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Some results of nitrogen simulations with the model ANIMO

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Abstract

Simulation of the nitrogen behavior in the soil and the nitrogen uptake by winter wheat was performed using the model ANIMO. As input for the model ANIMO simulations of the hydrological conditions in the soil crop ecosystem were executed with the model SWATRE. Compared with measured data the simulation of nitrogen uptake by the crop was satisfactory. The simulation of mineral nitrogen in the soil agreed reasonably well with measured data for one of the experiments used for the analysis. The agreement was less for experiments with additional fertilizer applications in May and June.

Introduction

Intensification of agriculture has led to an increased fertilizer use, increasingly contaminating groundwater and surface waters. This contamination can have negative effects on other activities like municipal water supply and preservation of natural areas. The formulation and execution of a rational and effective policy to reduce the nitrogen load on groundwater reservoirs and surface waters requires a thorough understanding of the behaviour of nitrogen and its compounds in the soil.

There is a need to quantify the sources of nitrogen compounds from rural regions under various conditions of climate, soil type, water management, cropping pattern, and agricultural technologies. Nitrogen in the soil primarily originates from inorganic fertilizers, animal manures, organic matter, precipitation, biological fixation and irrigation water. It is mainly removed by crops, drainage water, denitrification and volatilization of ammonia.

The development of nitrogen models should not only focus on the selection of methods for detailed analysis of the physical, chemical and biological processes constituting the behaviour of nitrogen in the plant-water-soil system. The main aim should be to derive cause-effect relationships between agricultural practices as cropping pattern, fertilizer type, fertilizer rate and application technology, as well as water management and climatic conditions, and the generation of nitrogen compounds leaving the agricultural system. This paper deals with a description of the processes to be considered in nitrogen modelling and the performance of the model ANIMO (Agricultural NItrogen MOdel). Also a discussion of the uncertainties will be given in both measured field data and in the simulation results.

Description of the model ANIMO

A suitable model for regional use, simulating the nitrogen management in both agricultural areas and nature reserves, should be based on a clear and quantitative description of the main processes which are:
- mineralization and immobilization of nitrogen related to processes in the carbon cycle;
- nitrogen uptake by plants under conditions of both excess supply and limited nitrogen availability;
- denitrification related to (partial) anaerobiosis and decomposing organic materials, which im-

plicates the modelling of the oxygen and temperature distribution in the soil;
– soil moisture dynamics and nitrogen transport.

A complete description of the newest version of the model ANIMO is given by Rijtema et al. [6], the present paper only gives a brief description of the model principles. The central part of the model is the transport and conservation equation. By means of this equation the new concentrations of soluble compounds in all layers distinguished can be calculated after simultaneous transport and transformation processes. Assuming complete mixing in each identified model layer, the transport and conservation equation can be written as:

$$\frac{d\{V(n,t)C(n,t)\}}{dt} + \frac{dQ_a(n,t)}{dt} = \sum f_i C_i - \sum f_o C(n,t) - f_e S C(n,t) + k_0 L + k_1 V(n,t) C(n,t) \quad (1)$$

in which: n = layer number (–); t = time (d); $V(n, t)$ = moisture volume of layer n at time t (m); $C(n, t)$ = concentration in layer n at time t (kg m^{-3}); $Q_a(n, t)$ = nitrogen adsorbed at the soil complex (kg m^{-2}); $\Sigma f_i C_i$ = total incoming flux of nitrogen (kg m^{-2} d^{-1}); $\Sigma f_o C(n, t)$ = total outgoing flux of nitrogen (kg m^{-2} d^{-1}); f_e = transpiration flux (m d^{-1}); S = selectivity coefficient for crop uptake (–); k_0 = production rate coefficient of zero order (kg m^{-3} d^{-1}); k_1 = production rate coefficient of first order (d^{-1}); L = layer thickness (m).

Different analytical solutions for this equation have been introduced, depending on the change of the moisture content with time.

The model ANIMO can be linked in practice to any hydrological model for the calculation of fluxes and changes in moisture content per layer. In all cases the hydrological calculations should be executed completely before the model ANIMO can be applied. The output file of the hydrological model was used as input for ANIMO. We used the model SWATRE for the hydrological simulation using the given soil physical data as input. A description of this model is given by Belmans et al. [1] and Feddes et al. [3].

Though processes and transport of solutes in the unsaturated zone can be described one-dimensionally, this is not the case in the saturated zone, where also horizontal transport to different drainage systems should be considered. The model ANIMO has a pseudo two-dimensional transport module to calculate solute transport to different drainage systems.

The different organic materials added to or present in the soil contain nitrogen as well as carbon, so the transformations in the carbon cycle correspond with the transformations in the nitrogen cycle. To understand the processes in the nitrogen cycle it is necessary to quantify the processes in the carbon cycle too, because of the many interdependences between organic material and nitrogen. For the quantification of the carbon cycle a Jenkinson and Rayner [5] type of model formulation has been used.

The carbon cycle as used in ANIMO is given in Fig. 1. The input of carbon by organic plant parts and manure can be given by a number of fractions depending upon the decomposition rate and C/N ratio. The choice of the number of fractions is in principle free.

