Simulation of the nitrogen balance in the soil and a winter wheat crop

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Key words: Crop growth, immobilization, mineralization, modelling, nitrogen uptake

Abstract

A simulation model for winter wheat growth, crop nitrogen dynamics and soil nitrogen supply was tested against experimental data. When simulations of dry matter production agreed with measurements, nitrogen uptake was simulated accurately. The total amount of soil mineral nitrogen as well as the distribution of mineral nitrogen over the various soil layers were generally simulated well, except for experiments in which fertilizer was applied late in spring. In these experiments, applied nitrogen 'disappeared' because it could not be accounted for by the model. Some explanations for this disappearance are briefly discussed.

Introduction

Various models for the behaviour of nitrogen in the soil have been developed [7], and models to simulate crop nitrogen uptake and the effects of crop nitrogen status on crop growth are available [7, 26]. Most of these models were developed as research tools, and cannot be readily applied for management purposes, as they require too many site-specific input parameters that cannot easily be obtained by simple field measurements.

The purpose of the present study is to examine to what extent cereal growth, nitrogen (N) uptake and soil N dynamics can be simulated for a single field, by using input parameters that can be obtained from simple field measurements. The model was developed on the basis of existing theory and submodels for crop growth, N distribution in the crop and water and N dynamics in the soil, and was parameterized and tested against a set of experimental data from the Netherlands [11].

Model structure

The model comprises three submodels (Fig. 1) which simulate soil N dynamics, soil moisture dynamics, and crop growth and N uptake, respectively.

Soil moisture submodel

The soil is treated as a multilayered system with a finite number of compartments of variable thickness. Changes in moisture status of a compartment are calculated from the combined effect of water infiltration, extraction due to soil surface evaporation, water extraction by the roots and downward movement of water through the compartments.

Infiltration

When precipitation occurs, the first compartment is filled with water until field capacity (corresponding to a -100 cm pressure head) is reached, and excess water entering the compartment drains to the next compartment. This procedure is repeated for deeper compartments as long as drainage occurs.

Evaporation and transpiration

Potential soil surface evaporation and potential crop transpiration are calculated according to a
modified Penman approach [16], described in detail by Groot [9]. Actual soil surface evaporation is related to the soil moisture content of the upper soil compartment according to Van Keulen & Seligman [26], and moisture lost by evaporation is distributed over various soil compartments according to an exponential decay curve.

The actual rate of transpiration is related to the leaf area index of the crop, and to the soil moisture content of the rooted soil compartments according to Van Keulen & Seligman [26]. When actual transpiration is smaller than potential transpiration, gross canopy assimilation is reduced proportionally.

Soil nitrogen submodel

Nitrogen availability depends on the balance between N input through fertilizer application, decomposition of old organic matter (humus) and crop residues, and N output through crop uptake and transport out of the rooting zone. Denitrification and volatilization are not considered.

Mineralization – immobilization

Most models for soil organic matter dynamics distinguish between a microbial biomass pool and several soil organic matter pools, each representing material of different stability with regard to decomposition [12, 25, 28]. Generally, transformations are described by first-order kinetics and result in growth of biomass, which itself is subject to decomposition. These models have been useful for long-term simulations (decades, e.g. [12, 25]), but they are hard to initialize, because good methods for partitioning soil organic matter among different pools are lacking. Moreover, parameterization is rather speculative; for each of the transformations a decomposition rate constant and a yield efficiency factor is required.

In our model, organic matter dynamics is restricted to plough layer residues and plough layer residues and

Decomposition

In the model (C_{d,p}, amount of C)

\[ C_{d,p} = \frac{dC}{dt} \]

in which \( k_{d} \) constant (d-1; combined C pool; The response approaches and moisture content; proportiona release (N_d; the C/N ratio)

\[ N_{d,p} = \frac{dN}{dt} \]

A fraction is used for biological growth, given by:

\[ N_{\text{set}} = \frac{C}{\text{biomass}} \]

in which C biomass. W decomposition is occurs. In this N \( (N_{d}, \text{kg/} \text{mineral N initial decom} \)

\[ N_{d} = N_{d,0} - C_{d} \]

in the modelization

Mineralization

Only a small
stricted to the upper 30 cm, representing the plough layer. The only pools considered are crop residues and native soil organic matter.

