

## Modelling water flow, nitrogen uptake and production for wheat

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### Abstract

Soil water and temperature conditions were simulated for three years at three sites in the Netherlands, using a model named SOIL. Observed water table depths from one site with a sandy loam soil indicated bypass flow in macropores. Nitrogen turnover was simulated using the output of SOIL as input to a nitrogen model. To improve the nitrogen model, a crop-growth submodel was introduced, and simulations were compared with measured data for two seasons and three fertilizer treatments at the three sites. Mineral-N in the soil after application of fertilizer was substantially higher in the simulation than indicated by measurements in 4 out of 18 simulations. Regression analyses showed that simulated mineral-N content in the uppermost metre explained 64% of the observed variation. The corresponding values for nitrogen content ( $N_{ta}$ ) and biomass ( $W_{ta}$ ) of aboveground tissues were 86 and 93%, respectively. With a few exceptions annual values of  $W_{ta}$  and  $N_{ta}$  were simulated with an accuracy of approximately 20%. A sensitivity test showed that growth parameters and especially the light use efficiency parameter strongly influenced biomass production for fertilized treatments whereas the control of nitrogen uptake from soil was most important for non-fertilized treatments.

### Introduction

The nitrogen cycle in arable land has been formulated in many different mathematical models. The SOILN model was developed [20] emphasizing the need for a model of soil nitrogen transformations and losses. The model was formulated to agree with the current level of understanding concerning soil processes, but also such that it could be widely applied using information generally available from field investigations of nitrogen turnover.

From independent applications of the model we have found that an accurate estimate of nitrogen uptake by crops is crucial when predicting the nitrogen losses from soil. In these studies [3, 20], nitrogen uptake was simulated using a time dependent empirical function requiring parameter values unique for the site concerned. In this paper, we introduce a new crop growth model which regulates the uptake rate and which

can be parameterized from independent data sets. This model is named the CROP-GROWTH submodel.

Driving soil variables in SOILN were supplied by the SOIL model which simulated energy and water processes in the soil. Since both SOIL and SOILN have been described elsewhere [15, 20], we focus the model description on the CROP-GROWTH submodel. Hence, SOIL is only briefly described here, except for the part which deals with water flow in the soil. A description of the original version of SOILN is given by Bergström et al. [4].

### Description of the SOIL model

All symbols in the model description are explained and all parameter values used in the simulations are given in the appendix.

A water and heat model [15] provides driving

variables for the nitrogen model (e.g. surface runoff and infiltration, soil water flow between layers and flow to drainage tiles, soil water content, soil temperature and evapotranspiration). The water and heat model predicts these variables using standard meteorological data as driving variables. The water and heat model 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 layered soil profile. Phenomena like freezing/thawing of the soil and soil boundary processes such as snow-melt and interception of precipitation are considered in the model. A detailed description of the model for arable land conditions is given elsewhere [16, 18].

An option to account for bypass flow was included in the model to consider rapid flows in macropores during conditions when smaller pores are only partially filled with water (Fig. 1). The amount of water in the macropores is not accounted for explicitly. Instead, the infiltration flow rate at the soil surface or the vertical flow in the macropores at any depth in the soil profile ( $q_{in}$ ) determines the partitioning into the ordinary Darcy flow ( $q_{mat}$ ) and the bypass flow ( $q_{bypass}$ ). At the soil surface,  $q_{in}$  is the infiltration rate. At other depths,  $q_{in}$  is the vertical flow rate in the macropores ( $q_{bypass}$ ) from the layer above. We have:

$$q_{mat} = \max(k(\theta)(d\psi/dz + 1), q_{in}) \quad 0 < q_{in} < S_{mat} \quad (1)$$

$$q_{bypass} = 0 \quad 0 < q_{in} < S_{ma} \quad (2)$$

$$q_{mat} = S_{mat} \quad q_{in} > S_{mat} \quad (3)$$

$$q_{bypass} = q_{in} - q_{mat} \quad q_{in} > S_{mat} \quad (4)$$

where  $k(\theta)$  is the unsaturated conductivity at a given water content,  $\psi$  the water tension and  $z$  the depth coordinate. The sorption capacity is defined as:

$$S_{mat} = A_{scale} A_{rel} k_{mat} pF \quad (5)$$

where  $k_{mat}$  is the maximum conductivity of smaller pores (i.e. matrix pores),  $pF$  is  $^{10}\log$  of  $\psi$  and  $A_{rel}$  is the ratio between the vertical area of the

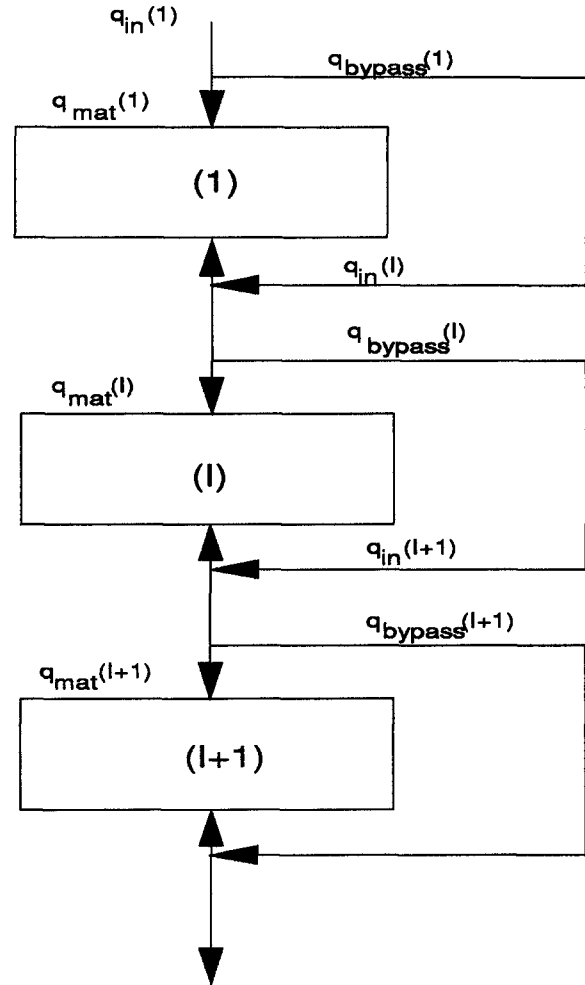


Fig. 1. Flow chart for bypass flow in the SOIL model. For explanation of the symbols is referred to the appendix.

compartment and the unit horizontal area. The vertical area has a depth equal to the compartment thickness and a horizontal length equal to that of the unit horizontal area.  $A_{scale}$  is an empirical scaling coefficient accounting for the geometry of aggregates.

The calculated water flow in the matrix ( $q_{mat}$ ) is used to update the water contents and the water tensions in the numerical solution, whereas  $q_{bypass}$  is directed without delay to the next soil compartment. However,  $q_{bypass}$  can never reach layers below the water table depth, which is the lower boundary condition for the use of Richards equation.

Only the simulated flow rate is considered in the nitrogen model. Hence, the partitioning be-

tween bypass and matrix water flow does not influence the solute transport.

In the saturated zone of the soil profile, a sink flow to drainage pipes ( $q_{\text{pipe}}$ ) is calculated for all compartments above the drain depth,  $z_{\text{pipe}}$ . The flow is calculated using Darcy's law as:

$$q_{\text{pipe}} = k_s A_{\text{rel}} ((z_{\text{pipe}} - z_{\text{gw}}) / L) \quad (6)$$

where  $k_s$  is the saturated conductivity,  $z_{\text{gw}}$  the depth to the water table and  $L$  a characteristic distance between drainage pipes. The vertical water flow in the saturated zone of the profile is calculated assuming water contents equal to the soil porosity in all layers except for the compartment where the water table depth is located. Conservation of mass is satisfied by redistributing between compartments.

### Description of the CROP-GROWTH submodel

CROP-GROWTH is a submodel which is included in the nitrogen turnover model SOILN although it is treated separately from the SOILN model in the description below. The amount of nitrogen in the soil simulated by SOILN is input to CROP-GROWTH. In turn the nitrogen up-

take predicted by CROP-GROWTH is input to SOILN. This interaction is made on a daily basis.

CROP-GROWTH can conceptually be divided into two submodels (Fig. 2). A biomass submodel (i) simulates production, based on the conversion of absorbed light into biomass [21] and empirical allometric functions. The growth equations and the functions determining the grain development were originally developed for field crops [1, 2] while the allometric functions (except for grain development) originate from measurements in short rotated willow stands [8]. A nitrogen submodel (ii) simulates plant uptake based on the idea that growth is the driving force for uptake [12], although it may be limited by the availability of nitrogen in the soil. The equations for nitrogen allocation in the plant (except for grain development) are similar to those used for willow [8] while the relations between uptake rate and root distribution were originally derived for field crops [20].