The different organic materials mentioned contain besides carbon also nitrogen. So the transformations in the carbon cycle correspond with transformations in the nitrogen cycle. The schematized nitrogen cycle is given in Fig. 2. It can be seen that part of the cycle corresponds closely with the carbon cycle. In this part the decomposition rate of organic carbon and the formation rate of soil organic material determines the mineralization and immobilization of nitrogen. The other part of the nitrogen cycle

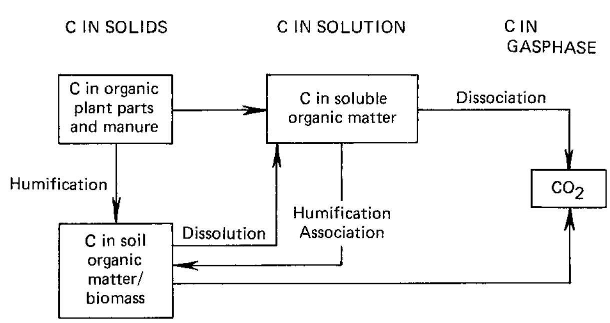

Fig. 1. The carbon cycle in the model ANIMO.

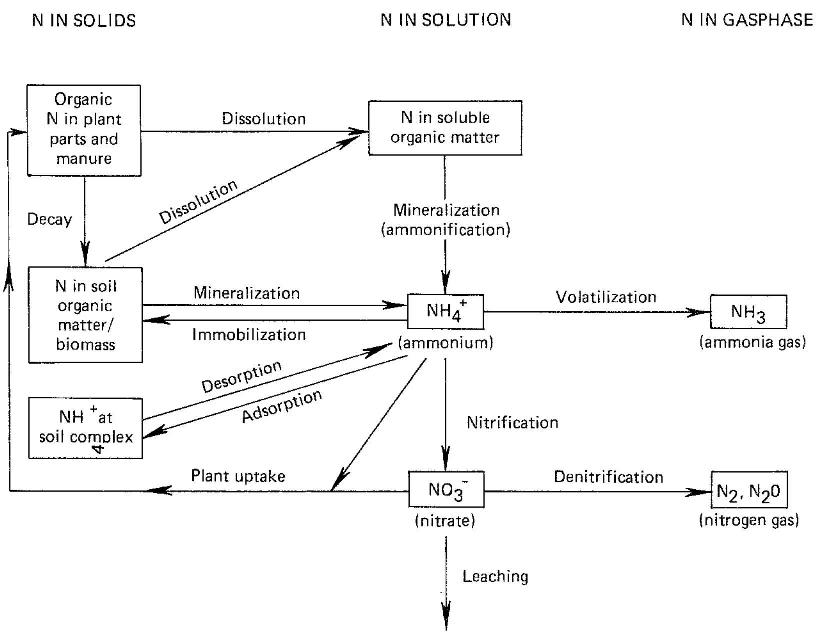

Fig. 2. The nitrogen cycle in the model ANIMO.

describes processes such as nitrification and denitrification. Nitrification is described as a first-order process, denitrification is described as a zero-order process with respect to nitrate, but as a first-order process with respect to organic carbon decomposition.

The ammonium ion with its positive charge can be adsorbed at the soil complex; this is formulated as linear adsorption.

NH_4 ions and NO_3 ions can be taken up from the soil solution by the plant roots using the transpiration flux and/or through diffusion. Both processes were taken into account by a proper choice of the selectivity coefficient S in Eq. (1):

$$S(t+1) = N_m(t)/N_r(t) \tag{2}$$

in which $S(t+1)$ = selectivity coefficient for timestep $t+1$, (−); $N_m(t)$ = maximum cumulative nitrogen uptake by the crop (kg m^{-2}); $N_r(t)$ = real cumulative nitrogen uptake (kg m^{-2}).

In the model the main environmental influences on the transformation processes are temperature, pH, moisture and oxygen.

The transformation rate for chemical and biological processes generally increases with temperature. The soil temperature at a certain depth z (m) from soil surface and at a certain day of the year was calculated using a simple sinus wave submodel with a damping effect for depths below the soil surface:

$$T(z,t) = T_a + A_0 \exp(-z/D_m) \times \cos(\omega t + \phi - z/Dm) \tag{3}$$

in which $T(z,t)$ = temperature at depth z and time t, (°C); T_a = average yearly temperature, (°C); A_0 = amplitude of temperature wave, (°C); D_m = damping depth, (m); ω = frequency of temperature wave, (rad d^{-1}); ϕ = phase shift, (rad).

Because the optimum temperature for biological processes is often around 30°C or higher, it can be assumed for the temperatures occurring in soil that the reaction rates increase with temperature. For temperatures from 0 to 26°C this curve has been described by the Arrhenius equation:

$$r(T) = Z \exp\{-a/(T+273)\} \tag{4}$$

in which: $r(T)$ = rate at temperature T (−); Z = constant (−); a = constant (°C).

For the effect of pH on reaction rates only one function for the various processes has been introduced in the model. The pH-reduction factor (r) is given as:

$$r = (1 + \exp\{-2.5(\mathrm{pH} - 5.0)\})^{-1} \quad (5)$$

Moisture content and oxygen status are strongly related in the soil and therefore they were treated together. Microorganisms need moisture to perform their functions. Below wilting point these are disturbed. Between the values pF 3.2 and 4.2 the reduction factor for moisture decreases linearly from 1.0 to 0.2.

