Modelling Nutrient Uptake of Sweet Pepper

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Abstract
        **Models simulating dry matter production have been developed for a large
number of greenhouse crops during the past decades. This paper describes how
plant-nutrient relationships can be incorporated in a model for greenhouse crops,
with sweet pepper as an example. Based on climatic data, the model simulates the
growth of plant organs, transpiration, water uptake and uptake of the various macro
nutrients.**
        **A mechanistic photosynthesis-driven model is used to simulate dry matter
production. For each plant organ its required concentrations of the various macro
nutrients are calculated, which depend on the ontogenetic age of the organ. The
required nutrient uptake is calculated from these required concentrations and the
dry weights of the organs. If there is no limitation in availability at the root surface
the actual uptake will equal the required uptake. When the root system cannot fulfil
the demand, uptake will be less, plant nutrient concentration will drop and crop
production is potentially reduced.**
        **The model was tested on data from two different climatic regions (France and
Spain). The model was also used to show some effects of the greenhouse climate on
water and nutrient uptake. The rate of water uptake per unit radiation as well as the
EC of the water taken up by plants was shown to vary considerably. Finally, the
utilization of the model in an integrated control and monitoring system is discussed.**

INTRODUCTION

        Greenhouse crops are often grown in soilless culture. In the present greenhouse
horticulture in Europe, nutrients and water supplies are coupled. This means that when
growers supply more water, they also supply more nutrients. To prevent any shortage
growers use excess amounts of nutrients and water. Growers control the total salt
concentration rather than the concentration of the individual nutrients. However, plant
demands for water and nutrients are not coupled (e.g. an increase in air humidity does not
substantially change the demand for nitrogen, but decreases water use). In addition the
demand for the different nutrients changes dynamically. This may lead to sub-optimal
below-ground conditions for plant growth. Therefore, even when a recirculation system is
used, growers regularly drain nutrients and water to the environment to prevent imbalances
of the nutrient solution in the root zone. This drainage burdens the environment.
        Regulations require the Dutch greenhouse horticultural sector to minimize losses
of water and nutrients to the environment. In addition, predicting and controlling product
quantity and quality are becoming increasingly important, in order to meet the demands
of the customers. This requires accurate control of water and nutrient flows, crop
production and quality.
        To develop systems for such accurate control of water and nutrients, models
simulating crop production and plant-nutrient relationships are valuable tools (e.g. Bar-
Yosef et al., 2004). Though a large number of (mechanistic) models for crop growth and
production of greenhouse crops have been developed and tested (Marcelis et al., 1998),

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most of these models do not consider nutrient relationships. This paper describes the simulation of plant nutrient relationships that were incorporated in a mechanistic model for crop growth and development. The model was tested on data from two different climatic regions (northern France and southern Spain). The model was developed within the framework of an EU project (CLOSYS: Closed System for water and nutrient management), where the model is being used as part of an expert system for water and nutrient management.

MODEL DESCRIPTION

A mechanistic model for sweet pepper has been developed that simulates dry and fresh weight growth of plant organs, transpiration, water uptake and demand and uptake of the various macro nutrients. Input to the model are global radiation outside the greenhouse and inside climate (temperature, air humidity and CO_2 concentration). The simulation runs shown in this paper also used the periodically measured LAI as input to calibrate the parameters for leaf area formation. The crop model is primarily based on the INTKAM model for simulation of plant water relations and dry matter production (Gijzen, 1994). The simulation of dry matter partitioning, fruit set and fruit growth is primarily based on the model for cucumber of Marcelis (1994), but with parameters based on sweet pepper experiments. The model consists of routines for greenhouse radiation transmission, radiation interception by the crop, leaf energy balance, leaf and canopy transpiration, leaf and canopy photosynthesis, dry matter production, dry matter partitioning among plant organs (roots, stem, leaves and individual fruits), fruit harvest, nutrient demand and nutrient uptake.

Greenhouse radiation transmission, radiation interception, photosynthesis and transpiration are calculated with time intervals of an hour. The time step of calculation of dry matter production, partitioning, fruit harvest, nutrient demand and uptake is one day.

Interception of visible and near infra red radiation, canopy gross photosynthesis and canopy transpiration are calculated for a multi-layered uniform canopy (Goudriaan and Van Laar, 1994). Leaf gross photosynthesis is calculated with the biochemical model of Farquhar et al. (1980) and leaf transpiration is based on the Penman-Monteith equation for the various layers in the canopy as described by Gijzen (1994).

Net assimilate production results from the difference between canopy gross photosynthesis and maintenance respiration. Maintenance respiration is calculated as a function of dry weights of the organs and temperature, according to Spitters et al. (1989).

