CLOSYS: Closed System for Water and Nutrient Management in Horticulture

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Keywords: pepper, rose, substrate, model, sensor, controller

Abstract

The EU project CLOSYS aimed at developing a CLOsed SYStem for water and nutrients in horticulture. The main objective was to control water and nutrients accurately such that pollution is minimized and crop quality enhanced. The closed system as developed in this project consists of crop growth models and substrate models, a new substrate, an expert system, a real time controller, fluorescence sensors, ion-selective sensors and a technical infrastructure.

Plant model: Mechanistic models for rose and sweet pepper were build and self-learning capacity was introduced. The models simulate crop growth, and demand and uptake of water and individual nutrients.

Plant sensor: A fluorescence imaging system was developed and tested to be used as an indicator for plant performance and stress factors.

Nutrient sensor: An on-line multi-ion sensor measures the concentration of individual nutrients pH and EC of the recirculating water in the greenhouse.

Substrate model: A 3D substrate model simulates the water and nutrient flows in the substrate depending on the root absorption and fertigation.

Substrate: A rockwool substrate with improved physical and chemical properties was developed to allow a better control of water and nutrient fluxes in the root-zone.

Expert system: The expert system, using model and sensor information and weather forecasts, determines a daily plan for fertigation. This plan contains the set-points for the real time controller.

Real time controller: The real time controller controls the water and nutrient supply. It upgrades the fertigation parameters (irrigation EC, dose and frequency) to satisfy the set-points issued by the expert system, depending on current status of the system and on time constants and dynamic characteristics of the system.

Technical infrastructure: All subsystems were integrated such that they can request data from the irrigation computer database. With these data, new set points for fertigation are calculated, whereafter the irrigation computer executes the requested tasks.

Closed system: All components together form the closed system for water and nutrients. The performance of the closed system was compared to a standard sweet pepper growing system. The system has been running satisfactorily during a prolonged period (1 and a half year). Water and nutrient use, its availability in the rooting zone as well as the recirculating drainage water were controlled accurately.

Proc. IIIrd IS on HORTIMODEL2006
Eds. L.F.M. Marcelis et al.
Acta Hort. 718, ISHS 2006

INTRODUCTION

In greenhouse horticulture nutrients are usually supplied together with water. To prevent any shortage growers use excess amounts of nutrients and water. Even in the case 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. As in present production systems nutrients and water are always supplied in excess amounts, possibilities to control and to plan crop growth and product quality by a regulated water and nutrient supply are hardly used by growers. In greenhouses, compared to open field production, above and below-ground conditions can be controlled to a large extent. This opens possibilities for a precise control of water and nutrient flows and crop production and quality. To realize this, management systems for water and nutrient supply should include:

- Controlling the nutrient supply independent from the water supply
- Controlling the supply of individual nutrients rather than total salt concentration
- Supply of water and individual nutrients in proportion to the demand of the plants, using a feed-forward control system
- The availability of an early, non-invasive, on-line warning system for deviations from optimal plant growth and quality

The results described in this paper are based upon the EU project CLOSYS. This project aimed at sustainability of crop production by developing a CLOsed SYStem for water and nutrients in horticulture. In this system water and nutrients are continuously re-used. The main objective was to realize an accurate control of water and nutrients in order to be able to minimize pollution and to enhance crop quality.

The closed system as developed in this project consists of crop growth models and substrate models, a new rockwool substrate, an expert system, a real time controller, fluorescence sensors, ion-selective sensors and a technical infrastructure.