The reduction in the transformation rate coefficients under wet conditions is generally caused by dilution effects and lack of oxygen in the soil system. In the model ANIMO this reduction has therefore been described on the basis of soil aeration. The aeration of the soil depends on the air-filled pore space, the diffusion coefficient and the oxygen consumption in the soil. The conditions for partial aeration in the soil have been described in the model by vertical diffusive transport through the air-filled pores and a radial horizontal transport through the water phase, while a stochastic approach has been used for the non-homogeneous distribution of the air-filled pores in the soil system. The conditions in the upper unsaturated zone are strongly determined by the results of the calculations of the hydrological model used, which determines the amount of percolating water to the groundwater reservoir, but also the soil moisture distribution and the oxygen transport in the unsaturated zone. A poor simulation of the soil moisture distribution by the hydrological model used automatically results in a poor simulation of the carbon and nitrogen cycle.

The model calculates the total oxygen requirement on the basis of the decomposition of the organic materials and nitrification. The difference between the maximum required quantity of oxygen and the available oxygen by diffusion has been used as a basis for the total denitrification in each layer. If insufficient nitrate is available a nitrate-related reduction factor for the decomposition of organic material will be calculated.

Available data

Data on soil moisture dynamics, nitrogen dynamics, crop growth and nitrogen uptake of extensive field experiments were collected by Groot and Verberne [4]. Fertilizer applications varying from 0–240 kg N per ha were applied between the months February and June. At each location groundwater levels were measured during the growing season of the year 1984. Since there were no data available of vertical fluxes in the saturated zone the model SWATRE was applied with a measured groundwater level as lower boundary. The output of the model SWATRE, used as input for ANIMO, gave the following data for each timestep: precipitation, evaporation, transpiration, runoff, groundwater level, moisture contents, fluxes to/from different compartments, boundary fluxes across the lower boundary and lateral fluxes to/from drainage systems per compartment.

Simulation results and discussion

The description of the simulation results will be limited to the upper meter of the soil profile since the available measured data on nitrogen turnover refer to this part of the soil. Mineral nitrogen is presented for the layers 0–40 cm and 0–100 cm to give an impresssion of the model results in the upper part of the soil.

Simulations were executed for the Eest and PAGV. Calculations were started with the Eest-data as this was the most complete dataset. The simulation of the nitrogen treatment N1 will be discussed in detail.

Eest N1

The water balance for the Eest experiments as a result of simulations with the model SWATRE is given in Fig. 3 for the top soil layer to 1 meter depth. In this balance the seepage and leakage indicate the total flow through the lower boundary at one meter depth. The leakage gives the total outflow to deeper soil layers during drainage conditions whereas the seepage gives the inflow by capillary rise through the lower boundary during periods with a surplus of evaporation

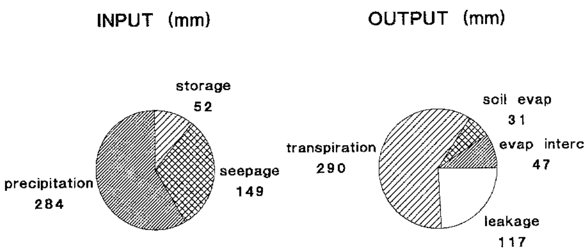

Fig. 3. Water balance of the top soil layer 0–100 cm; evap = evaporation, interc = intercepted water (Eest N1).

and a groundwater table at more than one meter depth. Figure 4 shows the simulated and measured moisture volumes for two layers. Simulated data followed the measured ones reasonably well.

The seasonal nitrogen balance for the Eest N1 field is given in Fig. 5. The results showed that the contribution of the fertilization input and availability of mineral N by mineralization were of the same order of magnitude, each contributing for about 40% of the total mineral N input during the period of growth. The N uptake of the crop was about 69% of the total available nitrogen as simulated by ANIMO. Denitrification losses were 31% of the total available mineral nitrogen.

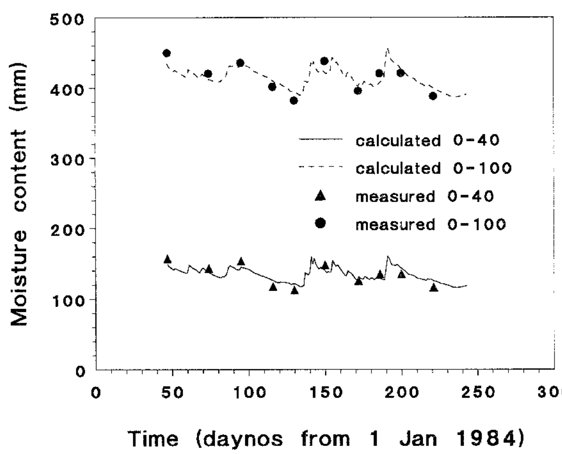

Fig. 4. Simulated and measured moisture volumes for the layers 0–40 cm and for the layer 0–100 cm (Eest N1).