The two submodels are linked in the sense that: (i) the biomass submodel uses the leaf nitrogen content as an input variable taken from the nitrogen submodel and (ii) the nitrogen submodel, in turn, uses the daily growth of leaf, straw, root and grain as input taken from the

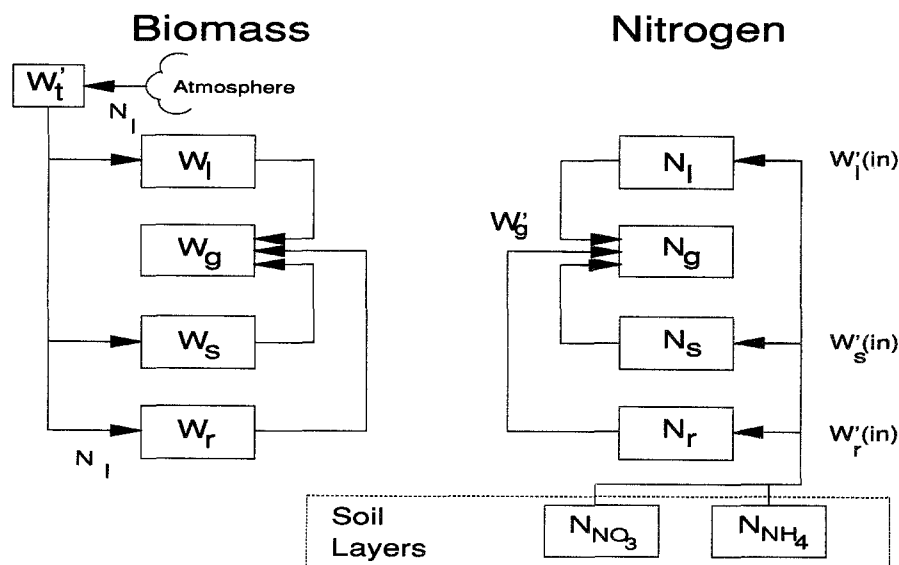


Fig. 2. Schematic description of the biomass submodel (left) and the nitrogen submodel (right).  $W$  and  $N$  are biomass and nitrogen respectively. Symbols outside boxes indicate how the submodels are connected. Indices are as follows: l = leaf; r = root; s = straw; g = grain and t = total. Inverted commas denote a daily change and (in) denotes a positive change.

biomass submodel (see Fig. 2). The combined model is relevant for horizontally uniform stands where growth is not altered by flowering, frost damage, insect attacks or similar disturbances. Growth is assumed not to be limited by nutrients other than nitrogen. Furthermore, aboveground litter fall is not explicitly accounted for but instead lumped together in the 'grain compartment'. This approach, instead of separating grain and litter in two compartments, has only a minor effect on the simulated development of the other tissues, since the grain compartment does not affect growth or nitrogen uptake. For simulations longer than one season or predictions of grain yield the litter must be distinguished from the grain.

The submodel runs with a daily time step. For each day, the calculations of the biomass submodel are made before those of the nitrogen submodel. Except for the vertical distribution of roots and the ratio between actual and potential evapotranspiration, environmental variables are the only required inputs. These variables are day length, daily sum of global radiation, daily mean air temperature, and soil nitrogen content. The latter is predicted by the SOILN model.

#### Biomass submodel

Growth starts at day  $t_0$  which is the first day when the daily mean air temperature exceeds the minimum temperature for photosynthesis ( $T_{\text{Min}}$ ). An initial amount of biomass is developed from assimilates stored in the seeds. The assimilates are partitioned between leaf, straw and root according to allocation equations (Eqs. 12–20, below). The newly formed tissues are assumed to receive maximum nitrogen concentrations from the seed (cf. Eqs. 27–29, below).

The daily total growth per unit area of soil surface ( $W'_t$ ) is proportional to the light intercepted by the canopy ( $I_i$ ):

$$W'_t = \varepsilon I_i f_T f_N f_w \quad (7)$$

where  $\varepsilon$  is the light use efficiency at optimal temperature, nitrogen and water conditions and  $f_T$ ,  $f_N$  and  $f_w$  are response functions ranging between zero and unity depending on temperature, plant nitrogen and water status respective-

ly. Inverted commas denote a daily change in the state variable.

$I_i$  is calculated from the global radiation ( $I$ ) according to Beers' law using the radiation extinction coefficient ( $k$ ) and the leaf area index ( $A_{\text{li}}$ ):

$$I_i = I(1 - \exp(-kA_{\text{li}})) \quad (8)$$

The temperature response function ( $f_T$ ) increases linearly from zero to unity as the daily mean air temperature ( $T$ ) increases from  $T_{\text{Min}}$  to  $T_{\text{Max}}$ :

$$f_T = (T - T_{\text{Min}})/(T_{\text{Max}} - T_{\text{Min}}) \quad 0 \leq f_T \leq 1 \quad (9)$$

The nitrogen response function ( $f_N$ ) is unity when the leaf nitrogen concentration ( $n_l$ ) equals its maximum value ( $n_{\text{lMax}}$ ) and decreases linearly to zero as  $n_l$  decreases to the minimum nitrogen concentration ( $n_{\text{lMin}}$ ).

$$f_N = (n_l - n_{\text{lMin}})/(n_{\text{lMax}} - n_{\text{lMin}}) \quad 0 \leq f_N \leq 1 \quad (10)$$

Finally, the water response function ( $f_w$ ) equals the ratio between the actual evapotranspiration ( $E$ ) and the potential evapotranspiration ( $E_p$ ).

$$f_w = E/E_p \quad 0 \leq f_w \leq 1 \quad (11)$$

where  $E_p$  is calculated according to the Penman-Monteith formula and  $E$  is a function of  $E_p$ . It should be noted that  $E$  and  $E_p$  are calculated in SOIL using a 'standard' leaf area development. Thus no feedback mechanism exists between leaf area predicted by CROP-GROWTH and  $f_w$ .

The plant biomass is divided into four compartments: root ( $W_r$ ), straw ( $W_s$ ), leaf ( $W_l$ ) and grain ( $W_g$ ). Allocation of assimilates among the compartments depends on the grain development. The grain starts to receive assimilates from the other tissues when the accumulated daily sum ( $i_v$ ) of an index becomes unity [2] (i.e.  $i_v$  acts as a switch that is used for starting the grain development).

$$i_v = \sum_{t=t_0}^t c_0(1 - \exp(c_1(T - C_2))) \times (1 - \exp(c_3(D - c_4))) \quad (12)$$

where  $D$  is the day length,  $T$  the daily mean air temperature and  $c_0$ ,  $c_1$ ,  $c_2$ ,  $c_3$  and  $c_4$  are coefficients. In the case of grain development (i.e.  $i_v \geq 1$ ) the daily increase of grain biomass ( $W_g$ ) is a fraction ( $b_g$ ) of the biomass in the other tissues:

$$W'_g = b_g(W_l + W_s + W_r) \quad b_g = 0 \text{ if } i_v < 1 \quad (13)$$

The amount of assimilates allocated to roots ( $W'_r$ ) is a fraction ( $b_r$ ) of the total daily growth, minus translocation of assimilates to grain during the grain period.

$$W'_r = b_r W'_t - b_g W_r \quad b_g = 0 \text{ if } i_v < 1 \quad (14)$$

$b_r$  is dependent on the leaf nitrogen concentration ( $n_l$ ), having a minimum value ( $b_{ro}$ ) at the maximum leaf nitrogen concentration ( $n_{l\max}$ ) and increasing as  $n_l$  decreases [7].

$$b_r = b_{ro} + 1 - (1 - ((n_{l\max} - n_l)/n_{l\max}))^{0.5} \quad (15)$$

The remaining part of the daily total growth is allocated to the aboveground biomass,  $W_{ta}$  ( $=W_l + W_s + W_g$ ).