Decomposition of crop residues

In the model, the rate of substrate decomposition \( C_{d,p}, \text{kg(C)ha}^{-1}\text{d}^{-1} \) is proportional to the amount of substrate \( C_s, \text{kg ha}^{-1} \):

\[
C_{d,p} = dC/dt = k_d C_s f_{i,m}
\]

where \( k_d \) is the first-order decomposition rate constant \( (\text{d}^{-1}) \) and in which \( f_{i,m} \) accounts for the combined effect of soil temperature and soil moisture content according to Verbruggen [29]. The response surface given in [29] is preferred to approaches in which the effects of temperature and moisture content are considered to be multiplicative. Nitrogen fluxes are assumed to be proportional to the carbon fluxes. The rate of N release \( (N_{d,p}, \text{kg(N)ha}^{-1}\text{d}^{-1}) \) thus depends on the C/N ratio of the substrate \( (CN_s) \):

\[
N_{d,p} = dN/dt = C_{d,p}/CN_s
\]

A fraction \( \varepsilon_b \) of the decomposed substrate is used for biomass growth, \( (1 - \varepsilon_b) \) is used for respiration. Thus, N required for optimum growth of biomass \( (N_{req,b}, \text{kg(N)ha}^{-1}\text{d}^{-1}) \) is given by:

\[
N_{req,b} = \varepsilon_b (C_{d,p}/CN_s)
\]

in which \( CN_s \) is the C/N-ratio of microbial biomass. When \( CN_s \) exceeds \( (CN_s/\varepsilon_b) \), decomposition is N-limited and net immobilization occurs. In this situation \( N_{req,b} \) is covered by mineral N \( (N_i, \text{kg(N) ha}^{-1}) \). When the amount of soil mineral N is not sufficient to cover \( N_{req,b} \), potential decomposition rates are reduced:

\[
N_d = N_{d,p}(N_i/N_{req,b})
\]

\[
C_d = C_{d,p}(N_i/N_{req,b})
\]

In the model nitrification is neglected, and mineralization directly yields mineral N as nitrate.

Mineralization of native soil organic matter

Only a small proportion of soil organic matter is mineralized each year \((1-2\% [14])\), and for simulations over a single growing period, changes in the amount of soil organic matter \((OM, \text{kg ha}^{-1}) \) may be neglected. According to Johnsson et al. [13], mineralization \((N_{d,o}, \text{kg(N) ha}^{-1}\text{d}^{-1}) \) is calculated as

\[
N_{d,o} = OM k_{om} f_{i,m} CN_{om}
\]

in which \( k_{om} \) is the specific mineralization rate constant \( (\text{d}^{-1}) \), and \( f_{i,m} \) is the combined effect of soil moisture content and temperature [29]. The C/N-ratio of soil organic matter \((CN_{om}) \) generally ranges from 8-15 [28]; the C/N ratio of biomass \((CN_b) \) and 'the growth efficiency of biomass \( \varepsilon_b \) are in the order of 10 and 0.33, respectively, and thus net immobilization is not expected to occur.

Nitrogen transport

Downward N transport occurs by downward water flow as calculated in the soil moisture submodel. Following the approach proposed by Burns [3], water and \( N \) entering a soil compartment are mixed with water and \( N \) already present in the soil compartment. The resulting concentration is subject to drainage.

Nitrogen uptake

In the model, different horizontal layers in the root zone are distinguished, each with its own root density and N concentration. The basic assumption of the uptake model is that the uptake rate is governed by demand as long as the transport rate of nitrogen from bulk soil to the root surface exceeds the required rate given by plant demand. The highest transport rate occurs when the concentration at the root surface is zero, the root behaving as a so-called zero sink. The zero-sink uptake rate can be shown to be proportional to the average concentration in the soil [6], where the proportionality constant depends on root density, the rate of flow of water towards the root and the diffusion coefficient of nitrogen in the soil, which in turn depends on the soil moisture content [2].

Uptake is calculated by iteration. First the nitrogen demand is divided by the total root
length to obtain the required uptake per unit root length. Multiplying this by the root length in a given layer yields the required uptake from that layer. If the potential uptake rate (zero-sink uptake rate) exceeds the required uptake rate, uptake from this layer equals the required uptake. If the potential uptake is lower than the required uptake rate, uptake from this layer equals the potential uptake rate.