RESULTS AND DISCUSSION

Plant Sensor

A multispectral fluorescence imaging system was developed, which allows whole leaf imaging of the major fluorescence bands of green leaves: blue, green, red and far-red (Buschmann and Lichtenthaler, 1998). The system was composed of a pulsed UV light source (Xenon-arc lamp with a UV-filter or, as an alternative, an UV-LED array with extremely high output was successfully used) inducing the fluorescence signal and a synchronized image intensified CCD-camera. Image acquisition and data analysis was carried out by a computer. In a number of experiments with different stress treatments applied to rose and sweet pepper plants the relation between plant status and the signals of the fluorescence imaging sensor was established. It was demonstrated that fluorescence ratios were most suitable to distinguish between different stress treatments (Langsdorf et al., 2000). The fluorescence ratios blue/red and blue/far red were increased by nitrogen deficiency but not by iron deficiency (Fig. 1), and decreased by heat stress. All four fluorescence bands decreased when oxygen limitation of the root zone occurred. Furthermore, light reflectance of the canopy seemed to be a good indicator for the leaf area index and the light interception of the canopy (see also Marcelis et al., 2000). When the stress was detected by the imaging system, photosynthesis measurements showed that also the rate of photosynthesis was reduced and usually stress symptoms could be seen by visual inspection. When plants were grown in a normal way in greenhouses no disturbances of the fluorescence signals were observed. It is concluded that fluorescence imaging can detect severe plant stresses, but before mild plant stress of greenhouse grown crops can be detected further developments are needed.

Plant Model

A model was developed that simulates crop growth and demand and uptake of water and individual nutrients of rose and sweet pepper (for more detailed description of the model see Marcelis et al., 2005 and Marcelis et al., 2006). The simulation of dry matter production is based on calculations of light interception, photosynthesis, respiration and dry matter partitioning. For each plant organ its required concentrations of the various macro nutrients are calculated. The required nutrient uptake is calculated from these required concentrations and the dry weight increase of the organs. Calculations of leaf transpiration and fresh weight growth were used to calculate the required water uptake. Actual uptake of water and nutrients was calculated by multiplying the required uptake by a reduction function. This reduction function depended on humidity (water content) and EC of the substrate. Self learning capacity (as described by Elings et al., 2004) was introduced into the model by automatic calibration of leaf growth parameters using sensor information of light interception as estimated by light reflectance (Marcelis et al., 2000).

The models were validated at four experimental sites in Europe (roses in Greece and The Netherlands and sweet pepper in Spain and France). The models showed good agreement with measurements of growth, water uptake and nutrient uptake (Fig. 2) (see also Marcelis et al., 2005; Marcelis et al., 2006; Brajeul et al., 2006). Furthermore it was concluded that for practical application self-learning capacity making use of historical and recent observations is important.

Nutrient Sensor

For an optimal control of a closed system it is important that beside EC and pH most individual major nutrients can be monitored by on-line sensors (e.g. Gieling et al., 2005b; Van Straten et al., 2005). A multi-ion sensor probe was developed and tested. NO_3^- (Fig. 3), K^+, Cl^-, and Na^+ could be measured accurately. Stability of the sensors was sufficient for measurements during >6 months for NO_3^- and Cl^-, while >2 months for K^+ and Na^+. Unfortunately the measurement of Ca^{2+} proved to be not stable enough. All ion sensors were Ion-Selective Electrodes (ISE's). An important aspect is the automatic calibration of the ion selective electrodes. Due to the newly developed stable reference electrode only one 1-point calibration a day and one 3-point calibration a week was sufficient for reliable measurements of all ion-selective electrodes. This reference electrode has a salt bridge with a small but constant and reliable outflow of electrolyte of less than one micro liter per hour. Due to this ultra low flow rate this reference electrode needs a refill of electrolyte only once in three months.

Substrate and Substrate Model

After a detailed characterization of the substrate physical properties, a numerical model based on Computer Fluid Dynamics (CFD) was developed that simulates the water and nutrient flows in the substrate depending on the root absorption and supply of water and nutrients (Bougoul and Boulard, 2005). After validation of the CFD model with respect to measurements of substrate hydraulic dynamics, it was used to perform an analysis of the properties for the ideal substrate to be used. Based on model calculations a composite rockwool slab was designed and manufactured with top and bottom parts having different physical and chemical properties. The top part of the rockwool was composed of high density horizontal fibers and the lower part of low density vertical fibers. This substrate can keep higher water content in its upper part due to the lower hydraulic conductivity and promote horizontal growth of roots whereas a high hydraulic conductivity in the lower part allows for a faster drainage and thus avoids the occurrence of anoxia (Fig. 4).

Mainly due to its long computation time, the CFD model is not suitable for control purposes. Therefore a simplified substrate model was also developed which was incorporated in the plant model.