$$W'_{ta} = (1 - b_r)W'_t \quad (16)$$

$W'_{ta}$  is partitioned between leaf and straw in accordance with the leaf area index development ( $A'_{li}$ ) and the specific leaf area ( $a_{ls}$ ). We assume that a balance exists between  $A_{li}$  and  $W_{ta}$ , expressed as the ratio  $b_i$  ( $=A_{li}/W_{ta}$ ) which decreases with plant size (i.e.  $b_i = b_{io} - b_{il} \ln(W_{ta})$ ). Then  $A'_{li}$  (in) is given according to [7]:

$$A'_{li}(\text{in}) = W'_{ta}(b_{io} - b_{il}(1 + \ln(W_{ta}))) \quad A'_{li}(\text{in}) \geq 0 \quad (17)$$

where  $b_{io}$  and  $b_{il}$  are coefficients. It is necessary to restrict  $A'_{li}$  (in) such that it cannot attain larger

values than that possible from the daily shoot growth and the specific leaf area (i.e. the condition  $A'_{li}(\text{in}) \leq a_{ls}W'_{ta}$  must be met). A decrease of  $A_{li}$  is considered by the loss of leaf biomass to the grain compartment. If we denote the leaf biomass increase with  $W'_l(\text{in})$  then the net leaf growth is given by:

$$W'_l = W'_l(\text{in}) - b_g W_l \quad b_g = 0 \text{ if } i_v < 1 \quad (18)$$

where

$$W'_l(\text{in}) = A'_{li}(\text{in})/a_{ls} \quad (19)$$

The straw growth ( $W'_s$ ) is the rest of the total daily increase minus the amount translocated to grain.

$$W'_s = W'_{ta} - W'_l(\text{in}) - b_g W_s \quad b_g = 0 \text{ if } i_v < 1 \quad (20)$$

### Nitrogen submodel

Nitrogen available for root uptake increases by the supply of nitrogen from mineralization, fertilization and atmospheric deposition and decreases by immobilization, leaching, denitrification and plant uptake. The combined effect of these factors gives the amount of nitrate ( $N_{\text{NO}_3}$ ) and ammonium ( $N_{\text{NH}_4}$ ) in different soil layers readily available for plant uptake. All factors affecting these pools, except plant uptake, are calculated by routines in the SOILN model other than the CROP-GROWTH submodel and are described by Bergström et al. [4].

Daily plant uptake of nitrogen from a soil layer ( $X_{\text{Nu}}$ ) is the sum of uptake from the pools of  $N_{\text{NO}_3}$  and  $N_{\text{NH}_4}$ . The uptake from each pool is the available fraction ( $c_u$ ) of the amount of nitrogen in the pool concerned. However, in both cases the uptake is proportional to the relative amounts of  $N_{\text{NO}_3}$  and  $N_{\text{NH}_4}$ ,  $x_{\text{fra}}$  ( $=N_{\text{NO}_3}/(N_{\text{NO}_3} + N_{\text{NH}_4})$ ) respectively  $1 - x_{\text{fra}}$ . If the daily uptake from each pool is  $N'_{\text{NO}_3}(\text{out})$  and  $N'_{\text{NH}_4}(\text{out})$  respectively, we have for a given layer ( $i$ ):

$$X_{\text{Nu}}(i) = N'_{\text{NO}_3}(\text{out})(i) + N'_{\text{NH}_4}(\text{out})(i) \quad (21)$$

where

$$N'_{\text{NO}_3}(\text{out})(i) = \min(c_u N_{\text{NO}_3}(i), x_{\text{fra}} X_{\text{Np}}(i)) \quad (22)$$

$$N'_{\text{NH}_4}(\text{out})(i) = \min(c_u N_{\text{NH}_4}(i), (1 - x_{\text{fra}}) X_{\text{Np}}(i)) \quad (23)$$

The potential root uptake ( $X_{\text{Np}}$ ) in each layer is dependent on the relative fraction ( $a_r$ ) of the total root surface in that layer, and the total daily nitrogen demand of the plant ( $X_{\text{Nd}}$ ). However, if  $X_{\text{Nu}}$  is lower than  $X_{\text{Np}}$  for the layer above ( $i-1$ ), a fraction ( $c_{\text{um}}$ ) of the deficit can be added to the potential root uptake of layer  $i$ . If this amount is denoted by  $X_{\text{Nm}}$ , we have:

$$X_{\text{Np}}(i) = a_r(i) X_{\text{Nd}} + X_{\text{Nm}}(i) \quad (24)$$

where

$$X_{\text{Nm}}(i) = c_{\text{um}}(X_{\text{Np}}(i-1) - X_{\text{Nu}}(i-1)) \quad (25)$$

The plant demand for nitrogen depends on the maximum nitrogen concentrations in root ( $n_{\text{rMax}}$ ), straw ( $n_{\text{sMax}}$ ) and leaf ( $n_{\text{lMax}}$ ) in the sense that the plant tries to supply the gross daily growth with nitrogen corresponding to these maximum concentrations.

$$X_{\text{Nd}} = n_{\text{rMax}} W'_r(\text{in}) + n_{\text{sMax}} W'_s(\text{in}) + n_{\text{lMax}} W'_l(\text{in}) \quad (26)$$

where  $W'_l(\text{in})$  is given by Eq. 19 whilst  $W'_r(\text{in})$  and  $W'_s(\text{in})$  are the right hand expressions of Eqs. 14 and 20, respectively, excluding the last term which represents allocation to grains.

Allocation of the daily total nitrogen uptake to root, straw and leaf is based on the idea that the roots receive nitrogen first, until they reach their maximum concentrations, followed by the straw and finally the leaf [8]. If  $N_r$ ,  $N_s$  and  $N_l$  are the amounts of nitrogen in root, straw and leaf, respectively, the daily uptake rates for the different plant parts are given by:

$$N'_r(\text{in}) = \min(X_{\text{Nu}}, n_{\text{rMax}} W'_r(\text{in})) \quad N'_r(\text{in}) \geq 0 \quad (27)$$

$$N'_s(\text{in}) = \min(X_{\text{Nu}} - N'_r(\text{in}), n_{\text{sMax}} W'_s(\text{in})) \quad N'_s(\text{in}) \geq 0 \quad (28)$$

$$N'_l(\text{in}) = \min(X_{\text{Nu}} - N'_r(\text{in}) - N'_s(\text{in}), n_{\text{lMax}} W'_l(\text{in})) \quad N'_l(\text{in}) \geq 0 \quad (29)$$

In the case of grain development, the allocation of nitrogen to grain ( $N'_g$ ) is the nitrogen concentration of the tissue concerned ( $n_r$  for root,  $n_s$  for straw and  $n_l$  for leaf) multiplied by the corresponding translocation of assimilates. Hence, the daily net changes in nitrogen contents of the tissues are as follows:

$$N'_r = N'_r(\text{in}) - b_g n_r W_r \quad b_g = 0 \text{ if } i_v < 1 \quad (30)$$

$$N'_s = N'_s(\text{in}) - b_g n_s W_s \quad b_g = 0 \text{ if } i_v < 1 \quad (31)$$

$$N'_l = N'_l(\text{in}) - b_g n_l W_l \quad b_g = 0 \text{ if } i_v < 1 \quad (32)$$

$$N'_g = b_g (n_r W_r + n_s W_s + n_l W_l) \quad b_g = 0 \text{ if } i_v < 1 \quad (33)$$

## Application of the models

### Validation data and input variables

The models were tested on experiments with winter wheat crops at three nearby locations in the Netherlands (the Bouwing, the Eest and PAGV). The validation data and input data and other information concerning the experiments can be found in Groot and Verberne [10]. The different fertilizer treatments are referred to as N1 (none or low N supply), N2 (intermediate) and N3 (highest) respectively.

The SOIL model was tested against measurements of water table depth and volumetric water content in different horizons of the uppermost metre. Climatic data sets from two locations, the Bouwing and the Eest, were used as driving variables for all three sites (the Eest was also used for PAGV). The data sets contained daily values of air temperature, air humidity, wind speed, precipitation and global radiation.

The SOILN model (and hence the CROP-GROWTH submodel) was tested against measurements of biomass production ( $W_s$ ,  $W_l$  and  $W_g$ ), plant nitrogen contents ( $N_s$ ,  $N_l$  and  $N_g$ ) and soil mineral-N content for different layers down to one metre depth. The test was performed by

first setting some parameter values, not available elsewhere, according to measured data at the Bouwing. Then the simulations were made for all sites using the same parameter set. Concerning the comparison between simulated and measured values, the Eest and PAGV was treated separately from the Bouwing in order to test the model on an independent data set. The test at the Bouwing then gave a test of the model with a parameter setting probably more correct than for the other sites. The fraction of total root surface found in each layer ( $a_r$ ) was set to the corresponding values for rooting density measured three times a year [10] and assumed constant during the periods between measurements.