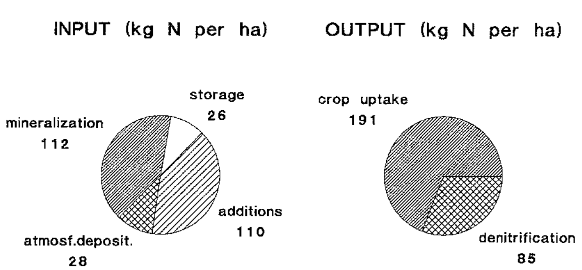

Fig. 5. Nitrogen balance of the top soil layer 0–100 cm (Eest N1).

A more detailed analysis of the nitrogen uptake by the crop is given in Fig. 6. The model ANIMO simulates total nitrogen uptake, including nitrogen present in roots and stubble, whereas the measured data were without this quantity. On the basis of available experimental data the quantity of nitrogen present in roots and stubble can be estimated at about 15 kg per ha. It appeared from Fig. 6 that measured and simulated nitrogen uptake during growth agreed reasonably well.

The total mineral nitrogen present in the soil of the Eest N1 field during growth is given for two layers in Fig. 7. Figure 8 shows the measured and simulated data separately for NH_4–N and NO_3–N for the layer 0–100 cm. It was remarkable that after the fertilizer addition of 60 kg N applied at dayno. 132 an increase in mineral nitrogen in the measured data did not occur. The simulated data, however, showed an increase in total mineral nitrogen immediately after application, followed by a sharp reduction in the days after application. Next to an increased uptake by the crop after this application also an increased denitrification reduced the quantity of mineral nitrogen in the soil, caused by partial anaerobiosis due to heavy summer rains. Figure 9A gives the distribution of precipi-

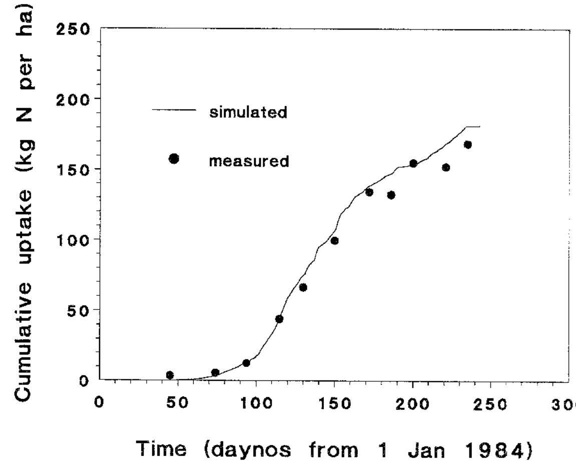

Fig. 6. Simulated and measured cumulative nitrogen uptake by the crop (Eest N1).

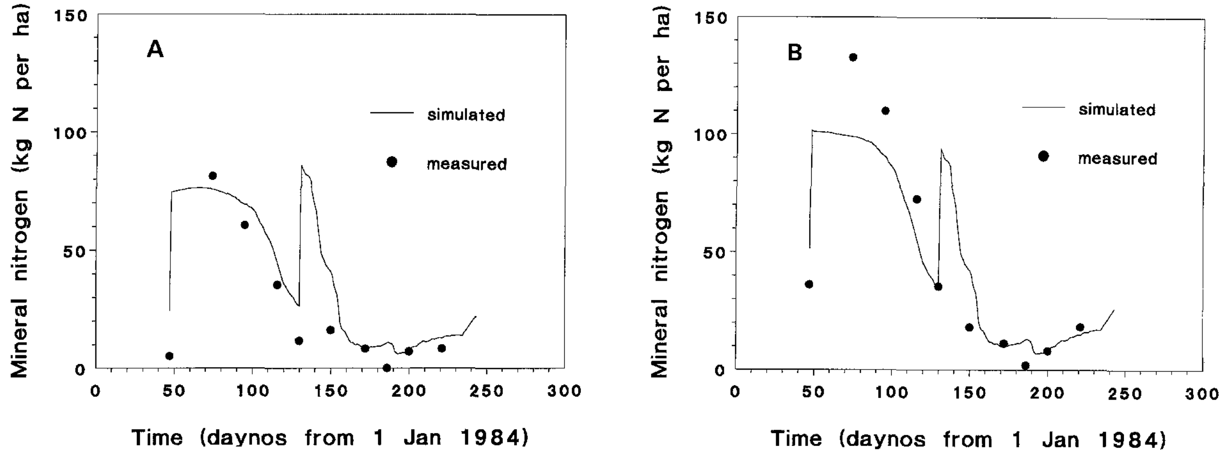

Fig. 7. Simulated and measured soil mineral nitrogen (ammonium + nitrate) for the layer 0–40 cm (A) and for the layer 0–100 cm (B) (Eest N1; applications of 50 and 60 kg N per ha at daynos 48 and 132 respectively).