Expert System and Real-Time Controller

The expert system, using model and sensor information and weather forecasts, determines a daily plan for fertigation. This plan contains the set-points of substrate humidity (water content of substrate), EC and composition of the nutrient solution for the real time controller.

The plant model including the simplified substrate model is used by an expert system to calculate the crop harvest, crop transpiration and nutrient uptake for the coming days based on weather forecast for 5 days. Using a forward dynamic programming algorithm the optimum set-points for substrate humidity, EC and composition of the nutrient solution for the coming days are calculated. These set-points are provided to a real time controller in order to be achieved. The real time controller controls the water and nutrient supply (Lecomte et al., 2005). It upgrades the fertigation parameters (irrigation EC, dose and frequency) to satisfy the set-points issued by the expert system, depending on its current composition and on time constants and dynamic characteristics of the system. The real time controller consists of a simulation model and command rules. The model is a classical representation in transfer function by means of the z transform for sampled signals. Outputs of the model are substrate humidity, substrate EC and drainage ratio (ratio drain:irrigation). Inputs are the volume of irrigated water and EC of the irrigation water, while solar radiation is a disturbance of the model. For the command rules predictive commands are used. The fertigation plan that minimizes a given criterion is selected. The criterion relates to the output errors (differences between set-points and realization), the cost of the generated commands and the relative variations of the commands (to minimize sudden variations of the actuators). In experiments it was shown that the real-time controller was well capable of realizing set-points for substrate humidity, substrate EC and drainage ratio (Fig. 5).

The Integrated Closed System

All subsystems (models, sensors, expert system, real time controller) were integrated such that they can transfer data to and from the irrigation computer database. With these data, new set points for fertigation are calculated, whereafter the irrigation computer executes the requested tasks.

This system as well as the new rockwool substrate were tested during two growing seasons at a research station in France (the first year from June until October and the second year from December until October). The performance of this CLOSYS system was compared to a standard sweet pepper growing system (see Brajeul et al., 2006). The system has been running satisfactorily during these two growing seasons. No significant difference in quality or yield were noticed between the CLOSYS and the standard treatment, in spite of differences in water consumption, substrate humidity, K/Ca+Mg ratio and Na and Cl concentration in the drainage between both treatments. Water and nutrient use, its availability in the rooting zone as well as drainage were controlled accurately (Brajeul et al., 2006).

The CLOSYS system consisted of different modules. The multi-ion sensor showed a good measurement reliability and repeatability. The sensor system can be considered an interesting tool for growers, but needs to be improved with regard to maintenance needs. LAI measurements by reflectance were found to be useful for calibrating the plant model as well as the calibration on historic data of plant nutrient concentrations. The composite substrate improved the vertical humidity gradient in the substrate. The real time controller showed a good reliability and could be considered as an alternative to the classical PID regulation systems (Proportional Derivative Integration system).

Model based systems are valuable tools to control water and nutrient management in greenhouses (e.g. Bar-Yosef et al., 2004; Elings et al., 2004; Gieling et al., 2005a; Van Straten et al., 2004, 2006). The CLOSYS system has been working with all of its modules from June 2004 until October 2005. At the end of both growing seasons, the quality and yield of harvested fruits were similar between both treatments (CLOSYS and standard system). From an ecological point of view, the automated system offers some positive impacts. The slab electric conductivity (EC) was correctly managed. In comparison with the standard treatment, the supplied and drained quantities were lower for most of the nutrients. The sodium and chloride accumulation in the drainage was also lower. In conclusion the CLOSYS system has shown its potential as an automated fertigation management prototype pursuing goals of the grower with respect to production, quality and environment.

ACKNOWLEDGEMENTS

This study was carried out with financial support from the European Commission under the RTD programme "Quality of life and management of living resources" (project QLRT-1999-31301). It does not necessarily reflect the Commission's views and in no way anticipates its future policy in this area. We thank Anne Elings, Pieter de Visser and Alain Lecomte for their contribution to this paper and Ep Heuvelink for critically reading the manuscript.

