MODELS IN AGRICULTURE AND FOREST RESEARCH

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SIMULATION OF NITROGEN BEHAVIOUR IN A CROP-SOIL SYSTEM

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ABSTRACT

Nitrogen dynamics in both soil and crop is a major consideration in modern agriculture. To improve insight in the nitrogen dynamics, several simulation models of nitrogen behaviour in the crop-soil system have been developed. Most of these are conceptual models, correctly describing the processes, but are too complex to apply for management purposes, as too detailed input parameters are required. Based on existing theory and models for crop growth, nitrogen distribution in the crop, and water and nitrogen dynamics in the soil, a simulation model has been developed. The model simulates nitrogen dynamics for a winter wheat - soil system, and requires only parameters that can be obtained from field measurements. A short description of the processes included in the model is given. For detailed information on the theory reference is made to existing literature.

I. INTRODUCTION

In most European countries, nitrogen fertilizer recommendations for cereals are based on the amount of inorganic nitrogen in the soil profile measured in early spring (Dilz, 1985). The total amount of nitrogen required for optimal crop production is usually given in three applications. Splitting the nitrogen application diminishes nitrogen losses by leaching, and generally increases both yield and quality (Dilz et al., 1982). However, this fertilizer recommendation system is not very flexible, and can hardly be adapted to the actual crop and soil situation for a given site.

To optimize fertilizer recommendations, it should be possible to compare the amount of soil mineral nitrogen available for crop uptake, with the nitrogen demand of the crop throughout the growing season. In the present situation, the available soil mineral nitrogen is measured by a single soil sample. This measured amount of mineral nitrogen may be subject to losses by leaching, may only be partly available for the crop as a result of dry soil conditions, or may not be reached as a result of limited root extension. In addition, mineralization and immobilization continuously change the available nitrogen pool.

The nitrogen demand of a winter wheat crop cannot be considered constant but depends on environmental conditions and on the stage of crop development. Weather conditions experienced by the crop determine to a large extent the actual nitrogen demand.

As conditions mentioned above should be taken into account in the determination of the optimum timing and rate of fertilizer application, it is evident that a single observation of the soil mineral nitrogen pool can easily result in erroneous assumptions about the amount of fertilizer required for optimal nitrogen uptake by the crop.

The amount of mineral nitrogen available for crop uptake and the nitrogen demand of the crop throughout the growing season, can be compared using simulation models. Several models for the behaviour of nitrogen in the soil have been developed (Frissel & van Veen, 1980), and models to simulate crop nitrogen availability and crop growth are available (Frissel & van Veen, 1980, Van Keulen & Seligman, 1987). Most of these models were developed as research tools, and cannot be applied readily for management purposes, as they require too many site specific input parameters that cannot easily be obtained by simple field measurements.

Based upon existing theory and models on water and nitrogen dynamics in the soil, crop growth, and nitrogen distribution in the crop, a simulation model has been developed that only requires input parameters that can easily be obtained at the field level.

The simulation model provides the possibility to compare various fertilization strategies as used in agricultural practice, and enables the identification of weak points of these strategies.

A short description of the model processes is given. For detailed information on the theory reference is made to the literature cited.

II. STRUCTURE OF THE MODEL AND SIMULATION LANGUAGE

The functional processes in the model are treated in various subroutines. The basic concept behind the model structure is to define an environment in which crop growth occurs, and to describe this environment by parameters that can be measured at the field level. The model structure is illustrated in Table 1.

The simulation model is written in FORTRAN-77, and runs on an IBM-AT microcomputer (520K memory, 20Mb fixed disk). The FORTRAN compiler is Microsoft-FORTRAN, version 4.00, 1987.

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PROGRAM NWHEAT

CALL INITIM initiates all variables associated with time

DO (while finish contitions not reached)

    CALL WEATHER reads daily weather data from weather data file
    CALL ASTRO calculates astronomical and photoperiodically active daylength
    CALL RADIAT calculates direct and diffuse radiation flux intensities
    CALL PENMAN calculates potential evaporation from a free water surface, a bare soil surface,
                and a crop
    CALL WATBAL calculates the soil water status

         CALL SOILR read physical soil data from the soil data file SOIL.DAT
         CALL EVSOIL calculates soil evaporation and distributes the withdrawn moisture over
                the soil compartments
         CALL WATOUT writes the soil water status to the soil water output file WATOUT.DAT

    CALL SOLTMP generates soil temperatures
    CALL NITBAL calculates the soil nitrogen status

         CALL NSOILR read soil nitrogen data from the data file NSOIL.DAT
         CALL NITOUT writes soil nitrogen status to the soil nitrogen output file NITOUT.DAT

    CALL PLANT simulates dry matter increase and nitrogen distribution of the winter wheat crop

         CALL PHENO calculates the development stage of the crop
         CALL ASSIM calculates the gross assimilation rate of the crop
         CALL CRPOUT writes crop status to the crop output file CRPOUT.DAT

    CALL TIMER updates time with the time step of integration

ENDDO
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Table 1 Outline of the simulation model for nitrogen behaviour in a winter wheat - soil system.

