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Simulation of soil nitrogen dynamics using the SOILN model

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Abstract

A model dealing with transport and transformations of nitrogen in soil is briefly described. The model has a one-dimensional layered structure and considers processes such as plant uptake, mineralization/immobilization, leaching and denitrification. A soil water and heat model provides daily values for abiotic conditions, which are used as driving variables in the nitrogen simulation. In this study, the model was run with data from a polder-soil area in the Netherlands, with winter wheat as the crop. The simulation results showed that if a measured time course of crop nitrogen uptake throughout the growing season is available, mineral-N dynamics in soil can be satisfactorily described with this model. The main problems identified in the simulations were related to the partitioning between above- and below-ground plant-N, and supplying the crop with sufficient N, as given by the measurements.

Introduction

A number of models dealing with transformations and transport of nitrogen in soil have been developed [3]. The degree of sophistication and applicability for the different processes included in these models varies considerably, from simple empirically based formulations to complex mechanistic approaches. The complexity in itself does not necessarily restrict widespread use, however. The applicability is often limited by the need for calibration, since models requiring calibration, both 'simple' and 'sophisticated', are not suited for sites which lack monitoring programs [3]. The SOILN model [11] described and used in this study is an example of a model which was developed with the intention of facilitating numerous applications. It has been applied to several sites and data sets of different areal and temporal scales [1, 2, 6, 7, 8, 11].

This paper briefly describes the SOILN model and the simulation results obtained when using a provided data set [5].

Materials and methods

Structure of the model

The model consists of two parts, which are used in sequence. In the first step, soil water and temperature conditions are simulated by a soil water and heat model [9] of which outputs are utilized as driving variables for the nitrogen model [11]. Common to both models is the vertical structure that facilitates division of the soil into different layers depending on the accuracy required and available information on basic soil physical and biological characteristics.

Water and heat transport. The water and heat submodel is based on two coupled differential equations describing heat and water transport (derived from Fourier's and Darcy's laws, respectively) in a one-dimensional soil profile [10]. Snow dynamics, frost, evapotranspiration, precipitation, groundwater flow, water uptake by plants, and drainage flow are included. The model predicts daily values of soil climate variables (soil temperature, and soil water content and tension) at any level in the soil profile, using standard meteorological data as driving variables.

The model also deals with water transport in the saturated zone. The flow rate from each saturated layer, above the depth of the drainage tiles, is calculated by taking into account the saturated conductivity and a gradient estimated as the difference between the mean depth of the groundwater table and the depth of the tiles divided by the distance between the drainage tiles. Vertical redistribution of water below the groundwater table is then calculated from conservation of mass and the water contents exactly at saturation. In addition to the water flow drained via the drainage tiles, the saturated water flow directed towards a stream or ditch is calculated with an empirical equation.

Surface runoff can occur due to limited infiltration capacity or limited permeability of the soil.

A detailed description of the water and heat model is found elsewhere [10].

Nitrogen transformations and plant N-uptake. Biological N-transformations in the model (Fig. 1) apply to each layer. Mineral-N pools include ammonium and nitrate. Organic-N is distributed over litter, faeces, and humus. Organic carbon pools are included for both litter and faeces to control nitrogen mineralization and immobilization rates. Undecomposed material (*e.g.* crop residues, dead roots, microbial biomass) constitute the litter component, while the humus consists of stabilized decomposition products.

Mineralization of humus-N ($N_{h\text{-}am}$; kg ha^{-1} d^{-1}) is calculated as a first-order rate process:

$$N_{h\text{-}am} = k_h e_t e_m N_h \tag{1}$$

where k_h is the specific mineralization constant (d^{-1}), e_t and e_m are response functions for temperature and moisture, and N_h is the mass of humus-N. Similarly, decomposition of the or-

