of the simulated root systems (Baldwin et al., 1972; De Willigen and Van Noordwijk, 1987).

Higher rates of mineralisation of nitrate from decomposing roots, nodules or senescent leaves are sometimes refered to be responsible for the higher nitrate content of the soil at harvest of faba beans. However, one has to consider that some of the mineralised nitrogen can be taken up again, when it is mineralised before nitrate uptake activity of faba bean roots stops because of ripening. A scenario calculation where the mineralisation was increased from 69 kg N ha^{-1} to 99 kg N ha^{-1} resulted in an enhancement of nitrate uptake of 24 kg N ha^{-1} and only 6 kg N ha^{-1} increase of soil mineral N content at harvest. This indicates that these processes probably play only a minor role in enhancing residual nitrate contents. The further increase of nitrate nitrogen in the soil after harvesting faba beans, however, is without doubt mainly caused by higher rates of mineralisation.

The main result of this study, that low rooting density limits nitrate uptake of faba beans, is in contradiction with most studies concerning the relationship between rooting density and nitrate availability to plants (Barraclough, 1986, 1989; Keulen et al., 1975; Willigen and Noordwijk, 1987). All these authors came to the conclusion, that because of the high mobility of the non-absorbed nitrate ion, transport of nitrate to roots is usually not a limiting factor of plant nitrate uptake. It is, however, necessary to look closely at the input parameters used in these studies. The cited investigations have been made with crops that have, at least in the top soil, root length densities about one order of magnitude higher than common root length densities of faba beans.

Root length densities as low as found for faba beans in the upper soil layers are found for most of the other important agronomic crops only in the subsoil. Kuhlmann et al. (1989), reported from an experiment with wheat where root length density may have limited uptake of nitrate from the deep subsoil (120 to 150 cm depth). The authors found a fair agreement between this observed uptake rate and a simulation of nitrate uptake with a mathematical model quite similar to that used in this study. Wiesler and Horst (1994) showed also a quite close relationship between root length density of maize cultivars in the subsoil and the extent of soil nitrate depletion, but their model calculations indicated that nitrate transport does not have limited uptake. This contradiction between model and measurement might be due to the critical assumption that the total root length has an uptake activity high enough to ensure that the root can act as a zero sink. Recent studies (Henriksen et al., 1992; Lazof et al., 1992) indicate that this may not be true, because uptake activity of older parts of the roots declines drastically. This assumption is also made in this study, but it may be speculated that root ageing plays a more important role in maize than it does in faba beans.

Conclusions

The hypothesis is confirmed: The nitrate uptake of faba beans is limited by the transport of nitrate from the bulk soil to the root surface. The decrease of nitrate uptake capacity of faba beans as a consequence of lower rooting density explains the observed differences of soil nitrate content between faba beans and oats during the vegetation period.

This conclusion is supported by results from other experiments (Kage, 1995), which demonstrated a very sensible restriction of N_2-fixation in presence of nitrate nitrogen. A serious repression of nitrate uptake activity of faba bean roots due to the nitrogen fixation activity therefore appears unlikely.

Acknowledgement

The author owes gratitude to Prof Dr K Baeumer for his suggestion to this study, many helpful discussions and continuously encouragement. Prof Dr W Ehlers and Dr U Müller kindly gave full access to the data of the field experiments. This study is based on work financially supported by the Deutsche Forschungsgemeinschaft (DFG).

References

Addiscott T M and Wagenet R J 1985 Concepts of solute leaching in soils: a review of modelling approaches. J. Soil Sci. 36, 411–424.

Baldwin J P, Tinker P B and Nye P H 1972 Uptake of solutes by multiple root systems from soil. II. The theoretical effects of rooting density and pattern on uptake of nutrients from soil. Plant Soil 36, 693–708.

Baldwin J P, Nye P H and Tinker P B 1973 Uptake of solutes by multiple root systems from soil. III. A model for calculating the solute uptake by a randomly dispersed root system developing in a finite volume of soil. Plant Soil 38, 621–635.

Barber S A 1962 A diffusion and mass-flow concept of soil nutrient availability. Soil Sci. 93, 39–49.

Barraclough P B 1986 The growth and activity of winter wheat roots in the field: nutrient inflows of high-yielding crops. J. Agric. Sci. 106, 53–59.

Barraclough P B 1989 Root growth, macro-nutrient uptake dynamics and soil fertility requirements of a high yielding winter oilseed rape crop. Plant Soil 119, 59–70.

Barraclough P B and Tinker P B 1981 The determination of ionic diffusion coefficients in field soils. I. Diffusion coefficients in sieved soils in relation to water content and bulk density. J. Soil Sci. 32, 225–236.

Beese F, Van der Ploeg R R and Richter W 1978 Der Wasserhaushalt einer Löß-Parabraunerde unter Winterweizen und Brache. Computermodelle und ihre experimentelle Verifizierung. Z. Acker Pflanzenbau 146, 1–19.

Beese F and Wierenga P J 1980 The variability of the apparent diffusion coefficient in undisturbed soil columns. Z. Pflanzenernähr. Bodenk. 146, 302–315.

BMG 1986 Verordnung über Trinkwasser und über Wasser für Lebensmittelbetriebe (Trinkwasserverordnung - TinkrsV). Bundesgesetzblatt Jahrgang 1986, 760–773.

Böhm W 1979 Methods for studying Root Systems. Springer-Verlag, Berlin.

De Willigen P and Noordwijk M V 1987 Uptake potential of non-regularly distributed roots. J. Plant Nutr. 10, 1273–1280.

De Willigen P and Noordwijk M V 1987 Roots, plant production and nutrient use efficiency. Ph.D. thesis, Agricultural University Wageningen.