#### *Parameterization of the SOIL model*

Only some of the necessary input to the SOIL model was determined from the available site specific information. Instead, most parameter values were taken from previous applications with the model to similar arable land conditions [14, 15, 16, 17, 19]. Only a few output variables were measured that could be used either for testing or calibration.

Soil properties (i.e. the water retention curves and hydraulic conductivities) were not available for the experimental sites concerned but for the same sites as for the climatic data [10]. These

data were fitted to slightly modified forms of the analytical functions of Brooks & Corey [5] and Mualem [22] according to Jansson & Thoms-Hjärpe [18]. The results for the sandy loam soil at the Eest are shown in Fig. 3. Similar results were obtained for the clay soil at Wageningen used for the Bouwing site, except that the unsaturated conductivity was very low in the subsoil in this case. The lower boundary condition for all sites was simulated assuming a network of drainage pipes at a depth of 1 m and a spacing of 10 m. The only parameter value that was adjusted by calibration was the factor for sorption capacity ( $A_{scale}$ ; Eq. 5) which was varied for the Eest site until a reasonable agreement was obtained between simulated and measured water table depths.

#### *Parameterization of the CROP-GROWTH submodel*

The parameter values for the CROP-GROWTH submodel are given in the appendix. Parameter values in SOILN were taken from Bergström et al. [4].

The specific leaf area ( $a_{ls}$ ) was determined for the Bouwing site as a mean of all treatments; however, some extreme values in the autumn were neglected. The fraction of biomass translocated to grains ( $b_g$ ) was arbitrarily assumed.

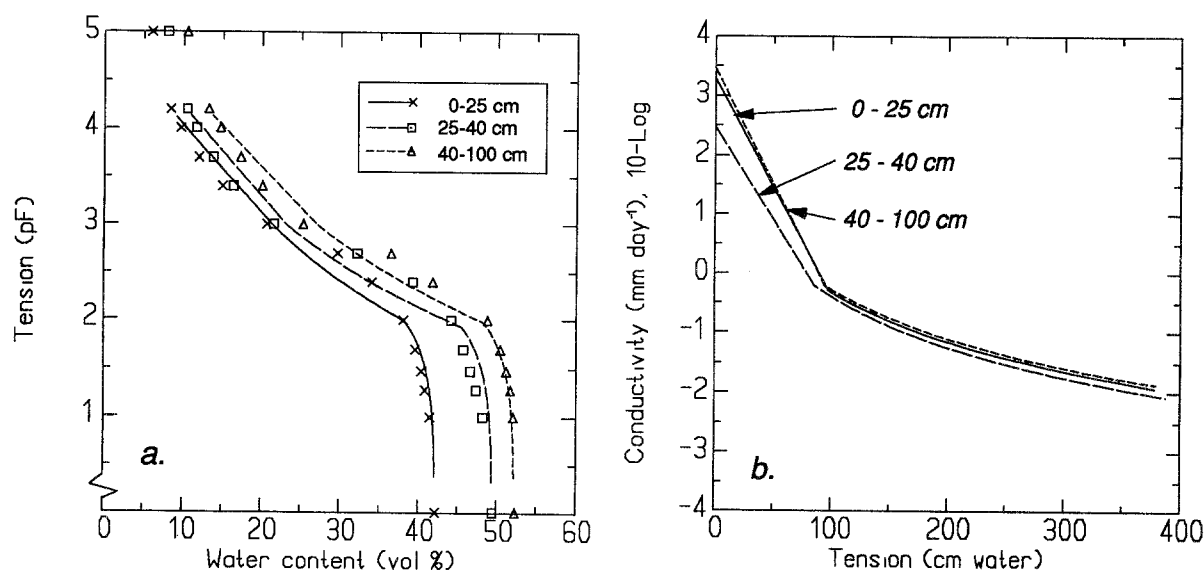


Fig. 3. Water retention curves (a) and unsaturated conductivity curves (b) used for the Eest soil.

Good estimates of the allocation coefficients  $b_{io}$  and  $b_{il}$  (used for calculating leaf area as a function of aboveground biomass) were achieved from the measured data for the three treatments at the Bouwing. The minimum fraction of biomass allocated to roots ( $b_{ro}$ ) was taken from data for barley and willow [11, 24, 9]. The coefficients ( $c_0$ ,  $c_1$ ,  $c_2$ ,  $c_3$  and  $c_4$ ) for determining the start of grain development were taken from Angus et al. [2]. The light extinction coefficient ( $k$ ) was set equal to 0.6. The temperature limits for no growth ( $T_{Min}$ ) and optimal growth ( $T_{Max}$ ) were roughly estimated from the literature [13, 23]. The light use efficiency ( $\epsilon$ ) was estimated from a literature review [6].

The fraction of N in the soil-nitrogen pool which can be taken up each day ( $c_u$ ) was set according to Bergström et al. [4]. The fraction ( $c_{um}$ ) of a deficit in nitrogen availability in one soil layer that can be replaced by nitrogen from the layer above was put equal to unity, i.e. the limitation by the parameter was cancelled. The maximum and minimum nitrogen concentrations ( $n_{lMax}$ ,  $n_{sMax}$  and  $n_{lMin}$ ) of aboveground plant tissues were estimated as mean values of the annual maximum and minimum values of the N3 and N1 treatments at the Bouwing. An estimate for the maximum root nitrogen concentration ( $n_{rMax}$ ) was taken from the literature [11, 8, 9].

### Initial values

The simulations with the SOIL model started on January 1st 1982 with water tensions corresponding to field capacity and with the water table depth at 1 m. Soil temperatures were set at 5°C throughout the soil profile.

The simulations with SOILN started at the time of first measurements of soil nitrogen content and total aboveground biomass ( $W_{ta}$ ). This time differed for each simulation but was always in the beginning of February. The measured values were used as initial values, and plant tissues were assumed to contain maximum nitrogen concentrations at this time.

### Simulations

The simulations generally overestimated water content at the Bouwing site, especially in the

subsoil between 40 and 100 cm depth. This was caused by the very low unsaturated conductivity of the subsoil, set in the model according to the soil properties at Wageningen, which were assumed to be representative for the Bouwing soil [10]. Instead, results from the Eest site during 1984 are presented (Fig. 4) since they represent a period with relatively frequent measurements of both soil water contents and water table depth. Observed drying and wetting patterns were reasonably simulated independent on the setting of the bypass option (Fig. 4a). However, the range of variation in the water content agreed better with the observations, especially in the topsoil, when assuming bypass to have occurred (Fig. 4b). The water table depth was a more sensitive indicator of bypass flow than the water content. Only the simulation including bypass showed reasonable similarities with the observations. Recharge at infiltration events was not possible to simulate without the bypass model approach.

One example of the simulations with SOILN is given for the N3-simulation at the Eest in 1983 (Fig. 5). The agreement between measured and simulated values was fairly good although leaf and straw nitrogen were overestimated from mid July to end of August. The decrease in total aboveground nitrogen in July was not reflected by the simulation and for about the same period soil nitrogen in the deepest layer was underestimated. In Fig. 5, measurements and predictions of soil nitrogen are shown for three different layers although they, in all other presentations, are summed up to one layer. It should be noted that the grain compartment includes litter fall (both in the simulated and the measured values).

The performance of the SOILN model was evaluated in terms of a regression line between measured and predicted values at the Eest and PAGV. This was done by linear least squares fitting (Fig. 6). The predictions of total aboveground production ( $W_{ta}$ ) were a little better than those of nitrogen uptake ( $N_{ta}$ ) which in turn were better predicted than soil mineral nitrogen. For the separate plant tissues, the best fit was found for the grain compartment and the poorest for nitrogen in straw (Table 1). The same correlation procedure performed for the Bouwing site gave similar results, indicating that the separa-



