Feed-Forward Control of Water and Nutrient Supply in Greenhouse Horticulture: Development of a System

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Abstract

Minimisation of nutrient and water loss to the environment, prediction and planning of production and product quality, such that they meet the demands of customers, and increased financial return are some of the goals of current greenhouse horticulture. This requires an integrated system for monitoring and control of the nutrient solution, plant growth and product quality. This paper describes the components of such a system.

Tomato was selected as example crop. Plant sensors for photosynthesis, radiation interception and fresh growth rate were developed and tested, and the combined plant-substrate model was validated against greenhouse experiments and commercial growth data. Techniques for auto-calibration of the crop model with sensor information were developed. Scenarios describing various fertigation regimes were defined, and a technique for the generation of set points for water and nutrient application on the basis of pre-defined optimisation goals was developed. These goals included drainage volume and nutrient concentration, nutrient application rate, fruit dry matter concentration, and fruit growth rate.

The overall system was evaluated in a greenhouse experiment. In comparison with simulated 'normal' cultivation, optimisation of water and nutrient application indeed resulted in reduced application and drainage rates, increased fruit growth rate, and a dry matter concentration that met the optimisation goal.

In conclusion, the monitoring and control system offers good prospects for efficient control of water and nutrient use, and control of crop growth in future control of greenhouse cropping systems.

INTRODUCTION

Common horticultural practice is to couple application of nutrients and water. Nutrient composition of the drain and substrate solution is usually analysed in an external laboratory every fortnight, on the basis of which the nutrient concentrations in the nutrient solutions are determined. During the next two weeks, recirculated drain and nutrient solutions are mixed until a certain electrical conductivity (EC) is reached. If the Na concentration in the drain reaches unacceptably high levels, drain is sluiced to the surrounding surface water. Increased crop transpiration leads to increased water and nutrient application. Applied nutrient quantities therefore usually exceed the needs of the crop. Moreover, possibilities to control crop growth and product quality by a regulated water and nutrient supply are not used by the growers. This approach leads to excess use of water and nutrients and their emission to the surrounding environment. The obvious solution is to supply water and nutrients based on the needs of the crop at each particular moment, which varies according to environmental conditions and crop development.

Those issues were addressed in the 'Hydrion-Line' project. The basic principle

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was to supply both water and nutrients on the basis of the daily need of the crop, which was determined through intimate physiological knowledge incorporated in a crop growth model. Analysis of solutions in the laboratory at a restricted number of days with associated time-delays is not necessary in this set-up, if ion-selective sensors are used. In contrast, a fertigation advice is given daily and implemented automatically.

This paper describes elements of an integrated system for on-line monitoring and control of the nutrient solution and of plant growth that enables such. The system is based on recirculation of drain water, and was tested for tomato.

MATERIALS AND METHODS

Overview

The system for on-line monitoring and control of the nutrient solution and plant growth consisted of a number of integrated software and hardware elements. Utilising real-time sensors, information regarding crop characteristics, crop production, and water and nutrient demand were forecasted. The optimal set points for the fertigation regime were selected, and were implemented by a real-time system. More specifically, the system consisted of the following elements:

- a system for on-line measurement of leaf photosynthesis, radiation interception and growth rate with sensors;
- a substrate model that predicts the effects of fertigation strategies on water and nutrient availability for the crop;
- a crop model with self-learning capacities that utilises sensor information, and that predicts water and nutrient demand, production and product quality;
- a set point generator that, on the basis of information provided by the combined plant-substrate model, and on the basis of pre-defined optimisation goals, selects for the near future the optimal fertigation strategy;
- a real-time system for the control of water and nutrient application, on the basis of the selected fertigation strategy and the actual climate.

During six years of research, the various elements were developed, tested and integrated in to a system that was tested in autumn 2002 in a ‘proof of principle’ experiment.

Crop Sensors

Estimation of nutrient demand was achieved through a crop growth model. However, even a well-calibrated and well-validated model may not always accurately describe the status of the crop. This involves unacceptable risks to the grower if the model is applied in a commercial setting. Therefore, critical plant characteristics were measured and fed to the crop model.