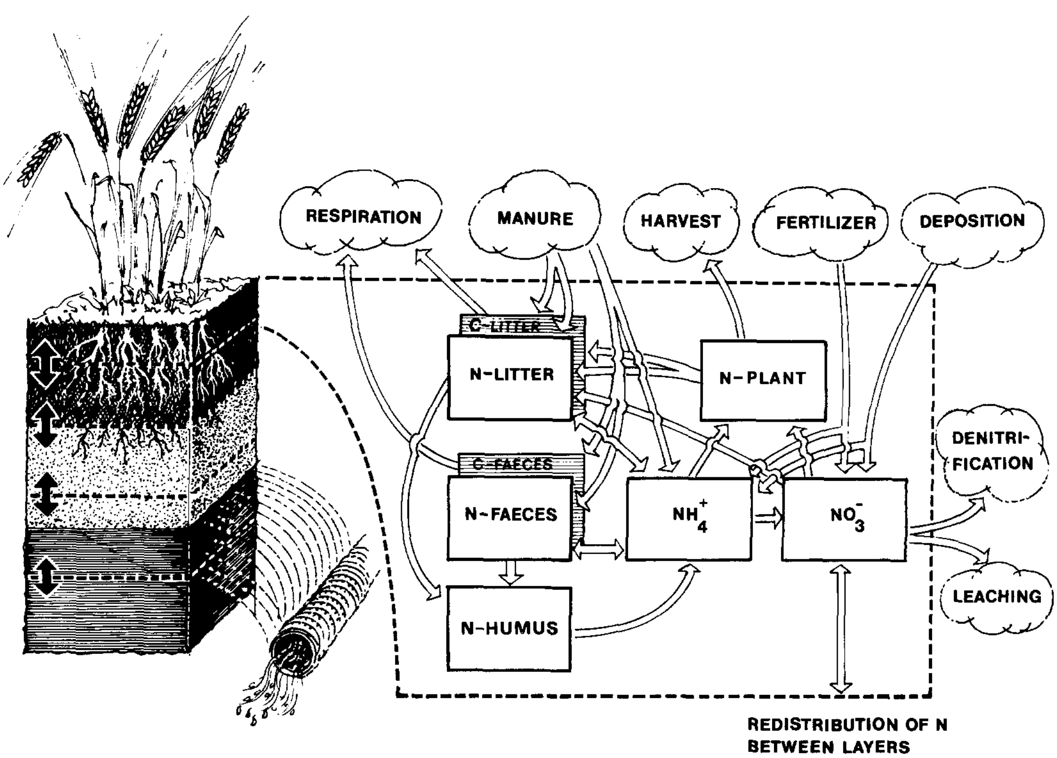

Fig. 1. Structure of the soil nitrogen model, showing state variables (boxes) and flows (arrows) included in the model. The model structure is replicated for each soil layer (From [11]).

ganic carbon pools of litter and faeces are calculated as first-order rate processes controlled by specific mineralization constants and the same abiotic response functions as above. Decomposition products are partitioned into three fractions according to a microbial synthesis efficiency (f_e) and a humification fraction (f_h). One fraction ($1-f_e$) is lost to the atmosphere as CO_2, the fraction $f_e(1-f_h)$ is assimilated and recycled within the pool, and the fraction $f_e f_h$ is stabilized as humus (Fig. 2). Corresponding nitrogen flows are calculated assuming a constant C/N ratio of decomposing biomass and humification products (r_0). The net mineralization or immobilization in the litter pool (kg ha^{-1} d^{-1}) is given by the balance between the release of nitrogen during decomposition and the nitrogen immobilized during microbial synthesis and humification, *i.e.*:

$$N_{l\text{-}am} = (N_l/C_l - f_e/r_0)C_{ld} \qquad (2)$$

where N_l and C_l are the actual masses of nitrogen and carbon in the litter pool, and C_{ld} is the decomposition rate of litter carbon (kg ha^{-1} d^{-1}). Mineralization from faeces is handled in the same way. When net immobilization occurs (*i.e.* $N_l/C_l < f_e/r_0$) the immobilization rate is reduced by assuming a maximum fraction of the mineral-N is available. Both ammonium and nitrate can be immobilized, but with preference for available ammonium.