III. MODEL DESCRIPTION

III.1 Calculation of daylength (subroutine ASTRO)

Based upon the latitude of the site for which simulations are performed, and on the Julian date, the daylength and the photoperiodically active daylength are calculated.

III.2 Separation of diffuse and direct radation (subroutine RADIAT)

The flux densities of the direct and the diffuse component of photosynthetically active radation are calculated according to Spitters et al. (1986). These values are used in the model to calculate canopy photosynthesis.

III.3 Soil surface evaporation and crop transpiration (subroutine PENMAN)

Potential soil surface evaporation and potential crop transpiration are calculated according to the Penman equation (1948, 1956).

III.4 Soil water balance (subroutine WATBAL)

Soil water dynamics can be simulated at various levels of detail. The method used in the present model requires only parameters that can be measured at the field level. The soil is treated as a multilayered system with 10 compartments. Each compartment is characterized by its thickness and its pF-curve.

When precipitation occurs, the first soil compartment is filled till field capacity, and all excess water entering the compartment drains to next compartments. This procedure is repeated for deeper compartments as long as drainage occurs.

Soil moisture losses may occur by drainage below the potential rooting zone, by crop transpiration and by soil surface evaporation. Moisture losses by transpiration can occur until a soil water tension of 15000 cm or a pF of 4.2 has been reached. Moisture losses below that value will only occur by soil surface evaporation. Soil evaporation is related to the moisture content of the surface compartment according to van Keulen (1975). The moisture loss by evaporation is distributed over various soil compartments according to an exponential decay function.

III.5 Soil temperatures (subroutine SOLTMP)

Mineralization and root extension growth depend on the temperature of the soil compartment in which the processes occur. To apply the model to a field situation, soil temperatures have to be recorded, or, if not available, they may be simulated from measured air temperatures. However, for a winter wheat crop difficulties arise, as processes of frost and defrost, and the effect of a snow cover should be taken into account. As this requires extra soil parameters, we have chosen for a simplified approach. Soil temperature are related to measured air temperatures by means of a delay function, and the delay in temperaure response is longer for deeper soil compartments.

III.6 Soil nitrogen balance (subroutine NITBAL)

Downward nitrogen transport and mixing:
Downward nitrogen transport only occurs by downward water flow as described in the soil water balance, and all nitrogen is assumed to be in the mobile phase. This part of the model has been validated against field data sets where chlorine movements were monitored, and simulations of

chlorine movement were satisfactory (Zandt et al.,1986).

The theory proposed by Burns (1974) is used to describe the mixing of soil mineral nitrogen and water. This implies that all water and nitrogen entering a soil compartment is completely mixed with water and nitrogen already present in the soil compartment. The resulting concentration is subject to drainage.

Mineralization:

Especially mineralization and immobilization are treated in more detail in various models. The more complex models take, in addition to a mineral nitrogen pool, an old organic matter pool and a fresh organic matter pool, a fourth nitrogen pool into account, the soil microbial biomass. As parameters to describe soil microbiological processes, such as initial amounts of microbial biomass and its maintenance respiration requirements are very hard to obtain, this approach has not been used.

Mineralization from old organic material (humus) is calculated according to a relative decay rate which is modified for the effects of soil temperature and soil humidity according to a two dimensional response surface derived in incubation experiments, described by Verbruggen (1985).

Decomposition of fresh organic matter occurs according to the same response surface, but depending on the nitrogen content of the crop residues, mineralization or immobilization may occur.

Nitrogen uptake:

Only when nitrogen concentrations in the soil are extremely high, nitrogen demand of a crop can be covered by nitrogen uptake in the mass flow of the transpiration stream (Nye, 1977; Burns, 1980). In addition to mass flow, nitrogen can be taken up by diffusion towards the roots. According to Johnsson et al. (1987, in press), it is assumed that during one day, not more than 8% of the mineral nitrogen available in a soil compartment can be taken up by diffusion. Uptake by diffusion is hampered at low soil water contents, and ceases below wilting point.

III.7 Simulation of plant processes (subroutine PLANT)

Simulation of plant processes is largely based upon van Keulen and Seligman (1987). Only a short description of the most important processes is given.

Phenology:

The winter wheat phenological development is described according to Porter (1984) and Weir et al. (1984), but the approach was adapted for Dutch conditions (Reinink et al., 1986). In this approach, Julian time is replaced by a thermal index, i.e. a temperature sum. This temperature sum is calculated as the sum of temperatures above a certain base value modified for effects of vernalisation and photoperiod. Base temperatures as well as sensitivity to vernalisation and photoperiod vary with stage of crop development.