Total uptake by the root system is the sum of the amounts taken up from the individual layers. If the uptake in each layer can proceed at the required rate, total uptake equals nitrogen demand and no iteration is required. If not, it is assumed, as indeed is often found, that roots in favorable positions can compensate for roots in less favorable positions [5]. If total uptake is lower than the nitrogen demand, the model checks whether uptake from these layers (that is where the potential uptake was higher than the required uptake rate), can be raised sufficiently to meet the total demand. This calculation procedure implies that roots growing under favorable conditions will compensate as much as possible for roots growing under less favorable conditions. It is thus assumed that information about the necessary behavior of the plant, as far as uptake is concerned, is instantaneously available throughout the entire root system.

In field experiments with winter wheat, N uptake declines after anthesis, but the mechanism for this decline is poorly understood. In the model this decline is mimicked by reducing the potential rate of uptake by a factor which represents the total root weight relative to the root weight at anthesis.

Crop submodel

Crop growth

Crop growth is calculated with the SUCROS model [23], but the model was slightly modified to account for the effects of N on crop growth. Gross canopy photosynthesis is calculated as a function of leaf area index, radiation distribution within the canopy, and the photosynthesis-light response curve of individual leaves. Maintenance requirements for various plant organs, calculated as a function of their weight and chemical composition according to Penning de Vries [17, 18], are subtracted from daily gross assimilation. Partitioning of remaining assimilates to leaves, stems, roots, reserves and grains is varied with the stage of crop development according to fixed empirical functions [9]. The rate of crop development is a function of ambient air temperature, but is modified to account for effects of vernalization and photoperiod [20]. After anthesis no vegetative growth occurs (see e.g. [9]), and assimilates are either stored in the stem as water-soluble carbohydrates (sink-limited grain growth) or allocated to the grains (source-limited grain growth). The sink strength of grains is characterized by a variety-specific potential rate of carbohydrate accumulation for single grains, which is a function of the ambient air temperature [21], multiplied by the total grain number. This number can be empirically related to total above ground dry matter at anthesis [30].

Assimilates allocated to various plant organs are converted into structural plant material, taking into account the energy required for conversion (growth respiration) as a function of protein content of the growing material [18]. In the present model, chemical composition is considered only in terms of proteins and carbohydrates. Leaf area index is calculated by multiplication of leaf weight by an average specific leaf area (m²·kg⁻¹) derived from experimental data [11].

Both the rate of photosynthesis and the rate of maintenance respiration increase with rising N content of vegetative plant parts [26]. Note that this was not the case in the original SUCROS model.

The potential rate of root extension was set at a value of 18 mm d⁻¹ [8]. This rate was reduced to account for the effects of soil moisture content according to Stapper [24] and temperature of the soil compartment in which root extension occurs [1, 4]. Once rooting depth and root weight are known, the root length distribution pattern is calculated. It is assumed that root length density decreases exponentially with increasing depth. The shape factor for the exponential decrease was fitted to the measurements of root length density in the data set [11].
Nitrogen uptake and distribution

Crop N demand is based on the concept of N deficiency. If the N content of a given plant part is below its maximum value corresponding to the current stage of development, a sink for N exists. Maximum values of N content were assessed from N3-treatments in the data set [11], that is those receiving the highest rate of N fertilizer. Actual N uptake proceeds at a maximum rate until crop demand is satisfied.

Once taken up, N is distributed over stems, leaves and roots in proportion to the relative demands of these organs. Nitrogen taken up after anthesis is assumed to be reduced and stored first in vegetative tissue. Subsequently it may be translocated to grains, which lowers both the N content and photosynthetic capacity of vegetative tissue. All N is available for translocation except the N which is incorporated in structural cell material. The time constant for N translocation is assumed to be equal to that for protein decomposition, i.e. in the order of 10 days [19].

The N requirement of grains is characterized by a variety-specific rate of N accumulation in single grains, which is a function of ambient air temperature [22], multiplied by the total grain number.

N translocation results in senescence of vegetative plant parts, and the rate of senescence is proportional to the rate of N depletion.

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Fig. 2. Comparison of measured and simulated total dry matter production for all locations and N treatments included in the data set [11] for 1983 (a) and for 1984 (b). Broken lines indicate a 20% deviation from the 1:1 line (solid line).
Simulations

Simulations were done for winter wheat experiments in 1982/1983 and 1983/1984 [11]. The experiments were done on three different locations (the Bouwing, the Eest and PAGV), and each experiment comprised three N fertilizer treatments.