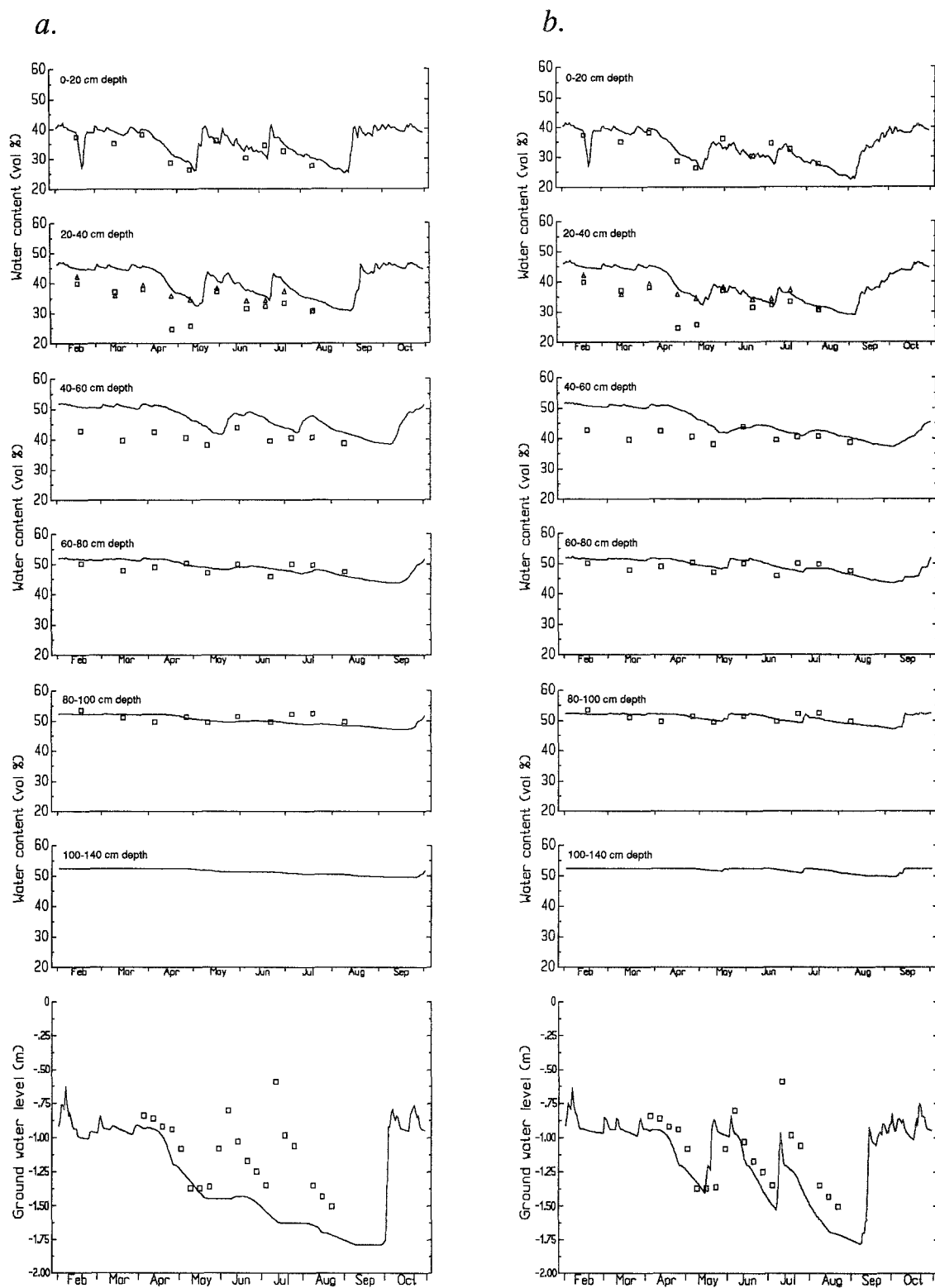


Fig. 4. Simulated and measured soil water contents and groundwater depths for the Eest site 1984. Simulations were done without (a) and with the bypass option (b). Lines are simulations and open symbols are measured values. In layer 20–40 cm squares represent measurements in the 20–30 cm layer and triangles represent measurements in the 30–40 cm layer.

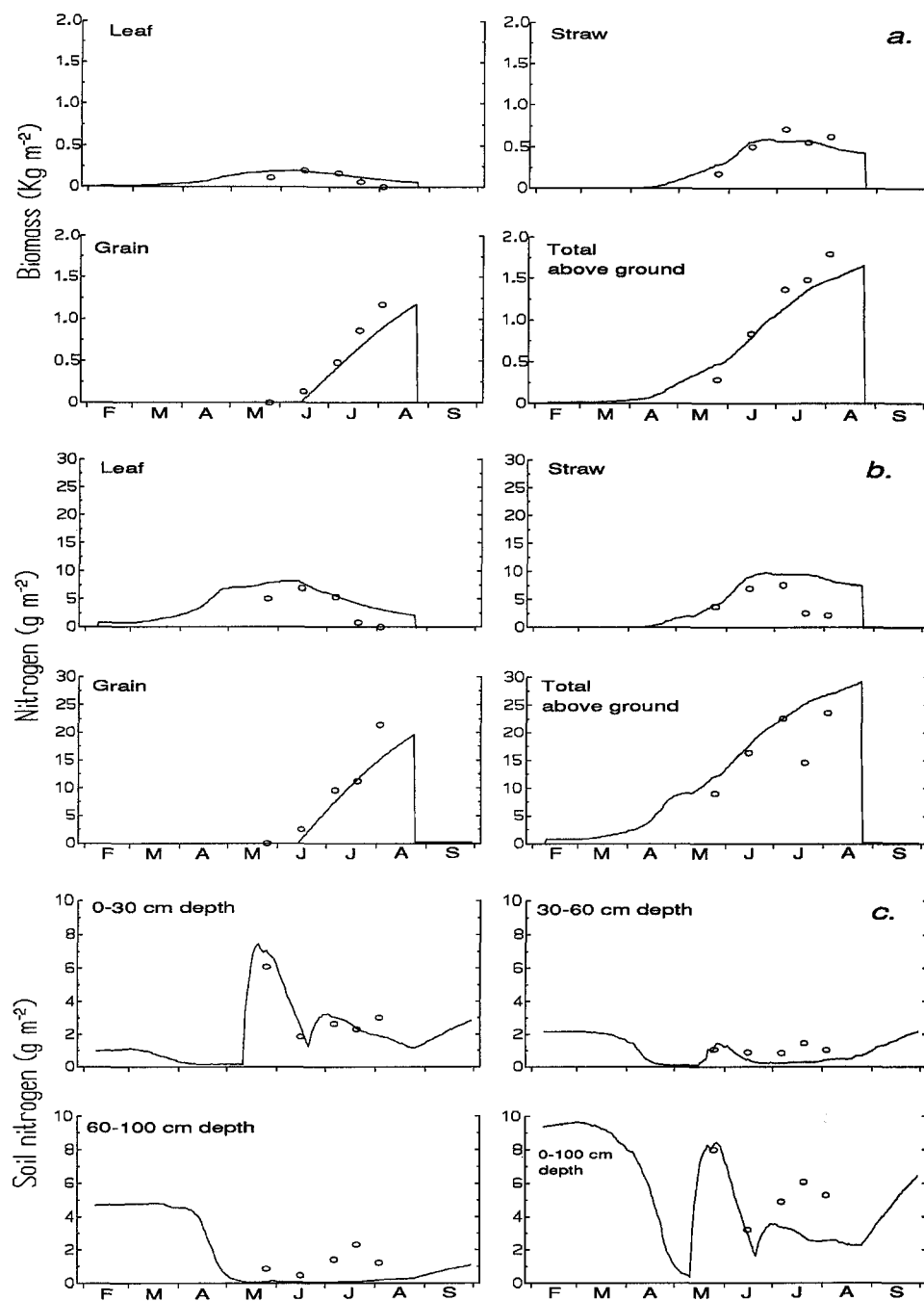


Fig. 5. Simulations (lines) and measurements (open circles) for the Eest in 1983 (N3-fertilizer treatment). The subpictures show leaf, straw, grain (+ litter) and total aboveground biomass (a), leaf, straw, grain (+ litter) and total aboveground nitrogen (b) and soil nitrogen in layers 0–30 cm, 30–60 cm, 60–100 cm and 0–100 cm (c).

