

Reprinted from

ECOLOGICAL MODELLING

**INTERNATIONAL JOURNAL
ON ECOLOGICAL
MODELLING AND
SYSTEMS ECOLOGY**

Ecological Modelling 81 (1995) 213–222

Simulation of temperature-, water- and nitrogen dynamics using the model CANDY

U. Franko *, B. Oelschlägel, S. Schenk

Umweltforschungszentrum Leipzig-Halle GmbH, Sektion Bodenforschung, Hallesche Str. 44, 06246 Bad Lauchstädt Germany

Received 8 September 1993; accepted 12 April 1994



Simulation of temperature-, water- and nitrogen dynamics using the model CANDY

U. Franko *, B. Oelschlägel, S. Schenk

Umweltforschungszentrum Leipzig-Halle GmbH, Sektion Bodenforschung, Hallesche Str. 44, 06246 Bad Lauchstädt Germany

Received 8 September 1993; accepted 12 April 1994

Abstract

The theoretical basis of the simulation model CANDY (CARbon-Nitrogen-DYnamics) is briefly described along with results of its application to a test data set. The model contains modules for calculating soil temperature, moisture content and the processes of the soil carbon–nitrogen cycle. The model inputs are weather data (air temperature, precipitation and global radiation on a daily basis), plant development characteristics (seeding, harvesting, crop height and root depth), soil texture data and agricultural management (irrigation, fertilization, manuring, tillage).

The test data material from two catchments in north Germany, one with loam soil (Neuenkirchen) and one with sand (Nienwohlde) included data from several nitrogen fertilizer treatments. The results show that the model outputs for temperature, moisture and nitrogen fit the observations quite well despite some deviations. Summarizing for all soil layers the square root of the mean quadratic differences of simulated and observed data are: for soil temperature ≤ 2.3 K for the loamy soil over a five-year period and ≤ 2.5 K for the sandy soil over a five-year period; for soil moisture ≤ 4.1 Vol.% for the loam and ≤ 4.4 Vol.% for the sand both over a three-year period.

The results of soil nitrogen in 0–90 cm depth depend on the particular site under consideration. In most cases 2/3 of the whole data was contained within the deviation class less than or equal to 40 kg ha^{-1} .

The differences between observed and simulated data are within the usual range for applications on farm fields.

Keywords: Nitrogen; Temperature; Water dynamics

1. Theory

The simulation model CANDY describes carbon and nitrogen dynamics in an agriculturally used soil down to 2 m depth. It is assumed that this soil region consists of 20 homogeneous soil

layers of 10 cm thickness which are described by a set of state variables. Simulation results are produced in one day steps. The model consists of the following submodels:

- the soil temperature model
- the hydrological model
- the crop model
- model of the organic matter turnover including the soil nitrogen model.

* Corresponding author.

The use of the simulation model is organized by a data bank desktop coming from the programming language FOXPRO (Fox Holdings Inc., 1991). The desktop allows

- the handling of weather, management and measurement data
- start of the daystep simulation
- forecasts of soil nitrate supply and organic matter level in steady-state.

1.1. The soil temperature model

The state variable of this submodel is soil temperature T . It is modeled by solving the heat flow equation (Suckow, 1986)

$$\frac{\partial(CT)}{\partial t} = \frac{\partial}{\partial z} \left(\alpha \frac{\partial T}{\partial z} \right) \quad (1)$$

where t is time (d), z is depth (cm), C is volumetric heat capacity of soil ($\text{J cm}^{-3} \text{K}$), T is soil temperature (K), α is thermal conductivity ($\text{J s}^{-1} \text{cm}^{-1} \text{K}^{-1}$).

Two boundary conditions for Eq. 1 have to be given. The soil temperature at 5 cm depth is defined as the weighted mean of the air temperatures of present day, yesterday and the day before, multiplied by a time-dependent correction factor. The correction is done to take into account the neglected meteorological elements and for the crop influence on surface temperature. As the second boundary condition zero heat flow is assumed in a depth of 200 cm.

1.2. The hydrological model

In this section the volumetric water content for all soil layers and the water equivalent of the snow cover are the state variables. The hydrological processes are modeled on the basis of the capacity concept: flow of water is only allowed by exceeding a soil-specific value of field capacity or uptake by evaporation and transpiration. The submodel consists of the following processes:

- draining of water by gravitation forces (Glugla, 1969):

$$\frac{dW}{dt} = -\lambda(W - W_{FK})^2, \quad W \geq W_{FK} \quad (2)$$

where t is the time, W is the water content (mm) of a soil column of defined thickness, W_{FK} is the water content at field capacity (mm), λ is the drainage parameter ($\text{mm}^{-1} \text{d}^{-1}$).