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Figures

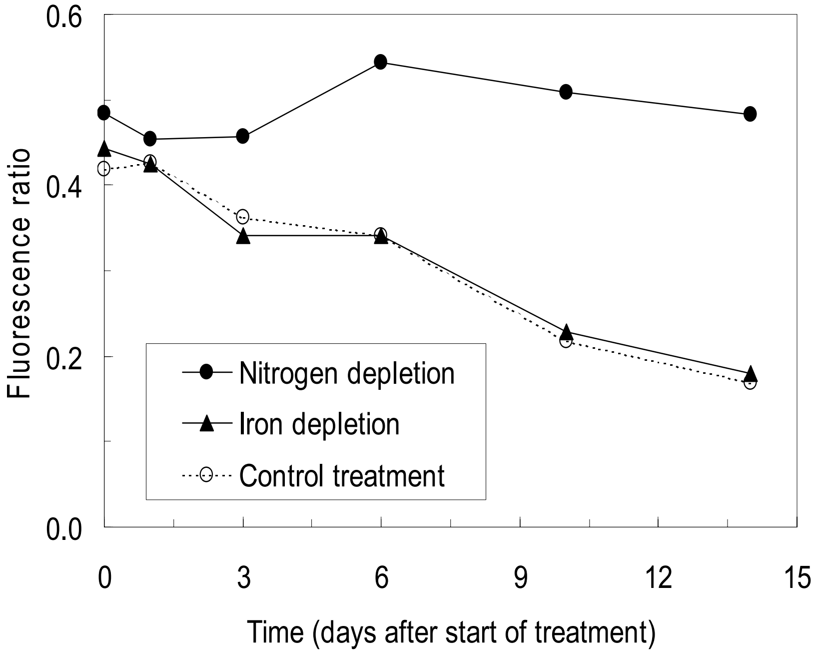

Fig. 1. Fluorescence ratio blue/far red (440 nm/735 nm) of sweet pepper plants grown on a full nutrient solution (control treatment) or when nitrogen or iron was withheld from the nutrient solution. Plants grown in a climate chamber were 40 days old at the start of the treatments.

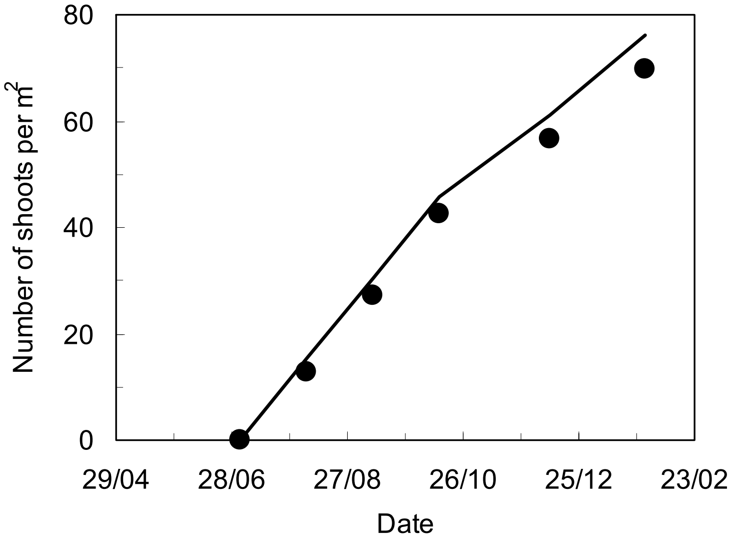

Fig. 2. Simulated (line) and observed (symbols) cumulative number of shoots formed for cut roses grown in a greenhouse. Input to the model were hourly climate data inside the greenhouse and outside radiation.