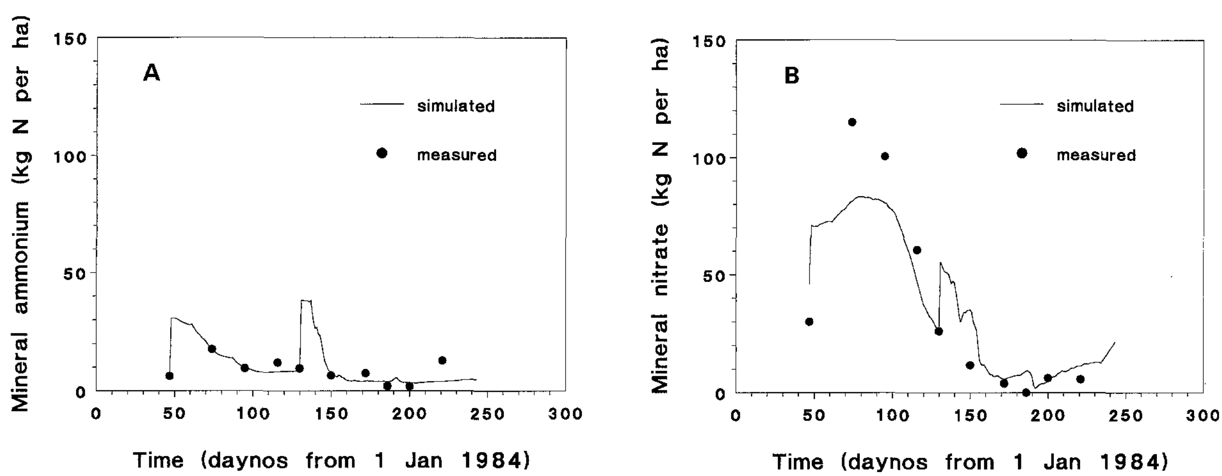

Fig. 8. Simulated and measured soil mineral ammonium (A) and nitrate (B) for the layer 0–100 cm (Eest N1).

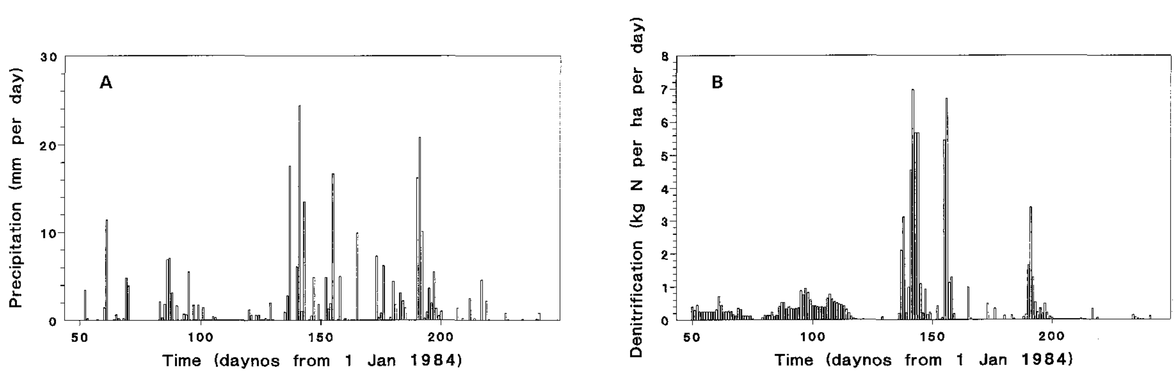

Fig. 9. The distribution of precipitation (A) and denitrification (B) during the growing season (Eest N1).

tation during growth. The simulated denitrification rate is presented in Fig. 9B, showing denitrification peaks coinciding with heavy rains. The calculated total reduction in mineral nitrogen in the soil followed the measured data reasonably well.

Eest N2, N3

Figure 10 shows the results for measured and simulated nitrogen uptake by the crop of the Eest N2 and N3 fields. Both fields received the same amount of nitrogen fertilization and can be considered as an experiment in twofold. The measured data of both fields as plotted in Fig. 10

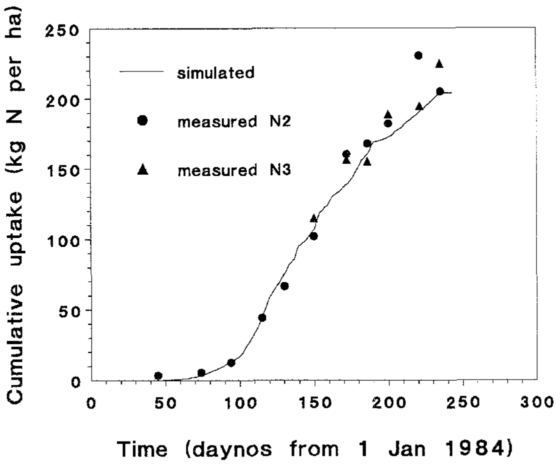

Fig. 10. Simulated and measured cumulative nitrogen uptake by the crop (Eest N2 and N3).

give an indication of the spatial variability of the measured data. The simulated data followed the measured ones reasonably well. Figure 11 gives the mineral nitrogen in the soil profile for two layers. The duplicated measurements give also an indication of the spatial variability in measured mineral nitrogen data. The simulated data appeared to describe the temporal variation in mineral nitrogen in the soil following the fertilizer additions of 60 kg N at dayno. 132 and of 40 kg N at dayno. 173 satisfying as compared with the measured data.

PAGV N1, N2, N3

Figure 12 gives the comparison between both measured and simulated nitrogen accumulation in the crop. The simulated crop uptake data for the three fertilizer treatments were in good agreement with the measured ones.