Assimilate partitioning between vegetative parts and individual fruits is simulated on the basis of the concept of sink strengths, as described by Marcelis (1994). In this concept the fraction of assimilates partitioned into an organ is calculated to be proportional to the ratio between its potential growth rate (sink strength) and that of all plant parts.

Rates of formation of flowers and leaves is calculated as a function of temperature. Abortion of flowers and fruits is calculated as a function of the source/sink ratio (ratio between assimilate supply and demand) and temperature, based on results of Marcelis et al. (2004).

Dry matter increase of the organs is calculated as the amount of assimilates partitioned into each organ divided by the assimilate requirements for dry matter production. Fresh weight growth of the different plant organs is obtained by dividing the dry weight of the organs by a constant dry matter content. The water uptake of the crop is calculated from transpiration and fresh weight growth.

The demand for nutrients mainly depends on the growth of the different plant organs as determined by factors other than nutrition (e.g. plant development, light intensity, temperature) (e.g. Le Bot et al., 1998). In the model the nutrient demand is calculated for each organ as the product of dry weight growth and required nutrient concentration, which is comparable to the approach of Mankin and Fynn (1996), Kläring et al. (1997) and Bellert et al. (1998). The required or maximum concentration is the concentration the plant itself aims at when there is no limitation in the nutrient supply.

The required concentration of each macro-nutrient was modelled for leaves, stems, roots and each individual fruit. These concentrations usually show an ontogenetic change. In the model for each organ the required nutrient concentration was described by an initial linear increase or decrease with temperature sum followed by a constant value; this relationship was described by 3 parameters: minimum and maximum concentration and slope.

When there is no limitation in water and nutrient supply, the simulated uptake by the plant will equal its demand. The model can be coupled to an elaborate substrate model that determines whether the root system can fulfil the demand for water and nutrients and calculates the uptake rates (see Marcelis et al., 2003). Instead of using an elaborate substrate model, water and nutrient uptake can also be calculated as the product of the required uptake and a reduction factor, where the reduction factor depends on humidity and nutrient concentrations in the substrate. In this paper only simulation results will be shown for situations where it was assumed that no limitations in nutrient or water availability occurred.

Shortage of nutrients in the rooting medium leads to low nutrient concentrations in the plant. Effects of low nutrient concentrations in the plants can be simulated by a combination of effects on leaf photosynthesis, leaf area development, and dry matter partitioning. This concept was applied to tomato by Marcelis et al. (2003). For sweet pepper only a limited number of experiments were conducted to quantify the effects of nutrient shortage on growth and its underlying processes. These limited data do not allow to simulate effects of nutrient shortage in terms of effects on different plant processes. Therefore, nutrient effects on growth were simulated as a reduction factor on the growth rate (rate of dry weight increase of the whole plant).

MATERIALS AND METHODS

Sweet pepper crops were grown in two different climate zones: Carquefou France (latitude 47.2 °N) and Murcia Spain (latitude 38.1°N). Two main stems per plant were retained. Seven destructive harvests of plants were performed to determine LAI, dry weight, fresh weight and nutrient concentrations (N, P, K, Ca, Mg and in France also S) of plant organs.

In Carquefou the cultivar Triple 4 (green fruits at harvest) was grown on Rockwool (Grodan, FL) in a glasshouse. The first experiment lasted from 17 Dec 2002 until 9 Oct 2003, and the second experiment from 17 Dec 2003 until 30 March 2004. Plant density was 3.1 plants per m^2. The composition of the irrigation water was according to De Kreij et al (1999). Water supply aimed at a drain ratio of 30-40%.

In Murcia the cultivar Requena F1 (California type; red fruits at harvest) was grown on Rockwool (Grodan, Expert) in a plastic greenhouse. The experiment lasted from 23 Jan until 24 July 2003. Plant density was 1.6 plants per m^2. The irrigation water was a Hoagland solution. Water supply aimed at a drain ratio of 30-40%.

RESULTS AND DISCUSSION

Crop dry weight was simulated well by the model. In the French experiment of 2003 final above-ground dry matter production (267 days after planting) was 2387 g m^{-2}, while the model predicted 2288 g m^{-2}; In Spain 761 g m^{-2} was measured and 773 g m^{-2} simulated (174 days after planting). Fruit dry weight was also well simulated in France (1514 g m^{-2} measured and 1513 g m^{-2} simulated), but not in Spain (446 g m^{-2} measured and 542g m^{-2} simulated. Obviously, dry matter partitioning into the fruits was in the Spanish experiment less than predicted by the model. Probably the model over-estimated fruit set under Mediterranean climate conditions.