1. Leaf Photosynthesis. Photosynthesis supplies assimilates for crop growth, and therefore, its quantification supplies a good starting point for modelling nutrient demand. Research was conducted in 2001 to establish the variation in photosynthesis characteristics over time and canopy depth. It was concluded that variation was sufficiently wide to incorporate measurement of leaf photosynthesis characteristics in the monitoring system. It appeared sufficient to measure at the top of the canopy, as photosynthesis characteristics here are correlated to those deeper in the canopy.

2. Radiation Interception. The amount of leaf area is a determining factor in the amounts of intercepted radiation and transpiration by the canopy. The combination of intercepted radiation and photosynthesis rate enables good estimation of assimilate production. A sensor that measures crop reflection proved accurate in estimation of intercepted radiation by the crop. Leaf area was computed using a light extinction coefficient of the crop of 0.78 for diffuse radiation.

3. Fresh Growth Rate. Simulated fresh growth rate follows from a large number of computations on physiological processes, and crop and environmental conditions. Its accurate estimation is crucial for estimation of nutrient demand. Every day, during the night (when the plant's water status was considered to be optimal), crop fresh weight was measured with load cells. Fresh weight of harvested fruits was determined immediately after harvest. Daily fresh growth rate was computed from the daily difference in crop fresh weight, and fresh weight of harvested fruits.

Substrate Model

A two-dimensional simulation model for describing water movement, solute transport and water and nutrient uptake by the roots (Heinen, 2001) was made suitable for a rockwool growing system. The model, coupled to the crop growth model described below, proved to satisfactory simulate observed effects of the EC of the nutrient solution on nutrient uptake (Heinen et al., 2003).

Crop Model

1. Model Development. The INTKAM crop growth model for tomato (Marcelis et al., 2000) simulates crop growth, plant-water relations and plant-nutrient relations. Leaf photosynthesis is computed with a biochemical model (Farquhar et al., 1980). Leaf transpiration rate is calculated with the Penman-Montheith equation, and makes use of the stomatal conductance model described by Nederhoff and de Graaf (1993). Water requirements for fresh mass growth are based on fixed values for dry matter content of roots, shoot and leaves, and a fruit dry matter content as a function of EC and day number (de Koning, 1994). Demanded nutrient uptake rates are derived from the demanded nutrient concentrations for each organ, which are a function of their temperature sums. The effects of N, P and K on photosynthesis, leaf area development and dry matter partitioning are incorporated, on the basis of experiments and literature data (de Groot et al., 2001, 2002; Del Amor and Marcelis, 2004; Fig. 1). For further details, see Marcelis et al. (2000).

2. Model Calibration and Validation. The model was calibrated for a spring and an autumn experiment in 2001, with regards to photosynthesis characteristics and demanded nutrient concentrations, and was validated against detailed data from three commercially grown crops in 1999 and 2000 in The Netherlands.

3. Self-Learning. The self-learning capacity of the model was implemented in the form of weekly auto-calibration of a number of model parameters on the basis of sensor information regarding photosynthesis, intercepted radiation and crop growth. First, parameter estimates of the Farquhar photosynthesis model were calibrated by using a genetic algorithm, in which the radiation response curves of the Farquhar model and of the measured CO_2 fixation were compared. Estimated parameters of the Farquhar-based response curve were the maximum electron transport rate at high radiation (J_{max}, µmol electrons m^{-2} s^{-1}), initial light use efficiency (α, mol [CO_2] mol^{-1} [absorbed photons]) and the curvature of the PAR response curve of electron transport (θ, -). The maximum carboxylation rate (VC_{max}, µmol [CO_2] m^{-2} s^{-1}) was assumed half the value of J_{max} (*cf.* Kosugi et al., 2003; Gunderson and Wullschleger, 1994).

Subsequently, intercepted radiation and fresh growth rate were calibrated using a random search procedure. Intercepted radiation was calibrated by varying temperature-dependent values of minimum and maximum specific leaf area (SLA; Heuvelink, 1989), and consequently leaf area. Growth rate of total fresh weight was calibrated with a correction factor on gross assimilation rate.