The course in mineral nitrogen in the soil for the 0–40 cm top layer is given in Fig. 13. A good agreement between simulated and measured data was present in the N1 experiment. The results were less for the N2 and N3 experiments. The fertilizer additions of 60 and 120 kg N per ha for respectivily the N2 and N3 fields at dayno. 135 and the addition to both fields of 40 kg N per ha at dayno. 160 affected the simulated mineral nitrogen in the 40 cm top layer considerably, whereas they did hardly affect the measured data.

The total mineral nitrogen simulated for the

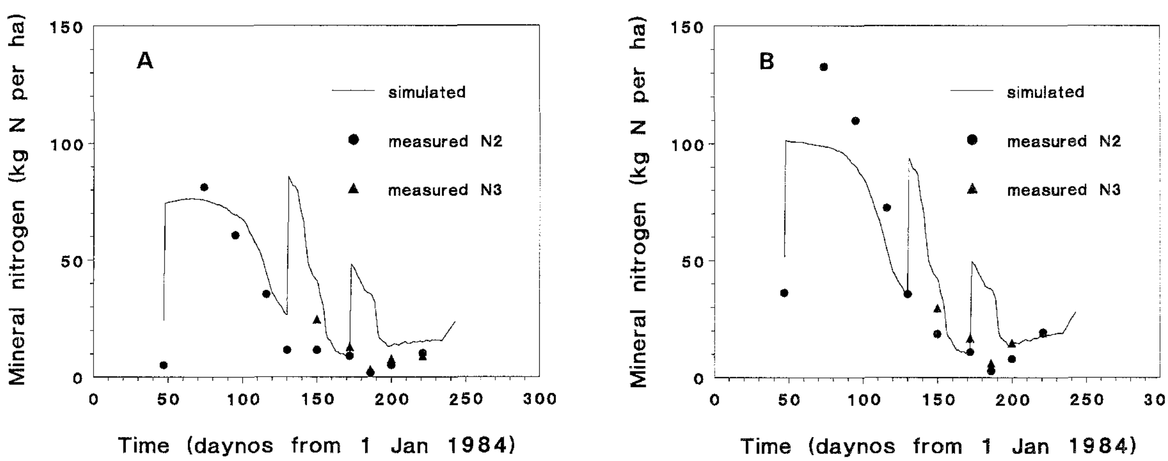

Fig. 11. Simulated and measured soil mineral nitrogen (ammonium + nitrate) for the layer 0–40 cm (A) and for the layer 0–100 cm (B) (Eest N2 and N3; applications of 50, 60 and 40 kg N per ha at daynos 48, 132 and 173 respectively).

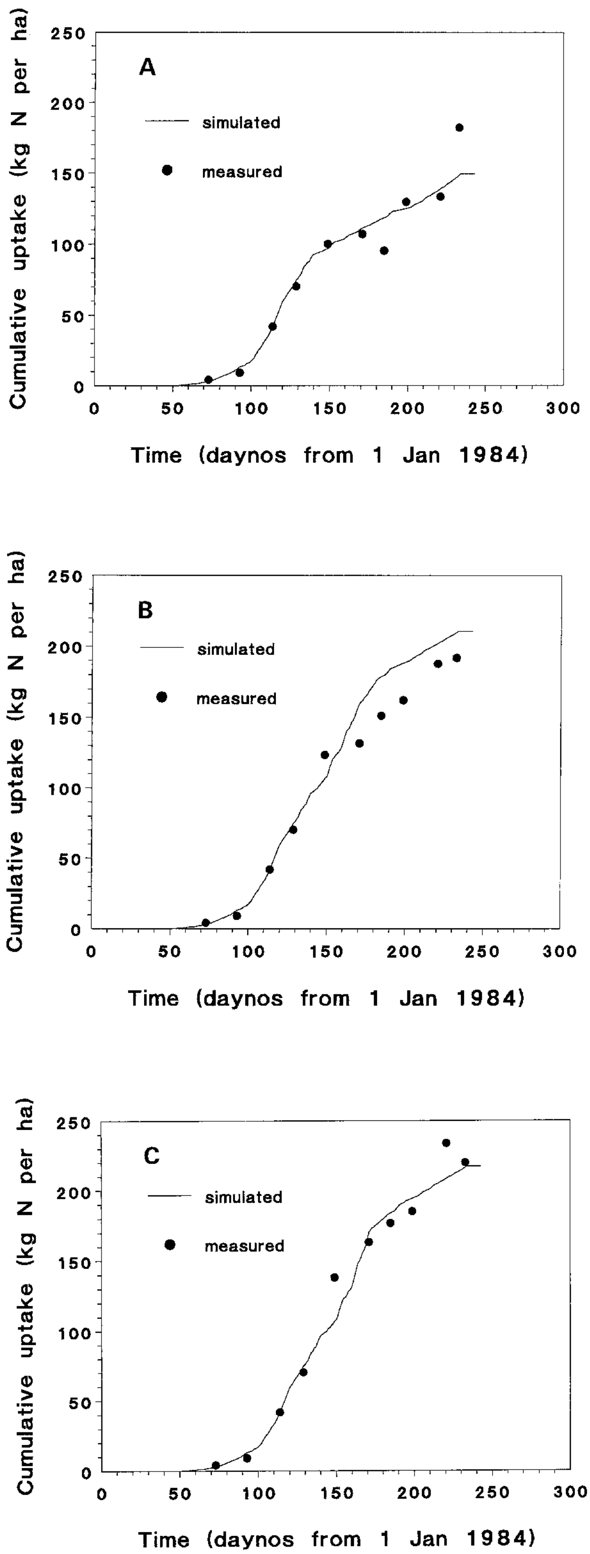

Fig. 12. Simulated and measured cumulative nitrogen uptake by the crop, PAGV N1 (A), N2 (B) and N3 (C).