It was assumed that in the experiments no nutrient limitations occurred, because there was always an abundant supply of water and nutrients and because total dry matter production agreed well with simulation results for situations without nutrient limitation.

The measured nitrogen concentration of all organs showed a clear ontogenetic decline (Fig. 1). A decline of plant N concentration has been described for many crops

(e.g. Marcelis et al., 2003). The simulated N concentration of fruits showed fluctuations due to the fact that the simulation was based on individual fruits, which showed a strong declining concentration from anthesis until harvest ripe. Each macro nutrient showed a different ontogenetic change. Plant nutrient concentrations changed during plant development because of changes of concentrations in some (e.g. K) or all organs (e.g. N, P) and/or because dry matter partitioning among organs with different nutrient concentrations, varied during the growing season (e.g. Mg). The model could easily be calibrated to show good agreement between measured and simulated nutrient concentrations of the plant and plant organs (Fig. 1). This calibrated model simulated nutrient concentrations well in an experiment one year later at the same research station, except for S (Fig. 3). S concentration in the 2003 experiment was rather variable, resulting in an inaccurate calibration. Hence, further calibration for S is needed. When this model calibrated for the French experiment was tested in the south of Spain distinct differences between simulated and experimental values occurred (Fig. 2). Differences between simulated and measured concentrations of the whole plant were partly due to errors in simulated dry matter partitioning. Calibrating the parameters for the concentrations in the different organs on the Spanish experiment, showed clearly the differences in concentrations between the Spanish and French experiment (Fig. 2). As there are numerous differences in growing conditions between the experiments, one could think of many reasons for the differences. The model has promising features, but further validation of the model is needed to conclude how well the model performs under different conditions and what are the limits for its applicability.

Global radiation is one of the main determining factors for water uptake by the plant. In young plants the water uptake per unit radiation was lower than in older plants (Fig. 4), due to the lower leaf area index and hence lower light interception by the crop. Beside the leaf area effect, the water uptake per unit radiation decreased with increasing radiation and tended to increase slightly again at the highest radiation levels (Fig. 4).

Note that in the greenhouse other climate variables also change when radiation varies. When all other climate variables were kept constant, similar type of curves were found. However, the scattering around the lines was less, and water uptake per unit radiation kept decreasing at the highest radiation levels. The uptake EC was dependent on development stage of the crop and climatic conditions, resulting in weekly as well as seasonal changes (Fig. 5). The average of the daily uptake EC was 1.2, which corresponds well with the value measured by Sonneveld (2000)

Growers usually keep the water supply per unit radiation and the EC of the irrigation water rather constant. The simulation results show that the uptake by the plants is definitely not constant. Adapting the water and nutrient supply to the demands of the plant may lead to further optimization of crop growth and quality as well as the sustainability of the production system.

Crop models showed to be a valuable tool for predicting plant growth and requirements for water and nutrients. When the model is coupled to a substrate model (see e.g. Marcelis et al., 2003) it can also deal with (temporary) limitations of availability of water and nutrients. These models can be used in a control system to optimise crop production and quality as well as to reduce pollution to the environment (see e.g. Marcelis et al., 2003).