- interception of water by the crop depending on the crop height (Koitzsch, 1990)
- calculation of potential evapotranspiration and the realization of the actual daily value (Koitzsch, 1990):

$$E_p = 0.0041(T_{\text{air}} + 22.7)(G + 2.09)$$

$$ET_p = \min(1 + 0.004h, 1.4) E_p \quad (3)$$

$$EI_p = 1.3 E_p$$

where T_{air} is the air temperature ($^{\circ}\text{C}$), G is the daily global radiation (MJ m^{-2}), E_p is the value of pan evaporation (mm d^{-1}), ET_p is the potential evapotranspiration (mm d^{-1}), EI_p is the potential evaporation of intercepted water by crop (mm d^{-1}) and h is the crop height (cm).

The actual value of evaporated water ET_a (mm d^{-1}) is the following sum of terms of Eq. 3 (Koitzsch, 1990):

$$\begin{aligned} ET_a = & 0.5 \min(EI_p, R_i) \\ & + \psi H_1 \max(0, (1 - R_i/EI_p) ET_p) \\ & + (1 - \psi) H_2 E_p \end{aligned} \quad (4)$$

where ET_a is the actual evapotranspiration (mm d^{-1}), R_i is the intercepted water (mm d^{-1}), ψ is the fraction of the soil surface covered by transpiring plants, and H_1 , H_2 are reduction coefficients, calculated as functions of water content (Koitzsch et al., 1980).

- process of snow accumulation and melting (Koitzsch and Günther, 1990).

1.3. The crop model

The crop model consists of parameters describing the time course of the state variables crop height, crop coverage of soil surface and root depth as piecewise-linear functions and nitrate uptake by the plants. Constant values are used for the intervals necessary to reach the

different plant development stages. The necessary parameters exist for a wide variety of crops.

In the standard version of CANDY the nitrate uptake is calculated by the following "s-shaped" function (Franko, 1989)

$$N_{\text{upt}}(t) = 0.5 \left(1 + \frac{\tanh((2t/V - 1)S)}{\tanh(S)} \right) N_{\text{Yield}} \quad (5)$$

where N_{upt} is the total nitrogen in the crop (kg N ha^{-1}), t is the time (d, with zero at the begin of plant uptake), N_{Yield} is the total nitrogen uptake at harvest (kg N ha^{-1}), V (d) is the crop-dependent length of the vegetation period, S is a crop parameter and \tanh denotes hyperbolic tangens function.

For this paper a new model version was applied which calculates the daily nitrate uptake by the equation

$$D_{\text{upt}}(t) = k_{\text{trans}} DT_a(t) \quad (6)$$

where $D_{\text{upt}}(t)$ is the daily nitrate uptake (kg N ha^{-1}), k_{trans} is the crop dependant transpiration factor ($\text{kg N ha}^{-1} \text{ mm}^{-1}$), DT_a is the daily amount of transpiration (mm).

1.4. The nitrogen dynamics

The simulation of soil nitrogen (N) is a part of the modeled organic soil carbon (C) cycle, which is the energy-supplying process. The soil organic matter taking part in the turnover processes is subdivided into three compartments: the added organic matter (AOM), the biologically active soil organic matter (BOM) and the stabilized soil organic matter (SOM). The turnover processes take place in the BOM pool only. The different pools are connected by matter exchange. For soil nitrogen two pools are considered: soil nitrate N_{nit} and soil ammonium N_{amm} . The state variables of this submodel are BOM, SOM, different forms of AOM, N_{nit} and N_{amm} . In the submodel the following processes are considered:

- *Input of mineral nitrogen* into soil from immissions or fertilizer

- *Leaching of dissolved nitrate* by convective water movement (Burns, 1974) with an additional assumption to account for dispersion. Of the total soil water content only the amount above the wilting point is considered available for nitrate transport.

- *Mineralization of organic matter in soil*: All processes of the C turnover are formulated as first-order reactions (Franko, 1990), the N processes are deduced from the specific C/N ratio of the different C compartments. The AOM pool decays with rate coefficient k_{AOM} . The relation of the BOM production to the AOM decay is described by the synthesis coefficient η . The BOM and SOM pools are characterized by a C/N ratio of 8.5. Depending on the C/N ratio of the decaying AOM pool nitrogen mineralization or immobilization occurs. The model may handle up to six different AOM pools. In addition a C loss to carbon dioxide for the BOM pool is modeled with coefficient k_{BOM} . The mathematical formulation of the considered processes is given by Eq. 7.

$$\begin{aligned} \frac{dC_{\text{AOM}}(t)}{dt} &= -k_{\text{AOM}}C_{\text{AOM}}(t) \\ \frac{dC_{\text{BOM}}(t)}{dt} &= \eta k_{\text{AOM}}C_{\text{AOM}}(t) - (k_{\text{BOM}} + k_s)C_{\text{BOM}}(t) \\ &\quad + k_a C_{\text{SOM}}(t) \\ \frac{dC_{\text{SOM}}(t)}{dt} &= k_s C_{\text{BOM}}(t) - k_a C_{\text{SOM}}(t) \end{aligned} \quad (7)$$

where C_{\dots} are the C contents of the corresponding compartments of soil organic matter (kg C ha^{-1}), k_{\dots} are the rate coefficients (d^{-1}), depending on soil temperature and moisture content, η is the dimensionless synthesis coefficient.