Nitrification of ammonium to nitrate is calculated as a first-order process, modified by the

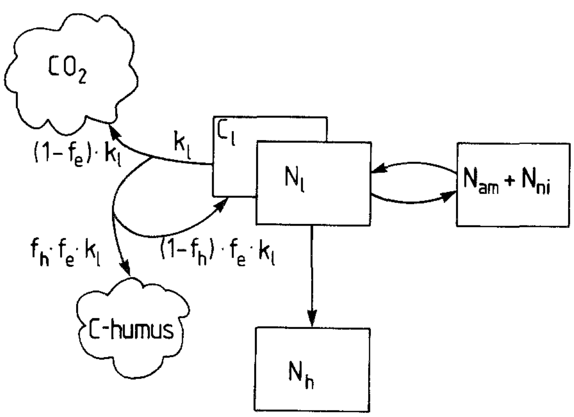

Fig. 2. Flow diagram showing carbon and nitrogen balances associated with litter (or faeces). Explanation of parameter symbols are given in the text (From [11]).

inclusion of a threshold level defined by an equilibrium nitrate/ammonium ratio, which is assumed to be characteristic for a particular soil. The transfer rate of ammonium to nitrate further depends on a specific rate contant (d^{-1}) and the same response functions for temperature and moisture as above.

The abiotic response functions regulating decomposition, mineralization, and nitrification are functions of soil temperature and soil water content. A Q_{10}-expression is used for temperature. An empirical relationship is used for volumetric water content, based on the assumption that the range within which water content is optimum is defined by two thresholds in dry and very wet soil.

Denitrification is calculated as a zero-order process based on a potential rate (kg ha^{-1} d^{-1}) and on response functions of temperature, water content, and nitrate concentration. The temperature response function is the same as that used for other microbial processes, while the response to water content is zero up to a value close to saturation, from where the response increases with increased water content to an optimum level at saturation. The nitrate concentration response is calculated with a Michaelis-Menten expression with a half-saturation constant (mg l^{-1}).

Plant uptake of nitrogen is controlled by a potential demand (logistic growth curve) which is distributed over an assumed root distribution. To limit nitrogen uptake if soil mineral-N concentration is low, a maximum availability fraction (d^{-1}) is assumed which is proportional to the total amount of mineral-N in each layer. This is similar to the situation described for immobilization. Compensatory uptake from any layer (except the uppermost layer) may also occur. When for a given layer the actual uptake is less than the demand, the difference between demand and actual uptake for this layer is added to the total demand of the crop in the layer below. Ammonium and nitrate are taken up by plants in proportion to amounts available in the soil solution.

Only nitrate is considered to be mobile, and nitrate flows are calculated as the product of water flow and nitrate concentration in the soil layer from which the water flow originates. Diffusion/dispersion is not explicitly accounted for, but due to the division of the soil profile into layers of finite thickness, numerical dispersion will occur.

The nitrogen model is described in more detail elsewhere [11].

Model application

The model was applied to experimental data for winter wheat grown in the Netherlands [5]. Simulations are only reported for the Eest site 1982/83 and 1983/84, because of the better agreement between simulated and measured water conditions for the Eest data compared to the other sites.

The adaptation of the model to the winter wheat crop was based on parameter values previously used for an application with barley [11]. However, some parameter values were changed to better reflect the conditions in the fall sown wheat.

The simulation of soil water and heat processes was the same as that described by Eckersten and Jansson [4], and is therefore not described here.

Since this study was not primarily aimed at simulating crop growth, and since comprehensive measurements of above-ground N-uptake by plants were available, we decided to use these values as target values for the simulation. This was only done, however, for the N_2 treatment in 1984. All the other simulations of plant N-uptake were parameterized in the same way, with the exception of the parameter determining potential uptake which was different between treatments and years. It was assumed that 80% of plant-N was fixed in above-ground parts, while the rest was located to roots. The C/N ratio of above- and below-ground crop residues was set at 50 and 25, respectively, as used in the previous barley study [11]. In order to provide the crop with sufficient N, as indicated by the measurements, the maximum availability fraction of mineral-N in the soil (see above) was doubled (from 8 to 16%) compared to the previous barley simulation.