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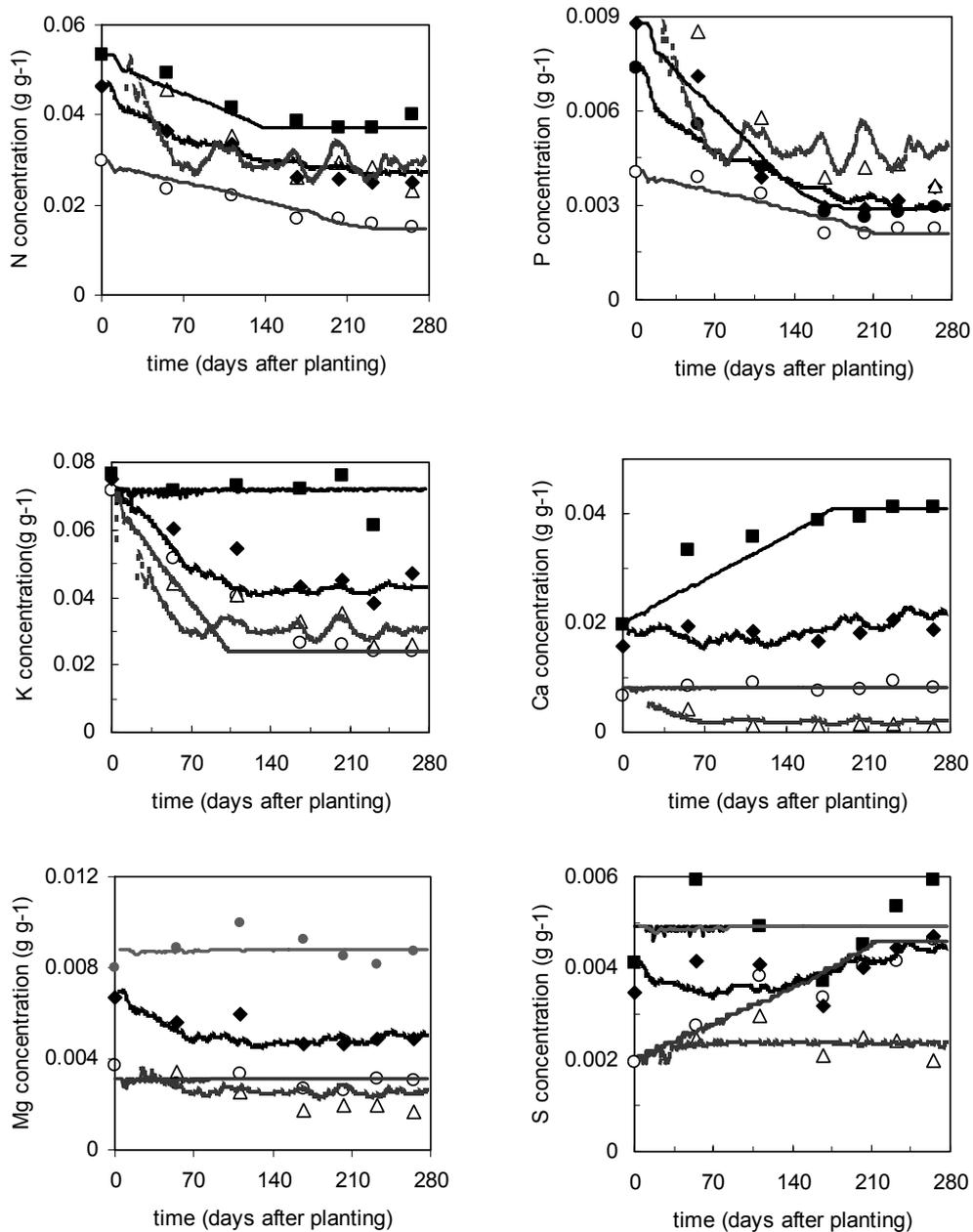
Fig. 1. Simulated (lines) and measured (symbols) time course of concentrations of the macro nutrients in leaves (square), stem (circle), fruits (triangle) and total plant (diamond) for a sweet pepper crop in France in 2003. Calibration experiment: The values of model parameters for nutrient concentrations of the different organs were calibrated on the measured data from this experiment.
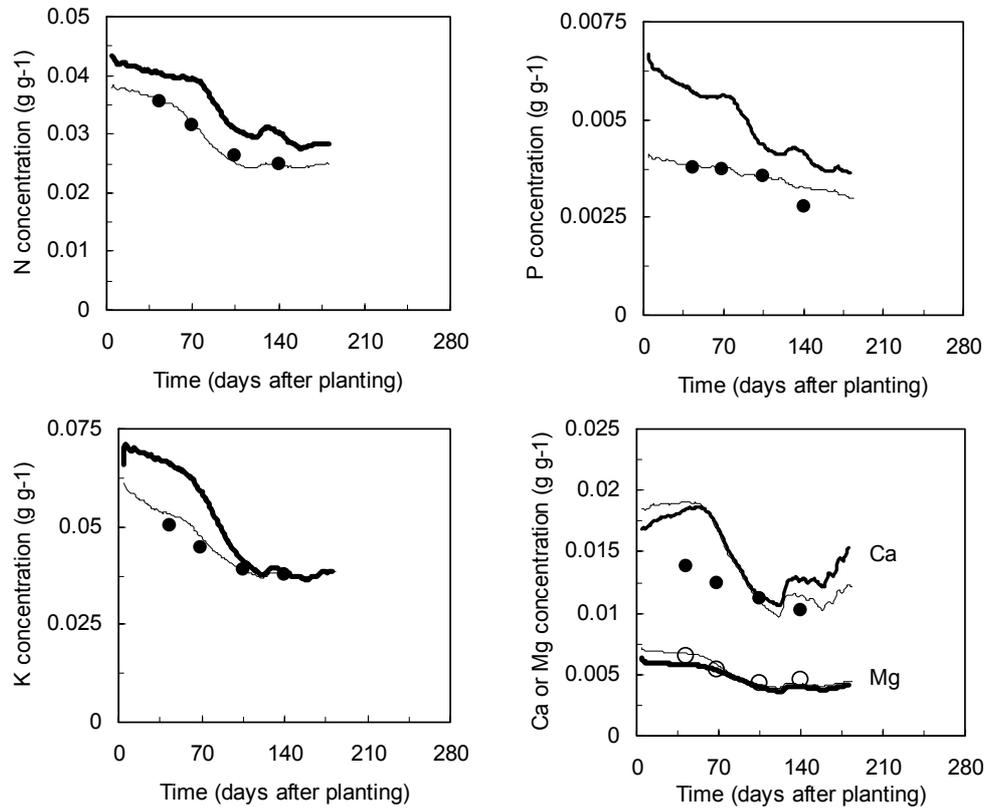
Fig. 2. Simulated (lines) and measured (symbols) time course of concentrations of the macro nutrients N, P, K, Ca and Mg in the total plant for a sweet pepper crop in Spain in 2003. The parameter values for nutrient concentrations in the model were the same as in Fig. 1 (bold line) or were calibrated on the measured data from this experiment (thin line).
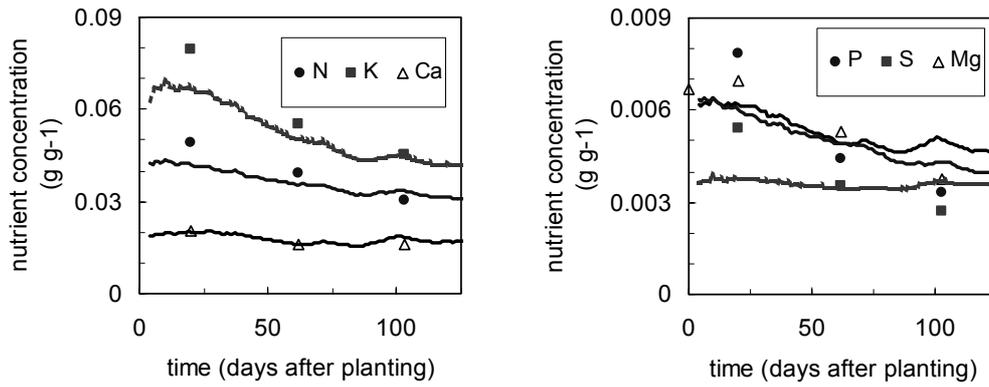