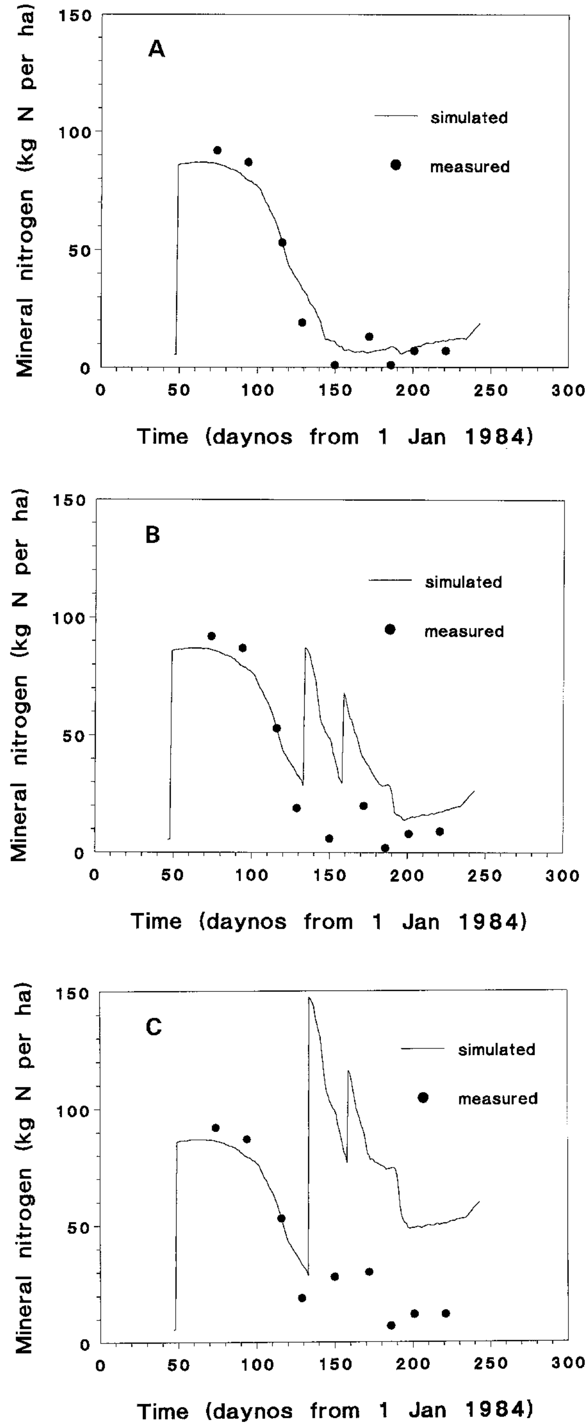

Fig. 13. Simulated and measured soil mineral nitrogen (ammonium + nitrate) at location PAGV, for the layer 0–40 cm, N1 (A), N2 (B), N3 (C) (N1: application of 80 kg N per ha at dayno. 48, N2: applications of 80 and 60 Kg N per ha at daynos 48 and 135, respectively, N3: applications of 80, 120 and 40 kg N per ha at daynos 48, 135 and 160 respectively).

soil profile from 0–100 cm, as given in Fig. 14, deviated from the measured data. The total increase in measured mineral nitrogen between dayno. 46 and 73 was 108 kg N per ha, while the fertilizer addition at dayno. 48 was only 80 kg per ha. The difference between increase in mineral nitrogen and addition seemed to be mainly due to the variation in mineral nitrogen in the layer 40–100 cm. At daynos 18, 46 and 73 the mineral nitrogen was respectively 52, 15 and 32 kg N per ha for this layer. The precipitation excess during this period was however very small, and denitrification is unlikely to have occurred.

The effects of the nitrogen additions of the N2 and N3 fields at daynos 135 and 160 on nitrogen uptake by the crop were simulated in a correct way as appears from Fig. 12. Also an extra denitrification rate during the summer rains was simulated. However, during the rainfall in the period from dayno. 141 to 155, as given in Fig. 9, a sharp rise of the groundwater table from 160 cm to 116 cm below soil surface was observed. It is not clear whether due to crack formation short-cuts in the soil system were present resulting in a rapid transport of mineral nitrogen below the maximum sampling depth of 100 cm, or not.