Duynisveld W H M 1983 Entwicklung von Simulationsmodellen für den Transport von gelösten Stoffen in wasserungesättigten Böden und Lockersedimenten. Texte Umweltbundesamt 17/83.

Ehlers W 1976 Rapid determination of unsaturated hydraulic conductivity in tilled and untilled loess soil. Soil Sci. Soc. Am. J. 8, 837–840.

Ehlers W 1977 Measurements and calculation of hydraulic conductivity in horizons of tilled and untilled loess-derived soil. Geoderma 19, 293–306.

Ehlers W, Hamblin A P, Tennant D and Van der Ploeg R R 1991 Root system parameters determining water uptake of field crops. Irrig. Sci. 12, 115–124.

Feddes R A, Kowalik P J and Zaradny H 1978 Simulation of Field Water use and Crop Yield. Simulation Monographs. PUDOC, Wageningen.

Gardner W R 1960 Dynamic aspects of water availability to plants. Soil Sci. 89, 63–73.

Groot J J R 1987 Simulation of nitrogen balance in a system of winter wheat and soil. Simulation Report. CABO-TT, Wageningen. 69 p.

Hauser S 1992 Estimation of symbiotically fixed nitrogen using extended N difference methods. *In* Biological Nitrogen Fixation and Sustainability of Tropical Agriculture. Eds. K Mulongoy, M Gueye and D S C Spencer. pp 309–321. John Wiley and Sons, Chichester.

Henriksen G H, Raj Raman D, Walker L P and Spanswick R M 1992 Measurements of net fluxes of ammonium and nitrate at the surface of barley roots using ion-selective microelectrodes: II. Patterns of uptake along the root axis and evaluation of the microelectrode flux estimation technique. Plant Physiol. 99, 734–747.

Hoyningen-Huene J 1983 Die Interzeption des Niederschlages in landwirtschaftlichen Pflanzenbeständen. DVWK-Schriften 57, 1–53.

Kage H 1992 Zu den Ursachen hoher Restnitratmengen beim Anbau von Ackerbohnen. Triade-Verlag, Göttingen,

Kage H 1995 Interaction of nitrate uptake and nitrogen fixation in faba beans. Plant Soil 176, 189–196.

Keulen H V, Seligman N G and Goudriaan J 1975 Availability of anions in the growth medium to roots of an actively growing plant. Neth. J. Agric. Sci. 23, 131–138.

Köpke U 1979 Ein Vergleich von Feldmethoden zur Bestimmung des Wurzelwachstums landwirtschaftlicher Kulturpflanzen. Ph.D. thesis, Univ. Göttingen.

Kuhlmann H, Barraclough P B and Weir A H 1989 Utilization of mineral nitrogen in the subsoil by winter wheat. Z. Pflanzenernähr. Bodenkd. 152, 291–295.

Lazof D B, Rufty T W and Redinbaugh M G 1992 Localization of nitrate absorption and translocation within morphological regions of the corn root. Plant Physiol. 100, 1251–1258.

Maidl F X, Suckert J, Funk R and Fischbeck G 1991 Standorterhebungen zur Stickstoffdynamik nach Anbau von Körnerleguminosen. J. Agron. Crop Sci. 167, 259–268.

Meyer C 1984 Zum Einfluß des Wasserhaushaltes auf die Ertragsbildung bei Ackerbohne und Hafer. Ph.D. thesis, Univ. Göttingen.

Müller U 1984 Wasserhaushalt von Ackerbohne und Hafer auf Löss-Parabraunerde. Ph.D. thesis, Univ. Göttingen.

Müller U, Meyer C, Ehlers W and Böhm W 1985 Wasseraufnahme und Wasserverbrauch von Ackerbohne und Hafer auf einer Löß-Parabraunerde. Z. Pflanzenernähr. Bodenkd, 148, 389–404.

Nye P H and Spiers J A 1964 Simultaneous diffusion and mass flow to plant roots. 8th Int. Congr. Soil Sci., Bucharest. pp 535–542.

Nye P H and Tinker P B 1977 Solute movement in the soil-root system. Blackwell, Berkeley.

Opara-Nadi O J 1979 A comparison of some methods for determining the hydraulic conductivity of unsaturated soils in the low suction range. Ph.D. thesis, Univ. Göttingen.

Peuke A D and Kaiser W M 1996 Nitrate or ammonium uptake and transport, and rapid regulation of nitrate reduction in higher plants. Prog. Bot. 57, 93–113.

Reid J B, Hashim O and Gallagher J N 1984 Relations between available and extractable soil water and evapotranspiration from a bean crop. Agric. Water Manage. 9, 193–209.

Remson I, Hornberger G M and Molz F J 1971 Numerical Methods in Subsurface Hydrology. John Wiley and Sons, New York.

Ritchie J T 1972 Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8, 1204–1213.

Thornley J H M and Johnson I R 1990 Pland and Crop Modelling. A mathematical Approach to Plant and Crop Physiology. Clarendon Press, Oxford.

Van Bavel C H M 1966 Potential evaporation: the combination concept and its experimental verification. Water Resour. Res. 2, 455–467.

Van Genuchten M T 1981 A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898.

Van Rees K C J, Comerford J N B and Rao P S C 1990 Defining soil buffer power - implications for ion diffusion and nutrient uptake modeling. Soil Sci. Soc. Am. J. 54, 1505–1506.

Wiesler F and Horst W J 1994 Root growth and nitrate utilization of maize cultivars under field conditions. Plant Soil 163, 267–277.

Wösten J H M and Genuchten M T 1988 Using texture and other soil properties to predict the unsaturated soil hydraulic functions. Soil Sci. Soc. Am. 15 J. 52, 1762–1770.

Section editor: H Lambers