- *Nitrification*: The turnover of ammonium into nitrate is implemented as a Michaelis-Menten reaction (McLaren, 1970). The rate coefficient has the same environmental dependencies as in the mineralization processes.

- *Denitrification*: Gaseous nitrogen losses into atmosphere are possible as the result of denitrifi-

Table 1
Initial values, used in the simulation runs

Mineral nitrogen:	40 kg N ha ⁻¹ , equally distributed from 0 cm to 200 cm depth
Water content:	field capacity
Temperature:	linear function with 0° C at 0 cm and 10° C at 300 cm depth
Soil organic matter (decomposable carbon):	
Bockschlag and Intensive Loam Site:	25 000 kg C ha ⁻¹
Intensive Sand Site:	19 000 kg C ha ⁻¹

cation processes. They decrease the nitrate pool according to the following equation

$$-L_{\text{gas}} = \frac{dN_{\text{nit}}(t)}{dt} = -k_{\text{den}} R_{\text{den}} N_{\text{nit}}(t) C_{\text{BOM}}(t) \quad (8)$$

where L_{gas} is the gaseous nitrogen loss rate (kg N ha⁻¹ d⁻¹), k_{den} is the reaction coefficient (kg C⁻¹ ha d⁻¹), R_{den} is a dimensionless reduction term, depending on soil temperature and soil water content.

2. Initial values and soil hydrological parameters used in the simulation runs

The following initial values (Table 1) and hydrological parameters (Table 2) were used in the simulation runs. They are based on regression

results from known texture data and from informed experience. Starting day of the simulation was each time the 1st January of the year, i.e. Bockschlag 1990, Intensive Loam Site 1987, Intensive Sand Site, usual fertilization (N4) 1989 and Intensive Sand Site, reduced fertilization (N6) 1990.

3. Results of the soil temperature model

The soil temperature submodel includes parameters for converting air temperature measurements into temperature at depth 5 cm. These parameters should be fitted using long-term records of air and surface temperature data. Because such data material was not available, a standard parameter set was used. The influence of the crop cover on surface temperature was

Table 2
Soil hydrological parameters, used in the simulation runs

	Field capacity [Vol%]	Wilting point [Vol%]	Parameter A (mm ⁻¹ d ⁻¹)
Bockschlag			
0–30 cm	32	11	0.16
30–120 cm	28	11	0.17
120–200 cm	34	18	0.17
Intensive Loam Site			
0–30 cm	29	10	0.23
30–60 cm	31	10	0.23
60–90 cm	33	10	0.23
90–170 cm	34	10	0.23
170–180 cm	13	3	0.76
180–200 cm	26	9	0.21
Intensive Sand Site			
0–30 cm	20	4	0.81
30–40 cm	17	3	0.73
40–80 cm	10	3	1.04
80–200 cm	6	2	1.15

Table 3
Arithmetic mean (Diff_m) in K and standard deviation (Diff_s) in K of N differences between observed and simulated data for soil temperature in different depths at the Intensive Loam Site

Period	Depth 5 cm			Depth 20 cm			Depth 50 cm		
	N	Diff_m	Diff_s	N	Diff_m	Diff_s	N	Diff_m	Diff_s
1987	355	-0.4	1.9	355	-0.3	1.4	363	-0.3	1.2
1988	360	-0.7	2.2	360	-0.6	2.0	360	-0.2	1.9
1989	358	0.1	2.5	358	0.3	2.1	358	0.2	2.1
1990	352	-0.9	2.1	361	-0.2	1.8	361	-1.1	1.3
1991	355	0.2	2.4	355	1.1	2.1	355	0.1	1.9
1989–91	1780	-0.3	2.3	1789	0.1	2.0	1797	-0.3	1.8

modeled by piecewise-linear correction functions based on the actual management data and standard parameters for reaching the maximum covering index which runs from 0 at emergence up to 1 at full crop cover.

3.1. Results of the Intensive Loam Site (Neuenkirchen catchment, field 278)

The cultivated crops during the considered time periods at this location were:

- winter wheat (30 Sep. 1988–8 Aug. 1989)
- sugar beet (10 Apr.–25 Oct. 1990)
- winter wheat (24 Nov.–22 Aug. 1991).