Set Point Generation

Set points for water and nutrient application were generated at the start of each day. The set point generator determines over a period of three days the optimal settings for the water and nutrient control unit, such that the target function was optimised. The combined plant-substrate model was executed using actual climate data up to the present moment, while for the future three days representative climate data were used.

Constraints to be met were:

- Drainage volume is more than 312.5 ml m^{-2} [greenhouse surface] d^{-1}, to enable measuring the drain;

- Daily drainage volume is at least 10% of daily irrigation volume, to ensure sufficient flow and homogeneity of the substrate;
- Fruit dry matter concentration (DMC) is at least 0.05 g g^{-1}, ensuring high-quality fruits.
- The supplied amounts of N, P, K, Ca, Mg and S are on a daily basis more than 90%, but less than 200% of crop demand. The first criterion prevents nutrient shortage and growth reduction, while the second criterion prevents excess application.

Given these constraints, financial costs for daily drainage volume were minimised, while financial profits for daily fresh growth was maximised.

Feed-forward regulation of water and nutrient supply was started at September 12 (day 255). Set point generation initially took place on the basis of 56 fertigation scenarios, *viz*., 3 or 4 ml water m^{-2} [greenhouse] per J [global radiation] cm^{-2} [greenhouse], supplied after 100 or 200 J [global radiation] cm^{-2} [greenhouse] (to be noted as 100/3, 100/4, 200/3 and 200/4), combined with 14 different sets of nutrient concentrations. Soon it appeared that both actual and simulated slab were drying, and therefore, at day 259, a time start irrigation at 7:30 h of 3 or 4 ml water m^{-2} was added to the irrigation regime. The values of 3 or 4 ml m^{-2} per J cm^{-2} correspond with crop transpiration at high levels of radiation. If radiation is lower, crop transpiration rates per J radiation are higher. Towards the end of the year, radiation reduced, and a minimum drain could not be maintained. The scenarios were therefore on day 310 changed to 100/3, 100/4.5, 100/6 and 100/7, in combination with time start amounts of 3, 4.5, 6, and 7 ml water m^{-2}, respectively.

Real Time System

A real time dispenser system converted the amounts of water and nutrients to be supplied in to amounts of specific ions and water to be mixed. It then fed the water-nutrient solution to the crop at the required rate.

Experiment

Tomato plants of cv. Aromata were planted in a greenhouse of 180 m^2 at August 13, 2002 (day number 225) at a density of 2.5 plants m^{-2}. First fruit harvest took place on October 9th (day 282), and the experiment was ended at November 12 (day 317). Supply of water and macronutrients was determined by the feed-forward set point generation; other set points, such as those for ventilation and temperature, were regulated in a normal manner. Mature fruits were harvested once a week. Four periodic, destructive harvests of total plants were conducted during the experiment.

RESULTS AND DISCUSSION

Auto-Calibration

The auto-calibration procedure was successful in describing the Farquhar photosynthesis light-response curve: most fits were characterised by $r^2 > 0.95$. Auto-calibration of photosynthetic characteristics resulted in maximum electron transport rates gradually decreased from 295 to 110 μmol electrons m^{-2} s^{-1} during the course of the experiment. The initial light use efficiency fluctuated around 0.3 mol [CO_2] mol^{-1} [absorbed photons], and the curvature of the PAR response curve of electron transport increased from approximately 0.5 to approximately 0.7.

The amount of intercepted radiation could be adequately calibrated (Fig. 2). At high levels of intercepted radiation, the related leaf area index (LAI) appeared very sensitive to variation in intercepted radiation. At times, it was necessary to accept a slightly lower light interception in order to prevent over-estimation of the LAI. This suggests the possibility that the light extinction coefficient used by the model (0.78) was different from the actual one. This will require some further investigation.