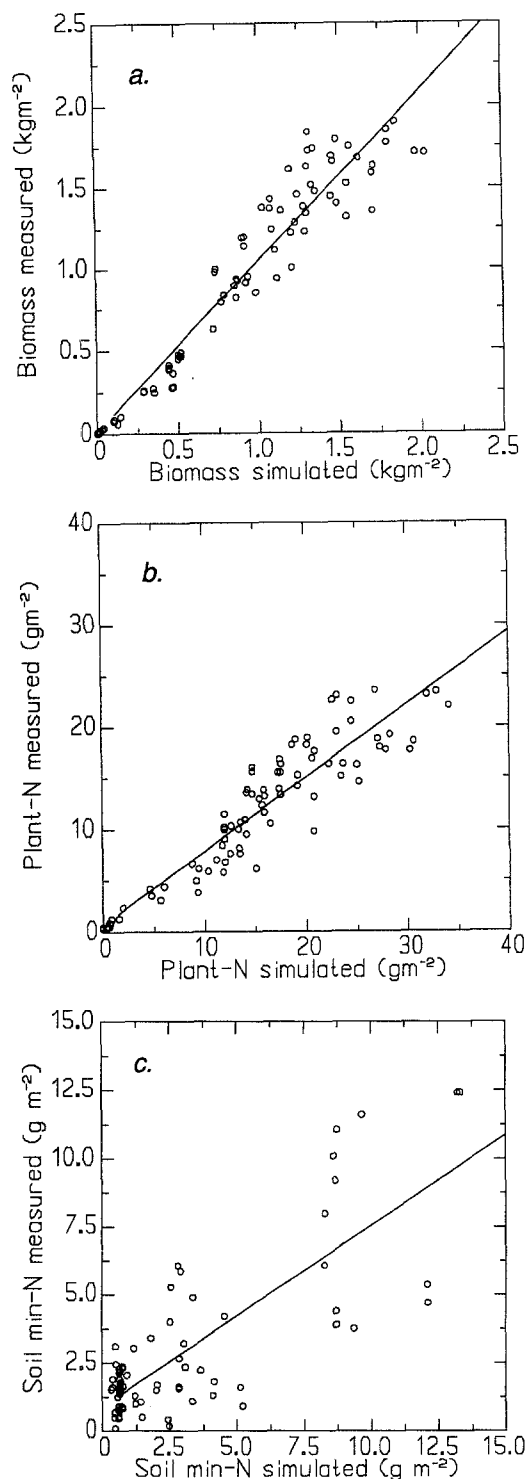


Fig. 6. Regression between simulated and measured values at the Eest and PAGV for aboveground biomass (a), aboveground plant nitrogen (b) and soil mineral nitrogen (c). Regression parameters for each of the lines are given in Table 1.

Table 1. Regression lines between the simulated and measured values of biomass ( $W$ ) and nitrogen ( $N$ ) for the Eest and PAGV. The regression follows: Measured value =  $a + b \times$  Simulated value

Variable	$R^2$ (-)	$a$ ( $g\ m^{-2}$ )	$b$ (-)	Sample
$W_{ta}$	0.93	10	1.04	86
$W_l$	0.61	-30	1.04	80
$W_s$	0.74	50	0.97	69
$W_g$	0.93	20	1.10	55
$N_{ta}$	0.86	0.7	0.72	85
$N_l$	0.62	-2.5	0.96	74
$N_s$	0.36	1.0	0.42	68
$N_g$	0.89	0.4	1.04	62
$N_{soil}$ (0-1 m)	0.64	0.9	0.67	78

tion of the Bouwing site from the others is of minor importance.

The seasonal maximum value of  $W_{ta}$  was normally simulated with an accuracy of  $\pm 20\%$  (Table 2). For  $N_{ta}$  the accuracy was of the same order, except for some PAGV simulations and, the non-fertilized polder at the Eest, where the error was up to 50%. This was mainly due to the poor predictions of soil nitrogen content immediately after fertilization.

The amount of biomass produced per unit of nitrogen taken up by the plant (nitrogen productivity) was estimated for the total of all aboveground plant parts, i.e. the nitrogen productivity here equals  $W_{ta}/N_{ta}$ . For measurements throughout the growing season the nitrogen productivity increased with the amount of nitrogen taken up but for seasonal maximum values it decreased with  $N_{ta}$  (Fig. 7). This was true both for simulated and measured values although this was much more pronounced for the latter. The correlations between nitrogen productivity and  $W_{ta}$  were much poorer in all cases.

### Sensitivity of the SOILN model

A sensitivity test was made, using the data set from the Bouwing site, to examine the effect of specified changes or errors in the values of parameters and input variables, on the simulated production. The parameters were split into four groups on the basis of which process they mainly

Table 2. Measured seasonal maximum values of the total aboveground biomass ( $W_{ta}$ ) and the total aboveground nitrogen ( $N_{ta}$ ).  $\Delta$  is the relative difference between simulated and measured value

Year	Treatm.	the Bouwing				the Eest				PAGV			
		$W_{ta}$ Kgm <sup>-2</sup>	$\Delta$ (%)	$N_{ta}$ gm <sup>-2</sup>	$\Delta$ (%)	$W_{ta}$ Kgm <sup>-2</sup>	$\Delta$ (%)	$N_{ta}$ gm <sup>-2</sup>	$\Delta$ (%)	$W_{ta}$ Kgm <sup>-2</sup>	$\Delta$ (%)	$N_{ta}$ gm <sup>-2</sup>	$\Delta$ (%)
1983	N1	1.47	-10	14.4	18	1.01	34	7.6	102	1.36	41	10.5	76
	N2	1.77	-21	21.3	5	1.74	-14	18.7	12	1.63	18	16.3	49
	N3	1.72	-9	25.4	16	1.80	-8	23.5	-11	1.78	14	23.1	47
1984	N1	1.52	-21	19.5	-20	1.63	-20	16.9	-23	1.75	-1	18.2	4
	N2	1.62	-11	26.3	-5	1.84	-20	23.0	7	1.86	8	19.2	49
	N3	1.71	-9	27.5	9	1.73	-15	22.5	-10	1.90	9	23.4	47

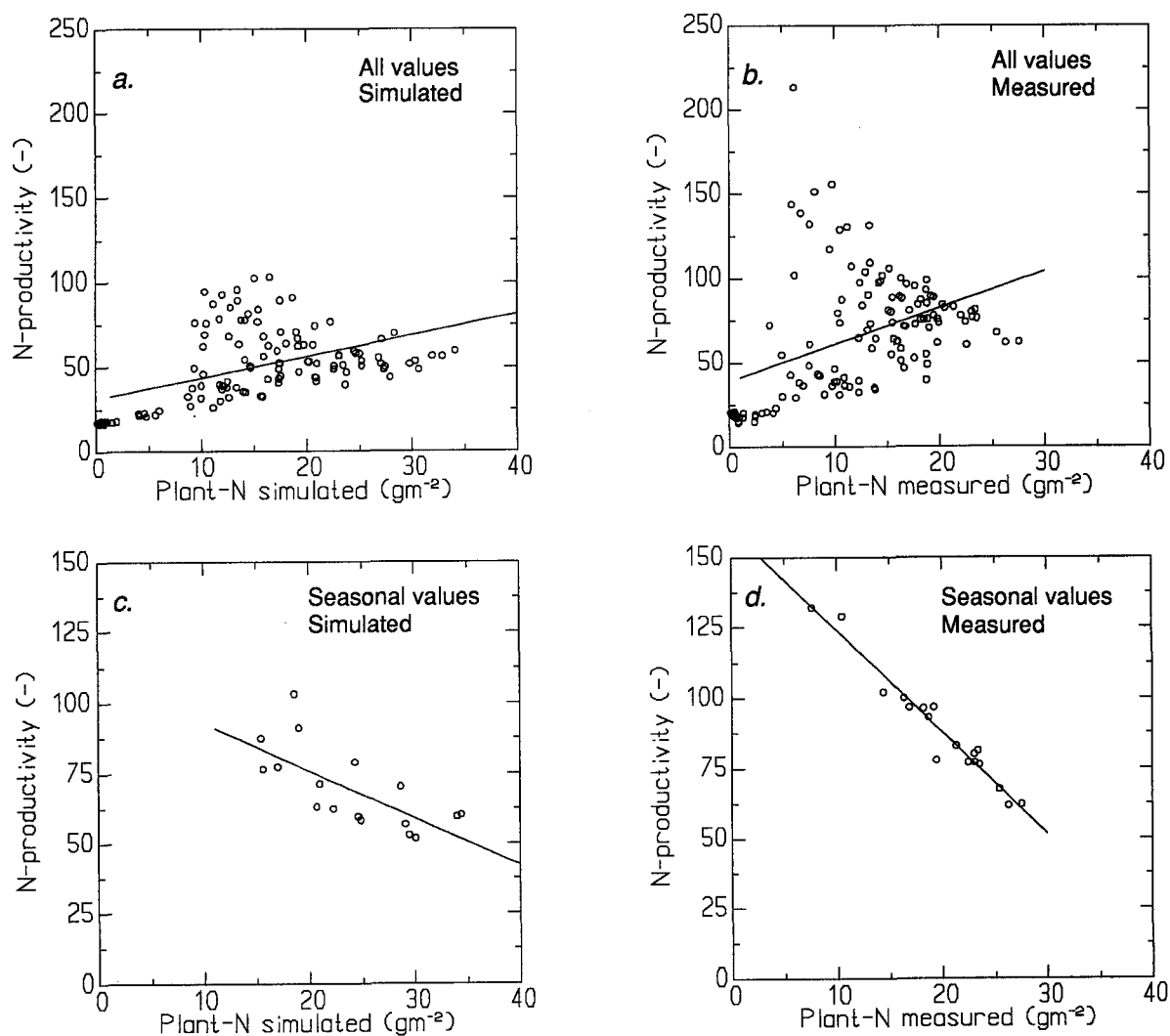


Fig. 7. Simulated and measured nitrogen productivity, defined as the total aboveground biomass divided by the total aboveground nitrogen ( $N_{ta}$ ) as a function of  $N_{ta}$ . The subpictures present all measurements throughout the growing season (a and b) and the maximum values at harvest (c and d).