The soil moisture-response function for microbial activity increased from 0 at the wilting point to an optimal rate at a water content of 13% above the wilting point, and decreased linearly from 8% below saturation to 0.6 at saturation. The temperature-response function was identical to that used in the barley simulation, *i.e.* using a Q_{10}-relationship with a Q_{10}-value of 3.

The rate constant for humus mineralization was reduced by 28.6% (from 7.0×10^{-5} to 5.0×10^{-5} d^{-1}) compared with the original barley simulation. In fact, the chosen value in this simulation was the average of several earlier model applications [1, 2, 6, 7, 11].

The nitrate/ammonium ratio in the soil was lowered from 8 as used earlier [11] to 6, motivated by site specific measurements.

In the first model application with barley, little emphasis was put on simulation of denitrification dynamics. Recently, this has been done in more detail by Johnsson *et al.* (unpublished), who found a soil moisture activity range (see above) of 18% to be more reasonable, as used in this simulation, rather than 10%, as before.

Dry deposition (0.05 kg N ha^{-1} d^{-1}) and nitrogen concentration in precipitation (3 mg l^{-1}) were adjusted to give reasonable values of total N-deposition, typical for the Netherlands.

Results and discussion

Plant N-uptake

There was a tendency to overestimate simulated N-uptake by plants in comparison to measurements, especially during the first part of the growing period (Fig. 3). A better agreement between simulated and measured values was obtained during 1984 than 1983, which may be partly explained by more reliable measurements during 1984. For example, drastic fluctuations in N-content of plants were measured both in the N_2 and N_3 treatments late in the 1983 growing season, which seemed quite unlikely (Fig. 3). During 1984, simulated and measured values of plant-N were the same in the N_2 and N_3 treatments (Fig. 3), since N-fertilization was identical in the two treatments.

A general limitation in the simulations concerns assumptions related to the partitioning between above- and below-ground plant-N. This was assumed the same for all treatments. Al-