Photosynthesis:

Canopy photosythesis depends on the light intensity above the canopy and on the extinction coefficients for the diffuse and direct components of radiation. Based on these characteristics, actual radiation absorption is calculated for three dephts in the canopy and at three moments of the day, and these values are introduced in the photosynthesis-light response curvės of individual leaves, to obtain the assimilation rate per unit leaf area in the layer considered for the relevant time. Integration over depth and over the daylight period is performed to obtain daily total gross canopy assimilation (Spitters, 1986).

The shape of the photosynthesis-light response curve depends on the nitrogen content of the leaf material (e.g. van Keulen and Seligman, 1987) and therefore, canopy photosynthesis is closely related to the nitrogen status of the crop.

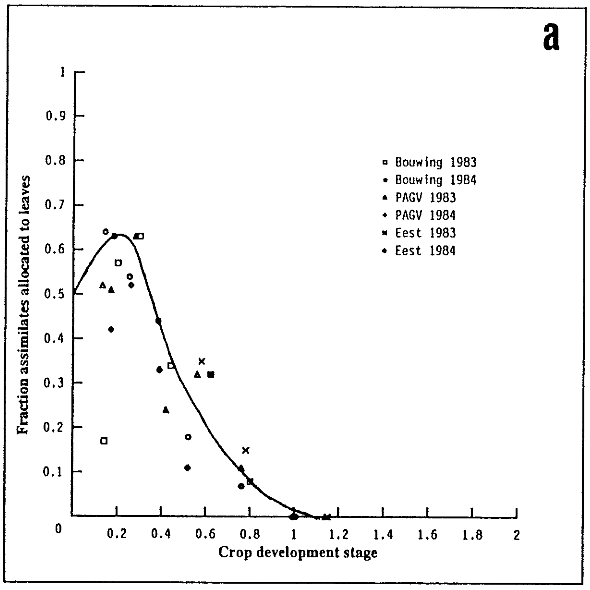
Maintenance respiration:

Maintenance respiration is calculated according to Penning de Vries & van Laar (1982), but the maintenance respiration coefficients are corrected for the nitrogen content of the plant material.

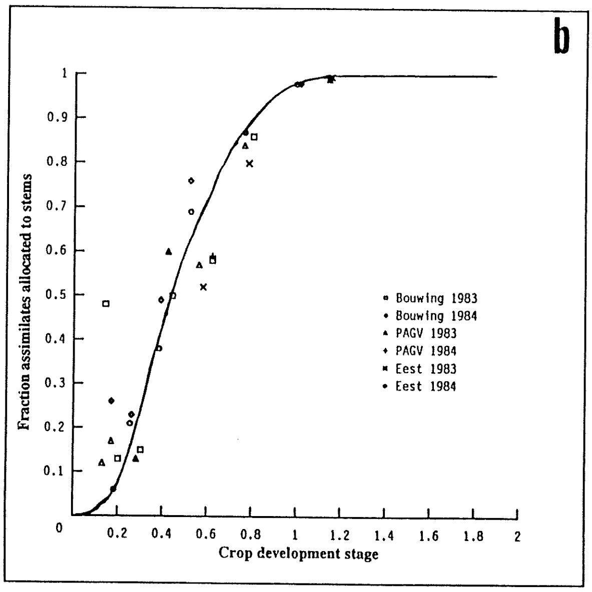
Assimilate distribution and leaf area growth:

Assimilates are allocated to stems, leaves and roots, according to distribution functions derived from field experiments (Figure 1). The leaf area index of the crop is calculated by applying a specific leaf area.