affect: growth, partitioning of biomass, partitioning of nitrogen, and plant nitrogen uptake. The input variables and initial values of state variables were placed in a fifth group. The values of each parameter were modified separately to cause an increase in the total production ( $W_t$ ). The parameters were changed by 10%, except for temperature values which were changed by 1°C. The relative differences (compared to the original simulation) in the maximum values of  $W_t$  and total plant nitrogen ( $N_t$ ), respectively, were chosen as indicators of sensitivity. The test was made both for the non-fertilized treatment (N1 in 1983) and treatment N3 in 1983, with a high application rate.

In the fertilized case, the effects of changes on total production ( $W_t$ ) were largest for the growth parameters (especially the light use efficiency,  $\epsilon$ ) but also for  $i_v$  (i.e.  $c_0$  in Eq. 12 was changed) which determines the start of grain development (Table 3). The lowest sensitivity was found for nitrogen partitioning parameters.  $N_t$  was affected about the same by all parameters, although it was much less sensitive than  $W_t$ . For the non-fertilized treatment the sensitivity was in general much smaller.  $W_t$  was most sensitive to the parameters controlling the partitioning of biomass but those dealing with partitioning of nitrogen were also important.  $N_t$  was very insensitive to the growth parameters. Instead, the low soil nitrogen status meant that the uptake of nitrogen was much more important as a regulator of growth.

Making a similar parameter modification, but of the opposite sign (the values in brackets in Table 3), showed whether the response to the change was proportional to the change in the parameter value (or input variable) or not. A clear non-proportional response was found for both  $\epsilon$  and air temperature ( $T$ ).

Some special situations were also analyzed (see Table 3) such as (i) a uniform distribution over depth of root surface area ( $a_r = \text{constant}$ ), (ii) a total availability for root uptake (in each layer) of the soil nitrogen ( $c_u = 1$ ) and (iii) no possibility of compensating a deficit in uptake from one layer by uptake from the layer just below ( $c_{um} = 0$ ). As the fertilization supply decreases the effect of (ii) is to dramatically in-

Table 3. The relative change during one growing season in the maximum values of simulated total biomass ( $W_t$ ) and total plant nitrogen content ( $N_t$ ) when values of parameters and input variables are changed by 10% (or those specified). The original values are those given in the appendix. ( ) is the effect when making the same relative change but of opposite sign. The original simulations are those of the Bouwing in 1983. N3 is high fertilizer treatment and N1 is no fertilization

		Relative change (%) in seasonal-max of:			
Para- meter	Change	$W_t$		$N_t$	
		N3	N1	N3	N1
Growth					
$k$	+10%	6 (-8)	1 (-1)	2	+0
$T_{\text{Min}}$	-1°C	3 (-4)	1 (+0)	1	+0
$T_{\text{Max}}$	-1°C	4 (-4)	1 (1)	2	+0
$\varepsilon$	+10%	13 (-17)	4 (-4)	4	+0
Partitioning of biomass					
$a_{\text{ls}}$	+10%	2 (-4)	4 (-3)	-1	1
$b_g$	-10%	2 (-2)	2 (-2)	3	1
$b_i$	+10%	4 (-5)	-3 (3)	3	-1
$b_{\text{ro}}$	-10%	1 (-1)	1 (-1)	+0	0
$i_v$	-10%	6 (-8)	7 (-5)	2	2
Partitioning of nitrogen					
$n_{\text{lMax}}$	-10%	+0 (-0)	3 (-3)	-2	-1
$n_{\text{rMax}}$	-10%	+0 (-0)	2 (-2)	-1	2
$n_{\text{sMax}}$	-10%	+0 (-1)	2 (-2)	-3	+0
$n_{\text{lMin}}$	-10%	+0 (-0)	4 (-4)	+0	1
Uptake of nitrogen					
$c_u$	a) +10%	+0 (-0)	2 (-3)	1	1
	b) = 1	1	89	3	109
$c_{\text{um}}$	a) -10%	-2 (-4) <sup>a</sup>	-1 (-2) <sup>a</sup>	-1	-0
	b) = 0	-13	-37	-11	-28
Input variables and initial values					
$I$	+10%	3 (-3)	3 (-4)	+0	+0
$T$	-10%	4 (+0)	4 (-2)	+0	1
$w_t(t_0)$	+10%	1 (-1)	+0 (-0)	+0	-0
$a_i$	+10% in layer 1 & -10% in layer 2	2	-0	+0	-0
	const. in all layers i.e. = 0.2	-28	-4	-36	-0

<sup>a</sup>) The modification is -20%

crease the production whilst (iii) causes a pronounced decrease in production. The vertical distribution of roots (i) was important to consider only in the fertilized treatments.

## Discussion and conclusions

In total, 18 simulations were made with the CROP-GROWTH submodel. Only one is shown here (Fig. 5) but, by comparing all of them with measured data, three different patterns of discrepancies were found. Firstly, the measurements of plant nitrogen above ground ( $N_{ta}$ ) showed (in about 70% of all cases) that after the grain development started,  $N_{ta}$  decreased during a period (cf. Fig. 5). However, it is not possible to simulate a decrease in  $N_{ta}$  with this version of the CROP-GROWTH submodel, since processes of nitrogen leaching from the plant and nitrogen translocation to roots are neglected. About simultaneously with these overestimates of  $N_{ta}$ , the soil nitrogen was underestimated. Secondly, in three non-fertilized cases there was a tendency for a too rapid decrease of  $N_{soil}$  and a too high increase of  $N_{ta}$  during the early part of the growing period. This indicated that plant uptake was overestimated which might be explained by the vertical distribution of roots ( $a_r$ ), the efficiency of plants to take up nitrogen ( $c_u$  and  $c_{um}$ ) or the plant demand (Eqs. 27–29), not being correctly simulated. Thirdly, soil nitrogen in the upper layer ( $N_{soil}$ ; 0–30 cm) was considerably overestimated in four PAGV simulations, which in turn caused an overestimation of  $N_{ta}$  from June to the end of the season (thus decreasing the slope of the line in Fig. 6). The model simulated an increase of  $N_{soil}$  after fertilization whilst the measured increases in the soil and plant could only account for 0–50% of the supplied nitrogen.

Nitrogen productivity ( $W_{ta}/N_{ta}$ ) was found to depend on the time period considered. The measured data showed that  $W_{ta}/N_{ta}$  increased during the season while for measurements at final harvest an opposite relationship existed (Fig. 7) which corresponded to a parabolic function between  $N_{ta}$  and  $W_{ta}$  (i.e.  $W_{ta} = 160.12N_{ta} - 3.615N_{ta}^2$ ), however, is not valid for high values of  $N_{ta}$ . The simulated data gave similar results, indicating that the CROP-GROWTH simulations reflected the observed behaviour concerning nitrogen productivity. However, this effect was underestimated especially for low values of  $N_{ta}$ , perhaps due to errors in the parameters controlling partitioning of biomass and nitrogen

or  $\epsilon$ . Nitrogen productivity was much better correlated with nitrogen uptake than biomass.

The introduction of the light use efficiency concept ( $\epsilon I_i$  in Eq. 7) results in a remarkable change of the effect of the light extinction coefficient ( $k$ ; Eq. 8), compared with commonly used growth models based on photosynthesis. Increasing the light absorption by increasing  $k$ , increases the production (Table 3). However, in the photosynthetic growth model the effect is the opposite [8], since a reduction of light on the leaves in the lower part of the canopy decreases the photosynthesis of the whole canopy. Production is, at high fertilizer treatments, remarkably sensitive to variations in  $\epsilon$  itself (Table 3).