Dry matter production, leaf area development and N uptake

In 1983, for each of the locations and for all N treatments, dry matter production was generally strongly underestimated by the model (Fig. 2a), while in 1984 simulations were in agreement with the measurements (Fig. 2b).

The major reason for poor results in 1983 was that the model underestimated leaf area development, resulting in too low a dry matter production (example: Fig. 3a). In 1984, the leaf area index was calculated accurately, resulting in a proper estimate of dry matter production (example: Fig. 3b). N uptake was also too low in 1983 because N demand is proportional to dry matter production (Fig. 4a). In 1984, proper simulation of dry matter production resulted in a more accurate simulation of N uptake (Fig. 4b).

![Graph showing leaf area index and total dry matter production]

**Fig. 4.** Time course of leaf area index and total dry matter production for the experiment Bouwing 1983 treatment N3 (a) and for the experiment Eest treatment N2 (b). ●: measurements of leaf area index, ■: measurements of total dry matter production, ——: simulation of leaf area index, ———: simulation of total dry matter production.

To compare soil mineral should be the remainder considered.

**Soil mineral**

Soil mineral initial amount that simulates agreed with treatment PAGV single N app.
To compare measurements and simulations of soil mineral N, the time course of crop N uptake should be simulated accurately. Therefore in the remainder of this paper only 1984 results are considered.

**Soil mineral N and crop N uptake**

Soil mineral N was not measured at sowing. The initial amounts of N at sowing were chosen so that simulated values at the first sampling date agreed with the measurements. For the experiment PAVG 1984 treatment N1, in which only a single N application was given early in the growing season, the measured and simulated dynamics of the total amount of soil mineral N in the 0–100 cm layer and the measured and simulated crop N uptake during the growing season are in good agreement (Fig. 5a). Fig. 6a shows also that the distribution of mineral N in the soil profile throughout the season was simulated accurately. In treatment N3, however, in which more fertilizer N was given later in the season, the simulated sharp increase in total soil mineral N was not reflected in the measurements (Fig. 5b). According to Fig. 6b the amount of mineral N is overestimated mainly for the layers 0–20 and 20–40 cm.
Soil moisture content

The simple soil moisture module simulated the relative fluctuations in soil moisture content for the layers 0–20 and 20–40 cm reasonably well (Fig. 7), but throughout the whole growing season the absolute value of simulated moisture content was too high. According to the model, the soil dries out in the deeper soil compartments (40–60, 60–80 and 80–100 cm, Fig. 7), but this drying is not at all reflected in the measurements. Presumably, capillary moisture movement occurred, which is not accounted for in the model.

Discussion

To simulate soil N dynamics in a crop-soil system, it is essential that N uptake is simulated accurately. In our approach, crop N demand is related to the simulated total dry matter of the standing crop, which in itself is very sensitive to the accuracy of leaf area index calculations. Simulation of leaf area development, especially for winter crops, is difficult, due to the interactions between leaf extension and leaf photosynthesis. At low temperatures leaf extension is limited, and due to the absence of sinks carbohydrates may accumulate, reducing the rate of photosynthesis, and thus dry matter production. To include these effects in a crop growth model, a detailed description of leaf emergence and areal growth of individual leaves is required. However, we doubt if such an approach will improve the accuracy of simulation of leaf area index, as it requires extra parameters and thus increases the uncertainty of the model outcome. One might as well adopt a much more simplified description of N uptake. Whitmore and Addiscott [32] fitted the N uptake using a site-specific maximum N uptake capacity, that is modified for the effects of temperature and mineral N availability during the growing season.