There was no exact management information submitted for 1987. The following assumptions were made: sugar beet (10 Apr.–1 Oct. 1987), emergence of winter wheat: 15 Oct. 1987.

To analyze the model behavior, the observed and simulated data in the depths 5 cm, 20 cm and 50 cm during 1987–91 will be compared. Table 3 shows two statistical measures of the differences

$$\text{Diff}_i = T_{\text{obs},i} - T_{\text{sim},i}, \quad i = 1, \dots, N; \quad (9)$$

where $T_{\text{obs},i}$ is the measured soil temperature, $T_{\text{sim},i}$ is its simulation value (both daily mean values in K), N is the number of measurements, Diff_m is the arithmetic mean of the N differences (K), and Diff_s is the standard deviation (K).

Diff_m and Diff_s are related to the square root of the mean quadratic deviation RMS by the following formula

$$\text{RMS}^2 = \text{Diff}_m^2 + (N-1)/N \text{Diff}_s^2. \quad (10)$$

Diff_m is only a weak indicator for the agreement of measurement and simulation. It gives an impression of the overall over- or underestimation of temperature during the analyzed period. The values in Table 3 are not much higher than the standard error of temperature measurement for which as a rule of thumb a value of 0.5 K is assumed. Diff_s is a measure for the mean measurement and model discrepancy after reduction for Diff_m. Its values are about five times larger than the accuracy of temperature measurement and are within the usually found range for the underlying modeling principle.

Further insight in the model behavior can be achieved by examining the time course of model and measurement. As an example the soil temperature in 5 cm depth in 1991 (Fig. 1) is chosen to illustrate some common features of the simulation results.

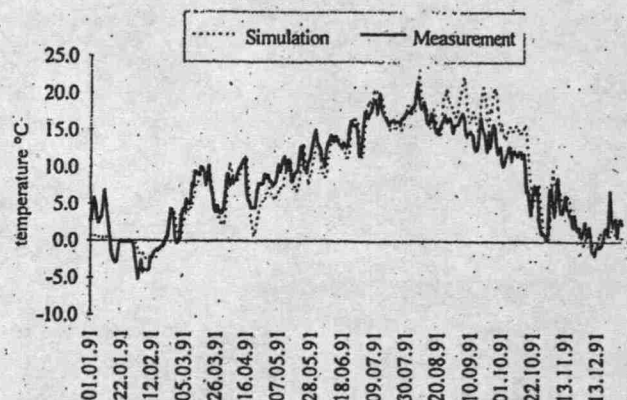


Fig. 1. Course of soil temperature in depth 5 cm in 1991 at the Intensive Loam Site.

Table 4

Arithmetic mean (Diff_m) and standard deviation (Diff_s), both in K, of N differences between observed and simulated data for soil temperature in different depths at the Intensive Sand Site. The differences are calculated after Eq. 9

Period	Depth 5 cm			Depth 20 cm			Depth 50 cm		
	N	Diff_m	Diff_s	N	Diff_m	Diff_s	N	Diff_m	Diff_s
1989	362	-1.1	2.4	362	-1.1	2.0	362	-1.1	1.6
1990	357	-0.8	2.5	357	-0.8	2.0	357	-1.0	1.8
1991	364	-0.3	2.3	364	-0.3	1.8	364	-0.4	1.6
1989–91	1083	-0.8	2.4	1083	-0.7	2.0	1083	-0.8	1.7

The time courses of the simulation data in the other depths show similar patterns, because the model prediction in 5 cm depth is the essential upper boundary condition for solving the heat equation.

The courses of simulation and observation in Fig. 1 are similar. Systematic underestimation of temperature appears in wintertime (characteristic for all simulation years), overestimation is found during September/October (appears in three of the five simulated years). This may be due to the fact that the standard set of parameters has been used for the transformation of air temperature into soil temperature in depth 5 cm without adaptation to special conditions at this site.

3.2. Results of the Intensive Sand Site (Nienwolde catchment, field 208 N4)

The cultivated crops during the analyzed time periods at this location were:

- potatoes (20 Apr.–26 Oct. 1989)
- sugar beet (14 Apr.–29 Sep. 1990)
- summer barley (4 Apr.–6 Aug. 1991).

The results of a comparison of simulation with measurements are shown in Table 4.