The reliability of the simulations of the physical conditions in the soil is not known. However, this was not thought to be an important reason for the discrepancies appearing in the crop growth simulations. The coupling between crop growth and the physical conditions in the soil is made via the mineral-N storage in the root zone. The mineral-N is of course strongly influenced by temperature, water content and water flows but during the intensive period of crop growth, large amounts of N were added as fertilizer and only small amounts were lost through leaching [4]. Instead, the systematic discrepancies in the crop growth predictions (e.g.  $N_{ta}$  in Fig. 6) to a large extent, can be explained by errors in parameter values (cf. Table 3) and/or the overestimation of  $N_{soil}$  after some fertilizations.

The results would have been different if simulations of crop growth had been done without initializing the mineral-N content with measured values prior to each simulation. The small number of observations made outside the growing season made evaluation of simulated nitrogen transformations in the soil and losses such as denitrification and leaching difficult to evaluate. This was also the case for observations of soil water conditions, with some exceptions. The most interesting observation concerning physical conditions was the water table depth. It was shown that the response of the groundwater depth was a more sensitive indicator of the soil physical properties than the soil water content. Both indicated a bypass flow in a sandy loam soil.

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## Appendix

### List of symbols and parameter values

Parameter values given are those used in the simulations for wheat. Category refers to the CROP-GROWTH submodel except if mentioned otherwise.

Symbol	Explanation	Value	Unit	Category
$A_{li}$	Leaf area index		–	Output
$A_{rel}$	Ratio between vertical area of soil compartment and unit horizontal area	0.2–0.4	–	Input <sup>a</sup>
$A_{scale}$	Scaling coefficient accounting for the geometry of soil aggregates	0.8	–	Input <sup>a</sup>
$a_{ls}$	Specific leaf area	0.022	$m^2 g^{-1}$	Input
$a_r$	Fraction of total root surface found in a soil layer		–	Input
$b_g$	Fraction of the biomass in plant tissues translocated to grain compartment	0.02	$d^{-1}$	Input
$b_l$	Leaf area to total aboveground biomass ratio		$m^2 g^{-1}$	Auxiliary
$b_{io}$	$b_l$ at unity $W_{ta}$	0.048	$m^2 g^{-1}$	Input
$b_{il}$	Coefficient relating $b_l$ to $W_{ta}$	0.0064	$m^2 g^{-1}$	Input
$b_r$	Fraction of daily total growth allocated to roots		–	Auxiliary
$b_{ro}$	$b_r$ minimum	0.15	–	Input
$c_u$	Fraction of N in the nitrate and ammonia pool possible to be extracted per day	0.16	$d^{-1}$	Input
$c_{um}$	Fraction of a deficit in N supply in one layer possible to be replaced by N from the layer just below	1.0	–	Input
$c_0$	Coefficient used for calculating $i_v$	0.0252	$d^{-1}$	Input
$c_1$	Coefficient used for calculating $i_v$	–0.153	$^{\circ}C^{-1}$	Input
$c_2$	Coefficient used for calculating $i_v$	3.51	$^{\circ}C$	Input
$c_3$	Coefficient used for calculating $i_v$	–0.301	$h^{-1}$	Input
$c_4$	Coefficient used for calculating $i_v$	9.154	$h$	Input
$D$	Day length		$h$	Input
$E, E_p$	Evapotranspiration, actual and potential, respectively		$mm d^{-1}$	Output <sup>a</sup>
$f_N$	Response function for nitrogen limitation to growth		–	Auxiliary
$f_T$	Response function for temperature limitation to growth		–	Auxiliary
$f_w$	Response function for water limitation to growth		–	Auxiliary
$i_v$	Index that determines the start of grain development		–	Auxiliary
$I$	Global radiation, shortwave, 300–3000 nm		$MJ m^{-2} d^{-1}$	Input
$I_i$	Shortwave radiation intercepted by canopy		$MJ m^{-2} d^{-1}$	Auxiliary
$k$	Light extinction coefficient related to leaf area	0.6	–	Input
$k_{mat}$	Saturated hydraulic conductivity, excluding the contribution of macropores	Fig. 3b	$mm d^{-1}$	Input <sup>a</sup>
$k_s$	Saturated hydraulic conductivity, including the contribution of macropores	Fig. 3b	$mm d^{-1}$	Input <sup>a</sup>
$k(\theta)$	Unsaturated hydraulic conductivity function	Fig. 3b	$mm d^{-1}$	Input <sup>a</sup>
$L$	Characteristic distance in the gradient term in Darcy's equation		$m$	Input <sup>a</sup>
$n_l, n_s, n_r$	N concentrations in leaf, straw and root		$g N(gDW)^{-1}$	Auxiliary
$n_{lMax}$	Maximal N concentration in leaf	0.06	$g N(gDW)^{-1}$	Input
$n_{rMax}$	Maximal N concentration in root	0.025	$g N(gDW)^{-1}$	Input
$n_{sMax}$	Maximal N concentration in straw	0.02	$g N(gDW)^{-1}$	Input

Symbol	Explanation	Value	Unit	Category
$n_{\text{Min}}$	Minimum N concentration in leaf	0.01	$\text{g N}(\text{gDW})^{-1}$	Input
$N_g, N_l, N_r,$ $N_s, N_t, N_{ta}$	Amount of N in grain, leaf, root, straw, total and total aboveground		$\text{g N m}^{-2}$	Output
$N_{\text{NO}_3}, N_{\text{NH}_4}$	Amount of nitrate-N and ammonium-N in the soil		$\text{g N m}^{-2}$	Output <sup>b</sup>
$N_{\text{soil}}$	Mineral-N in the soil, $N_{\text{NO}_3} + N_{\text{NH}_4}$		$\text{g N m}^{-2}$	Output <sup>b</sup>
$\psi$	Soil water tension		cm water	Output <sup>a</sup>
pF	pF value, defined as $^{10}\log(\psi)$	Fig. 3a	–	Auxiliary <sup>a</sup>
$q_{\text{in}}$	Vertical water flow, positive downwards		$\text{mm d}^{-1}$	Output <sup>a</sup>
$q_{\text{mat}}$	Vertical water flow, soil matrix		$\text{mm d}^{-1}$	Output <sup>a</sup>
$q_{\text{bypass}}$	Vertical water flow, soil macropores		$\text{mm d}^{-1}$	Output <sup>a</sup>
$q_{\text{pipe}}$	Sink flow from one layer to drainage pipes		$\text{mm d}^{-1}$	Output <sup>a</sup>
$S_{\text{mat}}$	Sorption capacity of aggregates		$\text{mm d}^{-1}$	Output <sup>a</sup>
$t$	Time coordinate		d	Auxiliary
$t_0$	$t$ when plant starts to grow		d	Auxiliary
$T$	Daily mean of air temperature		°C	Input
$T_{\text{Min}}$	Temperature limit for start of growth	2	°C	Input
$T_{\text{Max}}$	Temperature limit for optimal growth	10	°C	Input
$W_g, W_l, W_s,$ $W_r, W_t, W_{ta}$	Accumulated growth of grain, leaf, straw, root, total and total aboveground		$\text{g DW m}^{-2}$	Output
$x_{\text{fra}}$	Fraction nitrate-N of mineral-N		–	Auxiliary
$X_{\text{Nu}}$	Actual daily N uptake by plant		$\text{g N m}^{-2} \text{d}^{-1}$	Auxiliary
$X_{\text{Nd}}$	Daily N uptake demand by plant		$\text{g N m}^{-2} \text{d}^{-1}$	Auxiliary
$X_{\text{Nm}}$	Demand of N transferred from one soil layer to the layer below		$\text{g N m}^{-2} \text{d}^{-1}$	Auxiliary
$X_{\text{Np}}$	Potential daily N uptake from one layer		$\text{g N m}^{-2} \text{d}^{-1}$	Auxiliary
$z$	Depth coordinate		m	Auxiliary <sup>a</sup>
$z_{\text{gw}}$	Depth of groundwater table		m	Output <sup>a</sup>
$z_{\text{pipe}}$	Depth of drainage pipes	1.0	m	Input <sup>a</sup>
$\theta$	Liquid water content		vol%	Auxiliary <sup>a</sup>
$\varepsilon$	Total growth per unit of intercepted radiation (300–3000 nm) at optimal temperature, nitrogen and water conditions	2.0	$\text{g DW MJ}^{-1}$	Input

- ' : Denotes the daily change of the symbol concerned  
 (in) : Denotes a positive change of the symbol concerned  
 (out) : Denotes a negative change of the symbol concerned  
 a : Refers to the SOIL model  
 b : Refers to the SOILN model

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