Fig. 3. Simulated (lines) and measured (symbols) time course of concentrations of the macro nutrients of the total plant for a sweet pepper crop in France in 2004. Validation experiment: parameter values for nutrient concentrations in the model were the same as in Fig. 1.
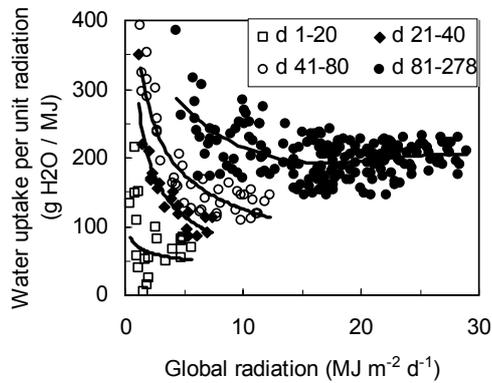

Fig. 4. Simulated effect of global radiation (outside greenhouse) on the daily water uptake per unit global radiation in a sweet pepper crop. Data are based on hourly climate values from the 2003 experiment in France (note that other climate variables were not constant). Four different periods are discriminated with different LAI values; LAI was 0.5 at day 20, 1.0 at day 40 and 1.8 at day 80.
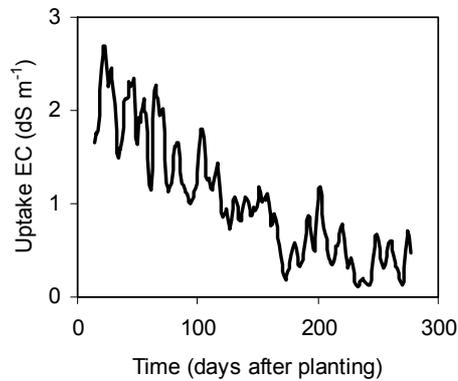
Fig. 5. Simulated time course of the daily EC of the water taken up by the roots of sweet pepper (ratio nutrient to water uptake). Data are based on hourly climate values from the 2003 experiment in France. EC was estimated as the concentration in meq/l divided by 20.