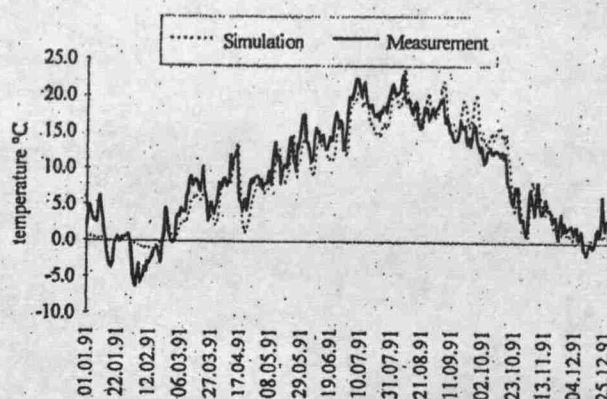


Fig. 2. Course of soil temperature in depth 5 cm in 1991 at the Intensive Sand Site.

The value of Diff_m for the whole period is 0.5 K lower than the loam site result but a systematic underestimation is present for all years of comparison. Diff_s for the sand site is in principle of the same order as for the loam site.

As an example for the simulation results the time course of temperature in 5 cm depth is shown in Fig. 2.

The time course shows the same systematic differences in wintertime and during September

Table 5

Arithmetic mean (Diff_m) in Vol.% and standard deviation (Diff_s) in Vol.% of N differences Diff_i between observed and simulated data for water content in different depths at the Intensive Loam Site

Period	Depth 0–30 cm			Depth 30–60 cm			Depth 60–90 cm		
	N	Diff_m	Diff_s	N	Diff_m	Diff_s	N	Diff_m	Diff_s
1989	19	0.4	3.9	19	-1.1	3.6	19	0.0	3.4
1990	27	0.9	4.2	27	-1.5	2.8	27	-2.3	2.7
1991	25	-1.3	3.9	25	1.2	3.8	25	-0.3	1.5
1989–91	71	0.0	4.1	71	-0.4	3.6	71	-1.0	2.8

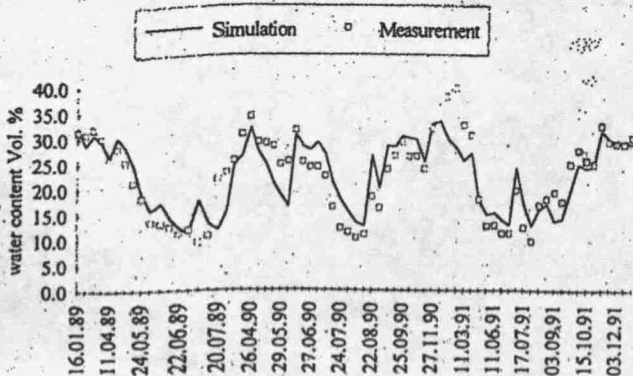


Fig. 3. Average water content (Vol.%) in the depth 0–30 cm at Intensive Loam Site.

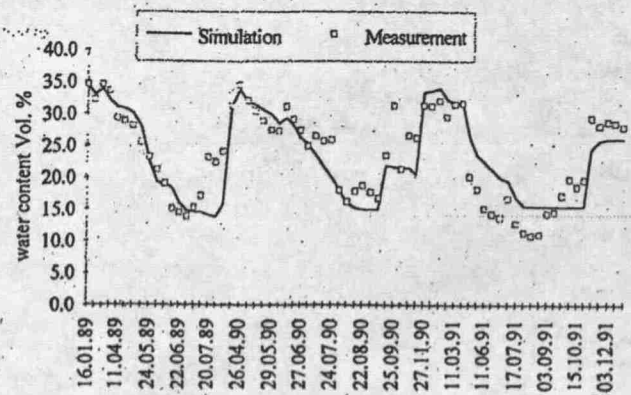


Fig. 4. Average water content (Vol.%) in the depth 30–60 cm at Intensive Loam Site.

and October as stated for the loam site. The reason is probably the same as for the other soil type and was also observed for the years 1989 and 1990.

4. Results of the soil water model

The soil water submodel requires the following site-specific soil parameters: field capacity, wilting point, bulk density, particle density, a drainage parameter and the content of clay and fine silt for the 20 soil layers. The values of field capacity and wilting point have been fitted by trial and error based on the measurement data from 1989–90. Measured bulk densities values provided in the data set. Other parameters were derived from the data set texture values after clustering the layers into different soil horizons (see Table 2).

4.1. Results of the Intensive Loam Site (Neuenkirchen catchment, field 278)

Table 5 gives some statistics about the differences

$$\text{Diff}_i := W_{\text{obs},i} - W_{\text{sim},i}, \quad i = 1, \dots, N; \quad (11)$$

where $W_{\text{obs},i}$ is the measured water content, $W_{\text{sim},i}$ is the simulated value (both daily mean values in Vol.%), N is the number of observations, Diff_m is the arithmetic mean of the N -differences (Vol.%), and Diff_s is the standard deviation (Vol.%).