Calibration of the growth rate of fresh weight proved necessary to account for uncertainties in simulation of maintenance respiration, dry matter partitioning, dry matter content, and a series of other physiological processes. Admittedly, other process variables could have been selected as well as calibration variable. Gross assimilation rate had been selected for its central position role in determining fresh growth rate. The calibrated value of gross assimilation rate consequently reflects deviations between simulated and actual rates of other processes.

Set Point Generation and Optimisation

The effects of the model-based feed-forward control were established by comparing simulation results for the optimised set points with those of a standard situation.

- The production criterion was met: set point generation resulted in an increased cumulative fresh fruit weight from 5071 to 5568 g m^{-2} (10 % increase) (Fig. 3).
- The increased cumulative fresh fruit weight was predominantly the consequence of reduced fruit dry matter content, as the increase in cumulative dry fruit weight was much lower, *viz*. from 317 to 326 g m^{-2} (3 % increase). Optimisation before September 22 (day number 265), reduced fruit DMC to 0.05 g g^{-1}. Later on, fruit DMC increased and decreased again.
- The temporary increase of fruit DMC was a consequence of the fact that the optimised set point for irrigation volume was too low to sustain simulated demanded water uptake by the crop and a sufficient simulated drain volume. Underestimation of the substrate's water content leads to overestimation of the EC and therefore increased fruit DMC. Observed drain amount were greater than simulated ones. Possible reasons for this are: over-estimation of transpiration, the two-dimensional instead of three-dimensional substrate simulation, time-dependent physical properties of the substrate that are not described by the model, and evaporation by the substrate. In order to avoid insufficient simulated irrigation, incorporation of greater irrigation volumes in future scenarios is recommended. This will enable the optimisation programme to better optimise the drain and fruit DMC criteria.
- The dynamics of the nutrient balance are illustrated in Fig. 4, which gives the example of NO_3. Although nutrient uptake was increased from 1.67 to 1.99 g m^{-2} when set points were optimised, nutrient application was reduced. This reduction was stronger than desired, however, as optimised nutrient drain was zero towards the end of the season (see above).

PROSPECTS

A model-based feed-forward control system for optimal fertigation in greenhouses is possible. Sensors supply the model with information regarding fluctuations in values of essential crop parameters, and a set point generator determines the optimal settings for the water and nutrient control unit, given a certain target function. The linkage of soft- and hardware has enabled communication of various systems.

Having concluded this, system improvements have to be realized in the following fields:

- The robustness of the system can be improved by the introduction of a feed-back system regarding the actual water and nutrient concentrations in the slab and drain (Gieling et al., 2003).
- The value of the light extinction coefficient has to be further investigated, reducing the need to use SLA in calibration of intercepted radiation.
- The fertigation scenarios have to be revised, especially with regards to the daily amounts of water supplied. Simulated slab drying and underestimation of drain has to be prevented.
- Some systems were not yet fully automated, such as the auto-calibration procedure. Once this has been achieved, the entire system can operate in a real-time mode.
- The representative climate data used for the optimisation procedure sometimes were fairly different from realized climate conditions. It should be considered to use climate forecasts, in order to reduce errors in selection of the optimal fertigation regime.