ASSIMILATE DISTRIBUTION



ASSIMILATE DISTRIBUTION



ASSIMILATE DISTRIBUTION

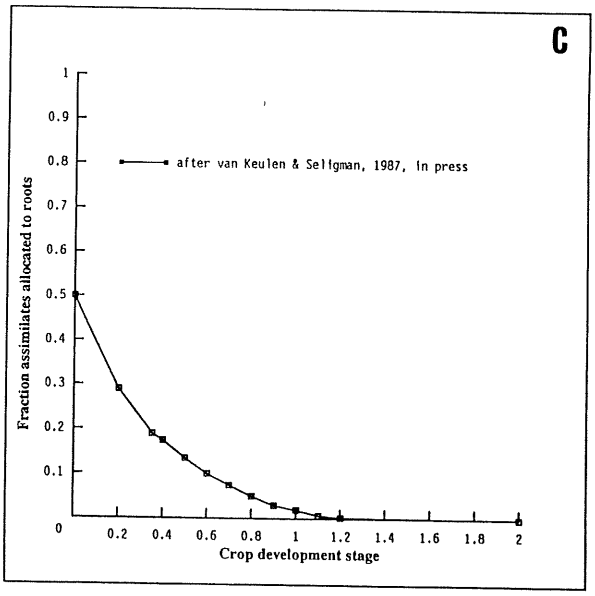
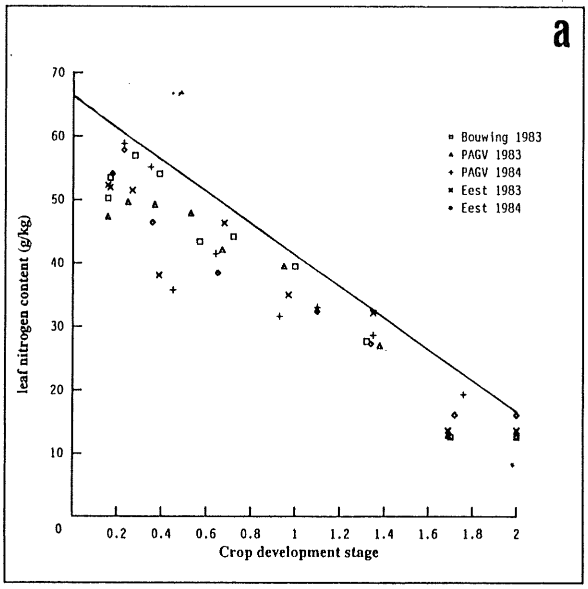


Fig. 1 Fraction of current assimilates allocated to leaves (fig. 1a), stems (fig. 1b) and roots (fig. 1c) as a function of the crop development stage, DVS. DVS = 0: emergence, DVS = 1: anthesis, DVS = 2; ripeness. Data have been measured in field experiments at different sites.

LEAF NITROGEN CONTENT AT OPTIMAL NITROGEN SUPPLY



STEM NITROGEN CONTENT AT OPTIMAL NITROGEN SUPPLY

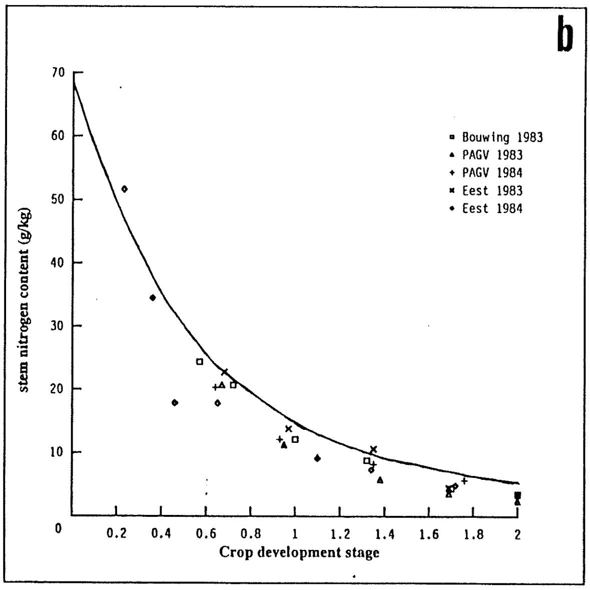


Fig. 2 Nitrogen content in leaves (fig. 2a) and stems and ears (fig. 2b) measured in field experiments at different sites with optimal nitrogen supply. The drawn line represents the assumed maximum nitrogen content.

Nitrogen demand:

From field experiments with optimum nitrogen supply, the optimum nitrogen content of each organ was derived as a function of the crop development stage. It is assumed that the maximum nitrogen content an organ can reach is slightly above the measured values (Figure 2). When the actual nitrogen content is simulated, the nitrogen demand of an organ is calculated as the difference between the maximum nitrogen content and the actual nitrogen content at a given development stage, multiplied by the weight of the organ. The nitrogen that is actually taken up from the soil depends on the soil mineral nitrogen availability. The nitrogen is distributed over the crop organs according to their relative demands.

IV. FINAL REMARKS

A remark has to be made on that part of the model that requires more attention, before a simulation approach aiming at optimum fertilizer recommandation can be introduced.

As crop growth can be simulated satisfactory, the soil aspects of the model are limiting and require a better understanding. Especially the processes of mineralization and immobilization of nitrogen are poorly understood. Simulation of mineralization by means of a fixed relative decay rate of old organic matter as described in Section III.6 cannot explain the large differences in mineralization as measured at different sites in actual agricultural practice.

A first improvement would certainly be a characterization of different soil types by means of a soil specific mineralization rate of old organic matter, instead of assuming the same relative decay rate for each soil type.

V. LISTING AND DETAILED DESCRIPTION OF THE MODEL.

A detailed description and a model listing are available upon request. Requests should be adressed to J.J.R. Groot, Centre for Agrobiological Research, Bornsesteeg 65, P.O. Box 14, 6700 AA, Wageningen, The Netherlands.

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