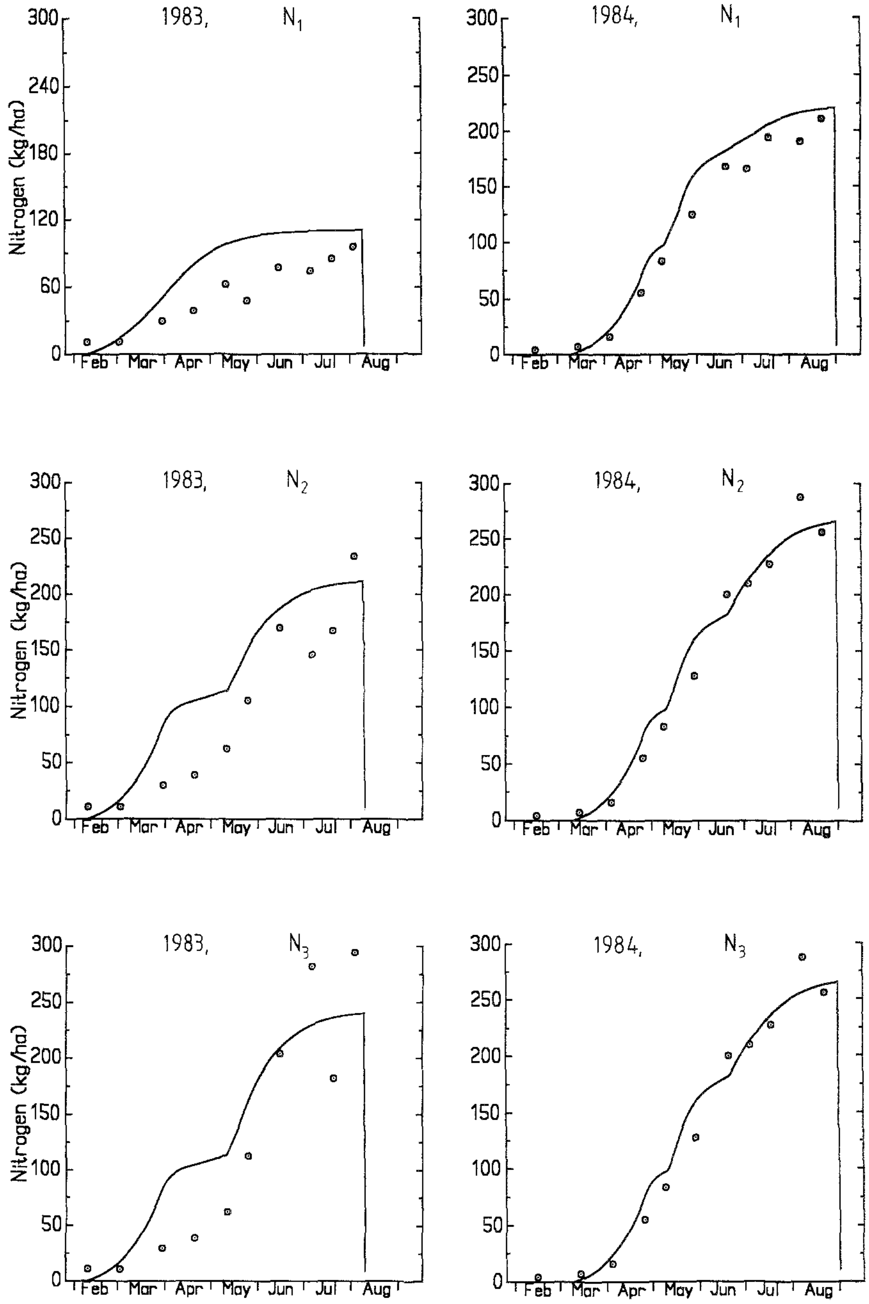

Fig. 3. Simulated (lines) and partly measured (dots) N-uptake by plants accumulated over each season (nitrogen in roots was never measured, but was assumed to be 20% of plant-N).

though no below-ground measurements were available, there is reason to believe that the treatment with low N-input (N_1) had a higher proportion of N located to roots compared with the treatments with higher N-inputs (N_2 and N_3). This may alter the deviations between simulated and measured values of plant-N. However, the export of N will not change by altering the partitioning of N within the plant, since the total N-uptake is increased. In a long-term perspective, higher proportion of roots will increase litter input and thus litter mineralization.

N mineralization and mineral-N dynamics in soil

All simulations of mineral-N content of the soil showed a reasonable agreement with the measurements (Fig. 4). Since plant N-uptake was simulated using measured uptake as target values (see above), this indicates that the chosen rate constants for humus- and litter-mineralization were reasonable values. Over the simulated period (1 Febr.–31 Dec.), the humus-N pool decreased by ca. 60 kg N ha^{-1}, while there was no net change of N in the litter pool (Fig. 5).