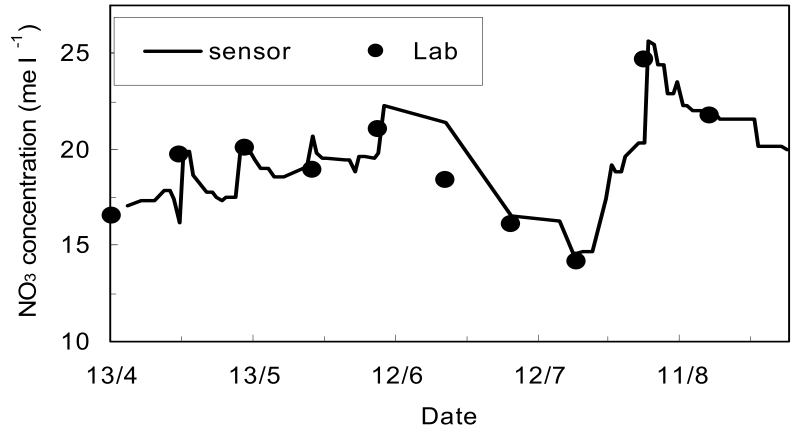

Fig. 3. Comparison between measurements of nitrate by the ion selective electrode and by laboratory measurements (IDAC). Nitrate was measured in the drainage water from April until the end of August.

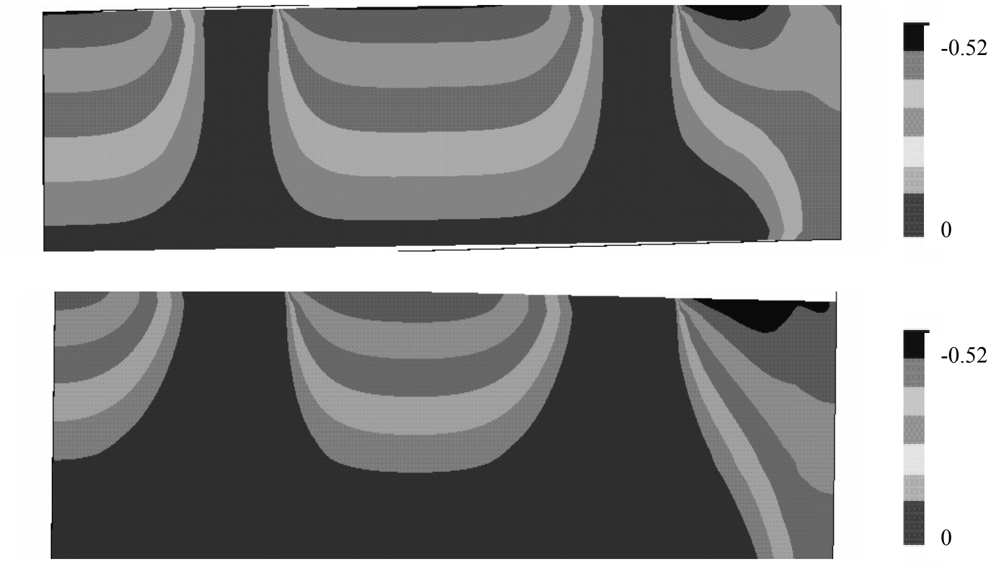

Fig. 4. Distribution of the water suction in the rockwool slab at the end of the first irrigation cycle in the morning for the Expert slab with homogeneous vertical rockwool fibres (top figure) and the composite slab with horizontal high density fibres at top and vertical low density fibers at bottom (lower figure). The distribution of water suction was calculated by a CFD model (range from 0 to 0.52 m water column).

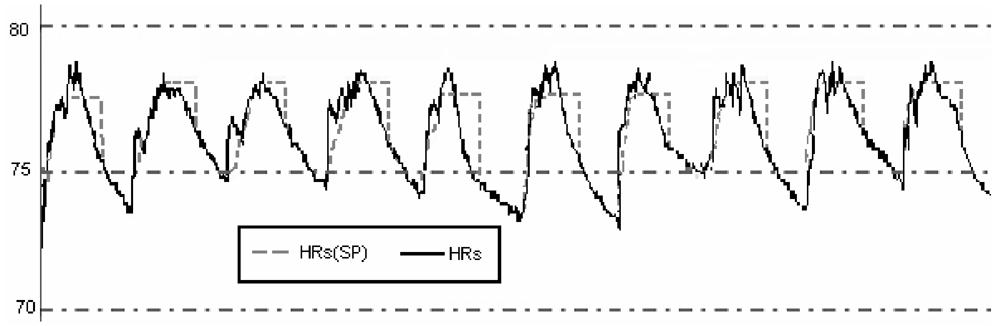

Fig. 5. Performance of the real time controller: set-points (SP) and realized values for the relative humidity of the rockwool slab (HRs; % water content) during 10 days.