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Figures

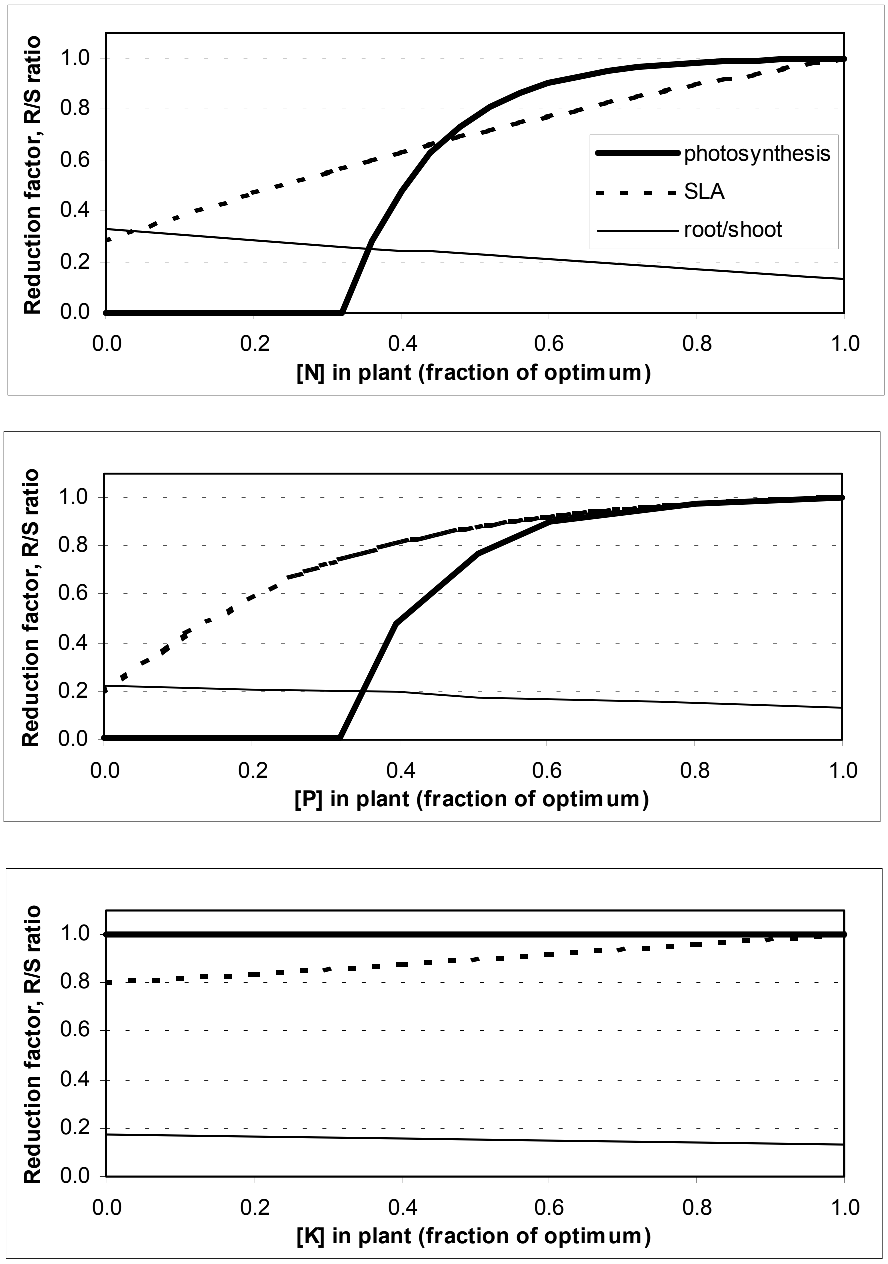

Fig. 1. The effects of the actual N, P and K concentrations in the plant relative to their optimal concentrations, on photosynthetic rate, specific leaf area, and dry matter partitioning between root and shoot.

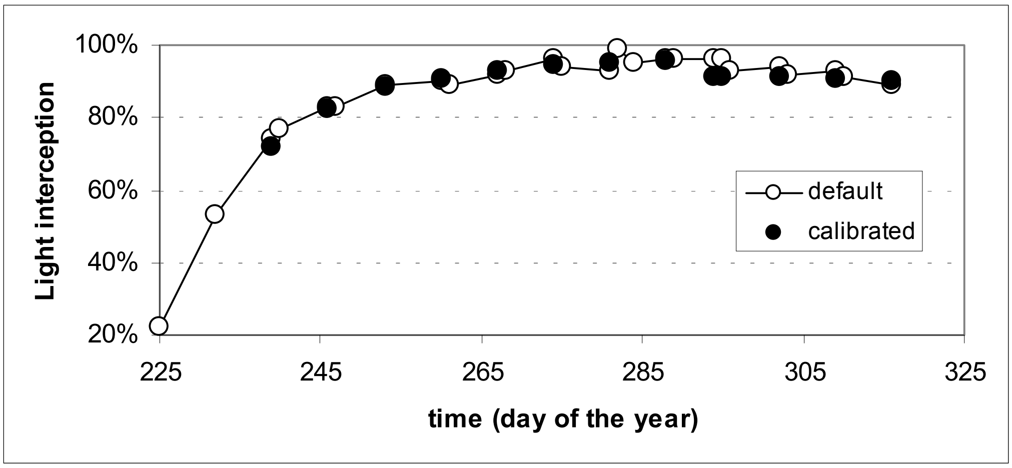

Fig. 2. Light interception by the crop computed by the default crop model, and the calibrated crop model.