The values of Diff_m indicate no severe overall deviation between observation and measurement over the whole time period. The Diff_s -values are slightly higher than those we have found for controlled field experiments (about 3 Vol.%), but are within the usual range for water model applications on farm fields.

Table 6

Arithmetic mean (Diff_m) in Vol.% and standard deviation (Diff_s) in Vol.% of N differences Diff_i between observed and simulated data for water content in different depths at the Intensive Sand Site.

Period	Depth 0–30 cm			Depth 30–60 cm			Depth 60–90 cm		
	N	Diff_m	Diff_s	N	Diff_m	Diff_s	N	Diff_m	Diff_s
1989	18	–3.2	3.7	18	0.9	2.9	18	0.2	2.1
1990	26	2.4	3.9	26	1.7	3.6	26	–1.1	1.3
1991	19	1.8	3.3	19	2.6	2.3	19	0.1	1.9
1989–91	63	0.6	4.4	63	1.8	3.1	63	–0.3	1.8

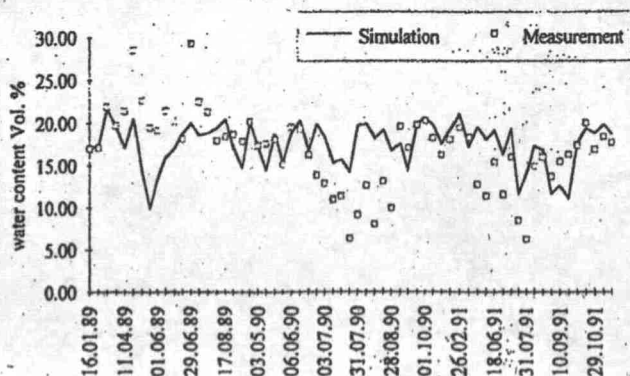


Fig. 5. Average water content (Vol.%) in the depth 0–30 cm at Intensive Sand Site.

For the example depths 0–30 cm and 30–60 cm the time courses of measured and simulated data are shown in Figs. 3 and 4.

It may be stated that the time courses of measurement data and simulation values are fairly 'parallel'. Systematic deviations in one direction (too wet or too dry over some period) with alternate signs in adjacent soil parts may be caused by errors in modeling the distribution of plant water uptake, because there was no adaptation of the plant parameters. All crops seem to prefer a water uptake from 'higher' layers than was modeled.

There is no explanation for the deviations in autumn 1989 and at the beginning of 1991 in the depth 0–30 cm.

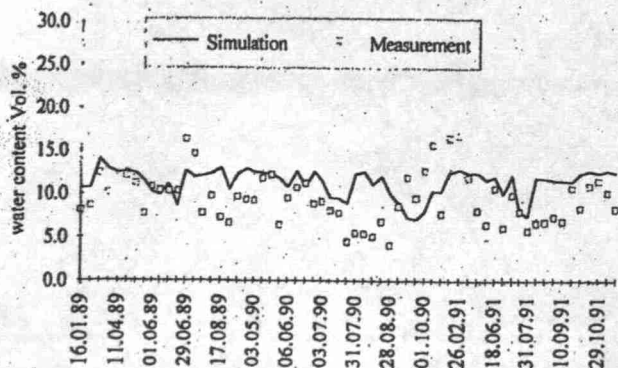


Fig. 6. Average water content (Vol.%) in the depth 30–60 cm at Intensive Sand Site.

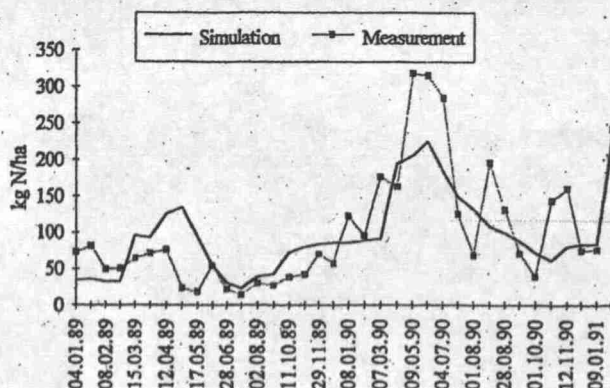


Fig. 7. Time course of mineral nitrogen in 0–90 cm depth, Intensive Loam Site, usual fertilization (N4).

4.2. Results of the Intensive Sand Site (Nienwolde catchment, field 208.N4)

The results for Diff_m and Diff_s indicate that the model does not fit as well as for the loam site (Table 6).

Once again the time courses of measurement and simulation data for the example depths 0–30 cm and 30–60 cm are shown in Figs. 5 and 6.