Soil mineral N and N uptake during the growing season could be simulated accurately for the 1984 experiments in which nitrogen was applied early in the season, as illustrated for PAGV 1984 treatment N1 (Fig. 5a). In treatments where nitrogen was applied late in spring, the amount of soil mineral N after the application was overestimated by the model (Fig. 5b). It could be argued that the long intervals between measurements of soil mineral N preclude detection of a sudden increase followed by a steep decline due to N uptake by the crop. N was applied during periods in which uptake rates were high (about 3 kg ha⁻¹ day⁻¹ between day 113 and 147, Fig. 5b), but this cannot explain the soil mineral N dynamics observed. In Fig. 5b only one example of this ‘loss’ of N is presented, but in the data set used for the simulations [11], this phenomenon was observed more often after fertilizer applications late in spring. In a series of fertilizer experiments with potatoes in which nitrogen was applied as NH₄NO₃, Neeteson et al. [15] observed that up to 80% of the N applied in April ‘disappeared’ immediately, but this fraction progressively decreased, and five weeks after application virtually all the N applied could be accounted for in either the soil or the crop. This reappearance, however, did not occur in the PAGV 1984 experiments (Fig. 5b).

Nitrogen can be immobilized by microbial growth, but to immobilize 100 kg(N) ha⁻¹ approximately 3000 kg carbon per ha is required if we assume a C/N-ratio of 10 for microbial biomass and a growth efficiency of 30%. In recent incubation experiments it has been observed that N can be immobilized almost instantaneously after application, without increased metabolic activity of the microbial biomass measured as CO₂-release (J. Hassink, pers. comm.). Nitrogen immobilization through a change in C/N-ratio of microbial biomass might be a cause of the ‘disappearance’.

Another possible explanation for the loss of fertilizer N in Fig. 5b was given by Wehrman and Coldewey-Zum Eschendorf [31], who applied ammonium fertilizer to rape plants grown in pots filled with a silty loam. Near the roots a concentration gradient of frequently fixed NH₄⁺ was measured, indicating that recently fixed NH₄⁺ was taken up. Recently fixed NH₄⁺ will not be extracted with 1 M KCl, the extraction agent generally used to determine soil mineral N.

Soil moisture content at field capacity was generally overestimated by the model (Fig. 7). Moisture content at field capacity was defined as the moisture content at a moisture tension of
Fig. 5. Time course of soil mineral N in the 0–100 cm layer and crop N uptake for the experiment PAGV 1984, treatment N1 (a) and treatment N3 (b). ○: measurements of soil mineral N, ■: measurements of crop N uptake, ---: simulation of soil mineral N, ---: simulation of crop N uptake.

Fig. 6. Simulated (lines) and measured (triangles) time course of soil mineral N for the layers 0–20, 20–40, 40–60, 60–80 and 80–100 cm, for the experiment PAGV 1984 treatment N1 (a) and treatment N3 (b).
Fig. 7. Simulated (lines) and measured (triangles) time course of soil moisture content for the layers 0–20, 20–40, 40–60, 60–80 and 80–100 cm, for the experiment PAGV 1984 treatment N3.

100 cm, read from the moisture retention curves in the data set [11]. The pF-curve used for the PAGV experiment was not established at the experimental site used in the simulations, but at a different location in the polder with a comparable soil type. Probably, the curve in the data set was not representative of the experimental site.

Another possible explanation for the overestimation of the soil moisture content at field capacity is the hysteresis in the pF-curve. In the data set [11], a so-called ‘desorption curve’ is given, but the ‘adsorption curve’ is generally shifted towards lower soil moisture contents [27, 33].

The model does not account for capillary rise. According to Fig. 7, this is unrealistic for polder locations with a fluctuating water table.

Fig. 5 illustrates that, in spite of the inaccuracy of simulated soil moisture contents, the uptake of N is simulated satisfactorily. Calculations with a detailed model for nitrogen uptake in relation to soil moisture content and nitrogen distribution, showed that as long as the soil was sufficiently moist, and roots were present, there was little physical limitation to N uptake [10]. Thus the accuracy of the simulated distribution of mineral N and the accuracy of simulations of soil moisture content are only of minor importance for accurate simulations of nitrogen uptake under the growing conditions as presented in the data set [11]. However, to calculate leaching losses of nitrate from the rooting zone, not only an accurate calculation of nitrogen uptake but also a proper simulation of mineral nitrogen distribution and soil moisture content are necessary.

Note
A listing of the simulation model is available from the authors upon request.

References
12. Jenkins soil organ experiments.
14. Kortkilev humusophyly dzer nr. 8
15. Neeteson, Dependencia Plant.
16. Penning & respirat higher pl
17. Penning & processes
18. Penning & higher pl different gramme.
19. Reinink & tation of conditions
20. Solfield I, Factors in in wheat
21. Solfield I, Nitrogen, development Physiol 4