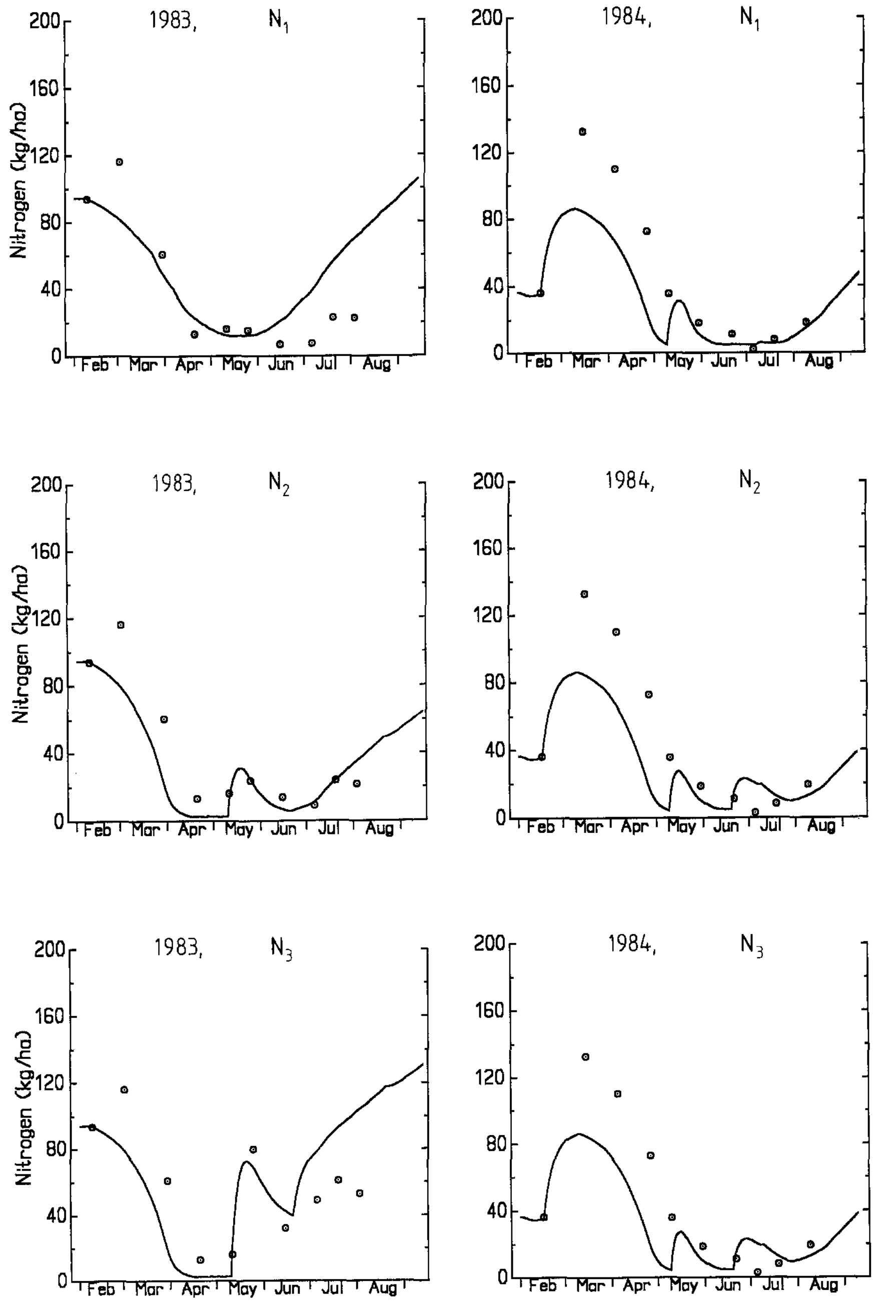

Fig. 4. Simulated (lines) and measured (dots) mineral-N contents in the soil down to a depth of 1 m.