General discussion and conclusions

Only one set of soil physical data was available for the Eest and PAGV experiments while the hydrological boundary conditions were derived from measured data of the groundwater table depth. The limited availability of these data prevented to analyse thoroughly the effect of spatial variation on soil physical properties and hydrological conditions. Van der Bolt et al. [2] showed in an analysis of the uncertainties in the performance of the model ANIMO on a field scale that the effects of different bulk densities and organic matter contents on the variation in soil properties did hardly effect the dynamic water balance simulations of the hydrological model. The input of the simulated soil moisture distributions in the model ANIMO, resulted in different aeration conditions. Results of the simulation of mineral nitrogen in the soil by the model

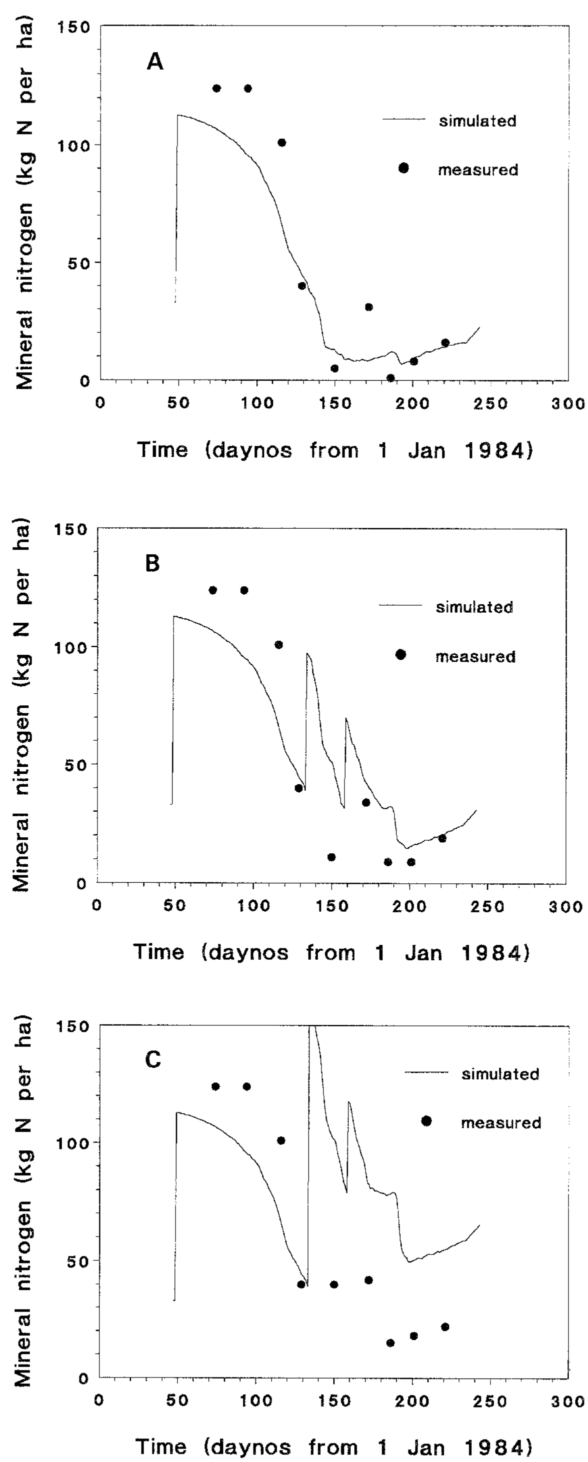

Fig. 14. Simulated and measured soil mineral nitrogen (ammonium + nitrate) at location PAGV, for the layer 0–100 cm, N1 (A), N2 (B) and N3 (C) (N1: application of 80 kg N per ha at dayno. 48, N2: applications of 80 and 60 kg N per ha at daynos 48 and 135 respectively, N3 applications of 80, 120 and 40 kg N per ha at daynos 48, 135 and 160 respectively).

ANIMO did strongly depend on the variation in moisture conditions. The variation in measured mineral nitrogen in the soil profile at different locations in the same field was of the same order of magnitude as the variation in the simulated values of mineral nitrogen due to the variation in soil physical properties. In both the Eest and PAGV experiments the variation in soil physical conditions has not been taken into account. Also the effects of bypass flow due to cracking in the soil profile has not been considered, which might partly explain the differences between measured and simulated mineral nitrogen in the soil.

The formulation of partial anaerobiosis in the model ANIMO gave only partially an explanation for the sharp reduction in mineral nitrogen in the soil profile after additions during the growing season.

The model ANIMO did give a good simulation of the accumulated nitrogen uptake by the crop for all the fertilizer treatments in the Eest and PAGV experimental fields.

References

1. Belmans C, Wesseling JG and Feddes RA (1983) Simulation model of the water balance of a cropped soil: SWATRE. J Hydrol 63, 3/4: 271–286
2. Bolt FJE van der, Pankow J, Roest CWJ, Toorn A van den (1990) De invloed van de stikstofhuishouding in de bodem op de grondwaterkwaliteit in waterwingebied 't Klooster. Rapport 31, 29 pp Wageningen, The Netherlands: The Winand Staring Centre
3. Feddes RA, Kowalik PJ and Zaradny H (1978) Simulation of field water use and crop yield. Simulation Monographs, 189 pp Wageningen, The Netherlands: PUDOC
4. Groot JJR and Verberne ELJ (1991) Response of wheat to nitrogen fertilization, a data set to validate simulation models for nitrogen dynamics in crop and soil. Fert Res 27: 349–383
5. Jenkinson DS and Rayner JH (1977) The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Science 123: 298–305
6. Rijtema PE, Roest CWJ and Kroes JG (1990) Formulation of the nitrogen and phosphate behaviour in agricultural soils, the ANIMO model. Report 30, (in press) Wageningen, The Netherlands: The Winand Staring Centre