In comparison with the results at the loam site the time courses of measurement data and simulation values are less 'parallel'. The problem may be due to the irrigation (especially in 1989 for the potatoes: 157 mm water in 6 portions) not always having the same efficiency compared with the model assumptions. Secondly the water uptake by

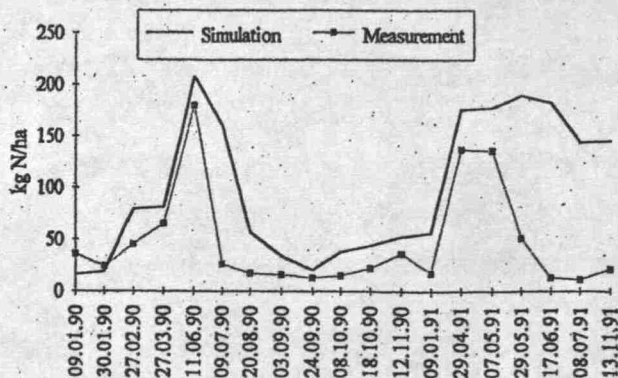


Fig. 8. Time course of mineral nitrogen in 0–90 cm depth, Intensive Sand Site, usual fertilization (N4).

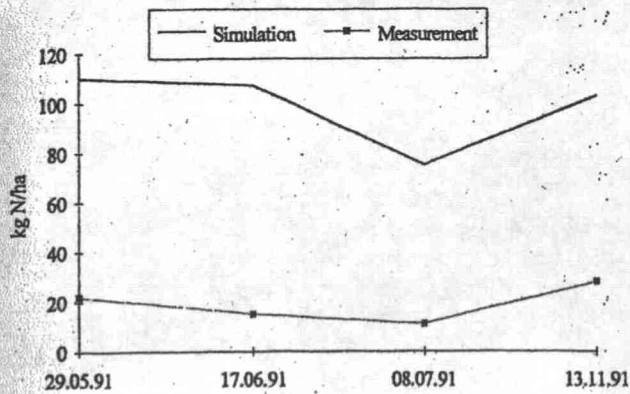


Fig. 9. Mineral nitrogen in 0–90 cm depth, Intensive Sand Site, reduced fertilization (N6).

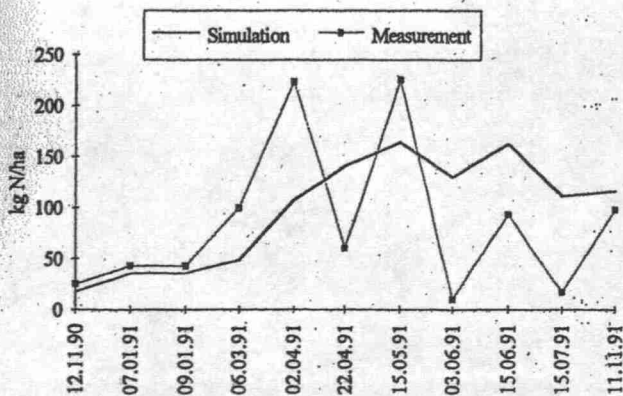


Fig. 10. Mineral nitrogen in 0–90 cm depth, Bockschlag, usual fertilization (N4).

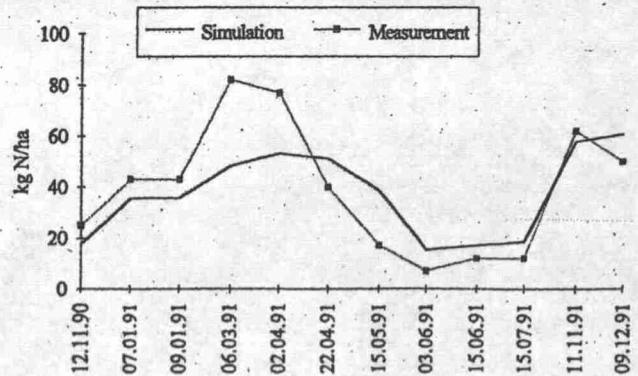


Fig. 11. Mineral nitrogen in 0–90 cm depth, Bockschlag, zero fertilization (N0).

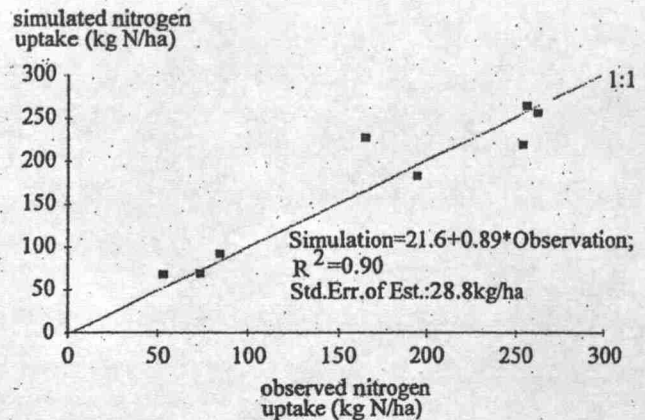


Fig. 12. Comparison of calculated and observed nitrogen uptake.