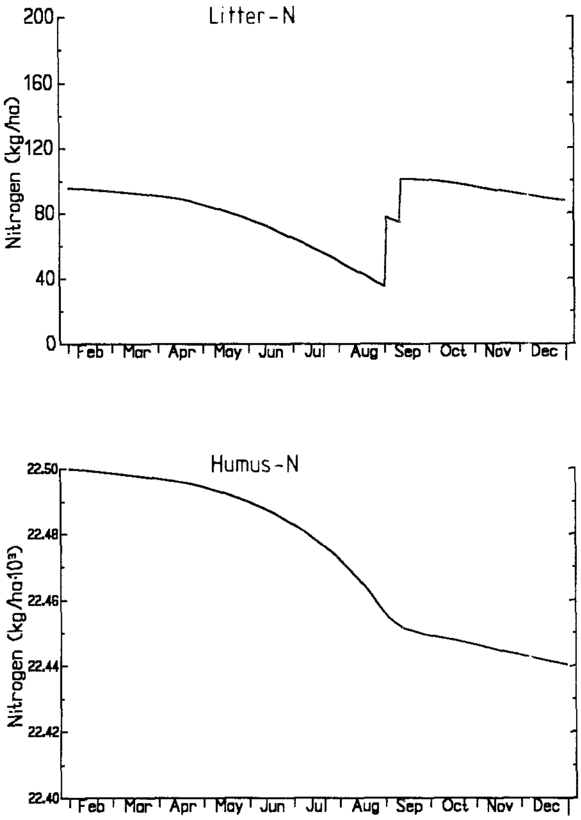

Fig. 5. Simulated variations in the litter- and humus-N pools in the soil (N_2 treatment during 1984).

These results refer to the N_2 treatment during 1984, for which plant N-uptake was calibrated. Whether this simulated decrease of humus-N is in accordance with actual field conditions could not be verified. However, to supply the crop with sufficient N, as indicated by the measurements, this decrease in humus-N is a likely explanation. There is reason to believe that the 'young' soil used in this study, with a relatively high organic matter content throughout the profile, also depletes its humus-N pool over the short-term, as in this study. Decreases of the humus-N pool during relatively short periods have also been shown in another simulation with the SOILN model, when applied to a perennial grass ley system [1].

As was shown for the plant N-uptake (see above), there was also a better agreement between simulated and measured mineral-N dynamics during 1984 than in 1983 (Fig. 4). This was especially obvious from June onwards, when the increase in simulated mineral-N values was clearly overestimated in 1983. Plant N-uptake slowed down and stopped much earlier during 1983 than during 1984 (Fig. 3), which could partly explain the overestimation. Moreover, the fact that plant N-uptake generally seemed to be simulated better during 1984, would also lead to an improved description of mineral-N dynamics, since N-uptake by plants is a large N-sink; *i.e.* small errors in plant uptake can lead to large deviations between simulated and measured mineral-N dynamics.

Concluding remarks

If measurements of nitrogen contents in plants over the season are available for calibration of

Table 1. Annual simulated nitrogen flows in the different treatments. Partial flows are given in parentheses. All values in kg N ha^{-1}

	1983			1984		
Flow	N_1	N_2	N_3	N_1	N_2	N_3
Fertilization	0	60	120	110	150	150
Deposition	34	34	34	36	36	36
Mineralization	161	156	155	154	137	137
Net litter min	(43)	(38)	(37)	(48)	(31)	(31)
Humus min	(118)	(118)	(118)	(106)	(106)	(106)
Humification	40	49	51	36	47	47
Plant uptake	110	211	240	221	266	266
Harvest	(77)	(148)	(168)	(155)	(186)	(186)
Crop residues	(33)	(63)	(72)	(66)	(86)	(86)
Leaching	11	4	4	19	17	17
Denitrification	9	10	15	20	19	19

the simple plant N-uptake approach in this model, mineral-N dynamics in soil can be satisfactorily described. However, quite often, only data on harvested nitrogen are available, which then requires a more sophisticated submodel for N-uptake by plants, including response functions for climatic variables (*cf.* [4]).

Various nitrogen flows, which have earlier been described satisfactorily with the model, were not possible to validate in these simulations. However, in order to get a general idea of the magnitude of these simulated flows, their annual sums are given in Table 1. Leaching and denitrification both reached ca. 20 kg N ha^{-1}. It is notable that the highest simulated leaching losses occurred in the treatment with lowest or no input of fertilizer-N. Total simulated mineralization was ca. 150 kg N ha^{-1}, again, with the highest amounts in the N_1 treatment. This must be due to lower immobilization over the short-term in the N_1 treatment than the other two treatments, depending on less input of crop residues with a high C/N ratio (50). In summary, these simulations indicate an improved nitrogen use efficiency with increased N-fertilization.

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