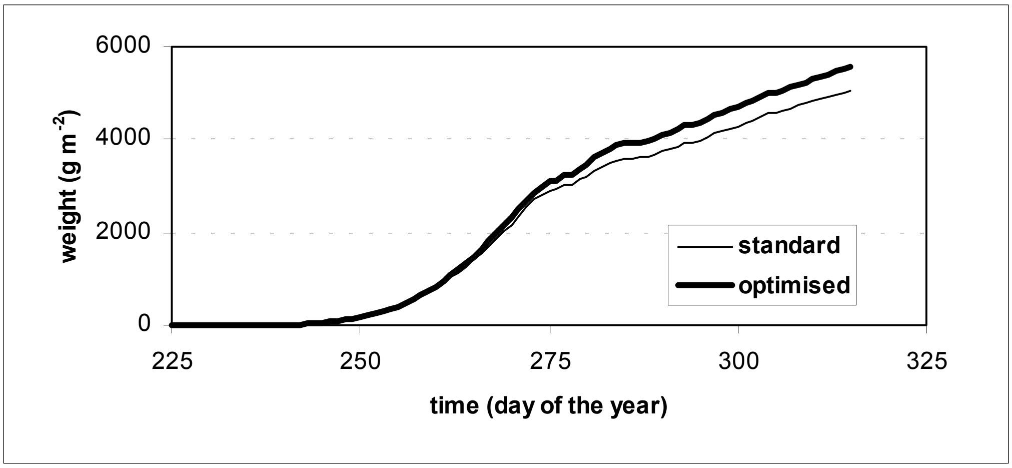

Fig. 3. Cumulative fresh fruit weight for a standard fertigation strategy, and for the optimised fertigation strategy, both simulated by the calibrated model.

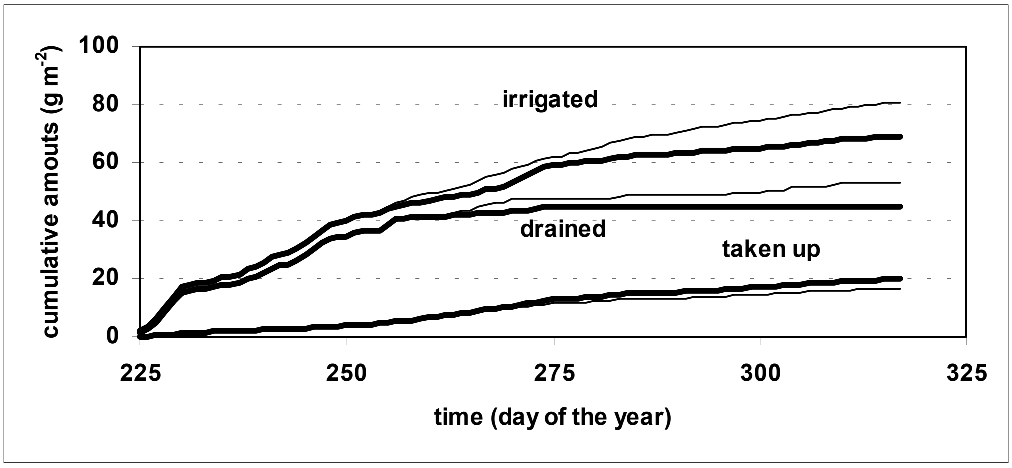

Fig. 4. Simulated cumulative amounts of irrigated NO_3, drained NO_3 and NO_3 taken up by the crop, for a standard fertigation regime (thin lines), and for the optimised fertigation regime (solid lines).