0–30 cm, 30–60 cm and 60–90 cm depths (not shown).

5. Results of the soil nitrogen model

The observed and simulated courses of mineral nitrogen in soil are shown in Figs. 7 to 11. In

the roots of sugar beet and of summer barley using the standard plant parameters of the model is realized too deep in the modelled soil profile. This is visible as systematic deviations of alternate signs between model and simulation in the

Table 7
Relative frequency of the differences between observation and simulation values for mineral nitrogen in 0–90 cm depth

Field	Relative frequency for the differences			
	0–20 kg ha ⁻¹	20–40 kg ha ⁻¹	40–60 kg ha ⁻¹	> 60 kg ha ⁻¹
Intensive Loam Site N4	36%	31%	6%	27%
Intensive Sand Site N4	32%	37%	5%	26%
Bockschlag N4	36%	0.0%	9%	55%
Bockschlag N0	75%	25%	0.0%	0.0%

general the agreement between simulation and observation is considered satisfactory except for the results on Intensive Sand Site in 1991 (Figs. 8, 9). In this year the calculated nitrogen uptake by the crop was much too low compared with the farmers results. This may be due to the very simple uptake model used in this case which does not consider ability of the crop to adapt to special conditions. In general there is a high variance in the observed data. This is more or less typical for farm-fields but the reason is yet unknown. Apparent rises in the mineral nitrogen content of more than 150 kg N ha^{-1} during one month may be caused more by spatial variability than by biological processes. In previous experience with the model using data from controlled field experiments the typical difference between observation and simulation was found to be 20 kg N ha^{-1} . Considering the mineral nitrogen in 0–90 cm depth (excluding results from the Intensive Sand Site, reduced fertilization (N6)), the frequency for differences less than or equal to 20 kg N ha^{-1} between simulation and observation ranges from 32% to 75%. The error class less than or equal to 40 kg N ha^{-1} shows frequencies from 36% to 100% (Table 7). It can be stated that the differences are nearly twice those of previously found observations in controlled experiments.

Plant nitrogen uptake has been calculated from plant water uptake from soil (transpiration). Considering the simplicity of this submodel the agreement between simulated and observed N-uptakes at harvest-time is satisfying (Fig. 12). The transpiration factors used here were found to be very similar to the values previously found for experiments in Bad Lauchstädt.

Acknowledgements

We would like to thank C. McVoy for his helpful comments concerning the translation of the manuscript. This research was partly supported by the Federal Ministry of Research and Technology within the project 01 LK 9106/2.

References

- Burns, I.G., 1974. A model for predicting the redistribution of salts applied to fallow soil after excess rainfall or evaporation. *J. Soil Sci.*, 25: 165–178.
- Fox Holdings Inc., 1991. FoxPro. Befehle & Funktionen, Hamburg.
- Franko, U., 1989. C- und N-Dynamik beim Umsatz organischer Substanzen im Boden. Diss. B (Habilitationsschrift), Akademie der Landwirtschaftswissenschaften der DDR, Berlin.
- Franko, U., 1990. C- und N-Dynamik beim Umsatz organischer Substanzen im Boden. Tagungsbericht AdL der DDR.
- Glugla, G., 1969. Berechnungsverfahren zur Ermittlung des aktuellen Wassergehaltes und Gravitationswasserabflusses im Boden. *A.-Thaer-Archiv*, 13: 371–376.
- Koitzsch, R., 1990. Bodenfeuchte- und Verdunstungsmodell BOWA. Interner Bericht. FZ Müncheberg, Müncheberg.
- Koitzsch, R. and Günther, R., 1990. Modell zur ganzjährigen Simulation der Verdunstung und der Bodenfeuchte landwirtschaftlicher Nutzflächen mit und ohne Bewuchs. *Arch. Acker. Pflanzenbau Bodenkd.*, 34: 803–810.
- Koitzsch, R., Helling, R. and Vetterlein, E., 1980. Simulation des Bodenfeuchteverlaufes unter Berücksichtigung der Wasserbewegung und des Wasserentzuges durch Pflanzenbestände. *Arch. Acker. Pflanzenbau Bodenkd.*, 24: 717–725.
- McLaren, A.D., 1970. Temporal and vectorial reactions of nitrogen in soil. *Can. J. Soil Sci.*, 50: 97–109.
- Suckow, F., 1986. Ein Modell zur Berechnung der Bodentemperatur unter Brache und unter Pflanzenbestand. Dissertation A, Akademie der Landwirtschaftswissenschaften der DDR, Berlin.