Development and Evaluation of an Automated Prototype for the Fertigation Management in a Closed System

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Abstract

In France, in order to prevent imbalances and accumulation of nutrients in the plant root zone, most of the soilless crops in glasshouses are cultivated in open drainage systems, which leads to water and fertilizer losses. The goal of the EU project CLOSYS (CLOsed SYStem for water and nutrient management) was to build a prototype which delivers water and nutrients according to the plant needs in a recirculating system. This prototype aimed at controlling production and quality as well as reducing nutrient accumulation or shortage in the root zone in a closed system and avoiding pollution of the environment. This paper deals with the development and the evaluation of the prototype in comparison with a classical closed system for a sweet pepper crop. This prototype includes: substrate and plant models incorporated in an expert system, using substrate and plant sensors, and a real time controller. Technical details and results of each module will be presented. The plant model provided proper simulations of growth and development parameters, nutrient concentrations in the plant organs, plant nutrient and water consumption. The expert system enabled the coupling between plant and substrate models, thus ensuring the system to take into account the weather forecasts. The real time controller managed to control relative water content and electric conductivity in the substrate slabs. A Leaf Area Index sensor was used to calibrate the plant model according to the real crop area development. As a conclusion, the CLOSYS system led to a lower nutrient consumption, lower sodium and chloride accumulation and a proper electric conductivity control in comparison with the classical closed system, while maintaining production and quality.

INTRODUCTION

Soilless crops in glasshouses cultivated in open drainage systems lead to water and nutrient losses representing 30 to 40% of the nutrient solution delivered to the plants (Brajeul et al., 2005). In substrate crops, the recirculation of drainwater can reduce the consumption of water by about 30% and of fertilizers by more than 50% (Vernooij, 1992). However, even in recirculating systems, growers have to drain nutrients and water out to the environment from time to time to prevent imbalances and accumulation of the nutrients in the root zone (Dieleman and Marcelis, 2005).

The EU project CLOSYS (CLOsed SYStem for water and nutrient management) aimed at sustainability of crop production by developing an automated fertigation management prototype for soilless crops with recirculation of drainwater, which delivers water and nutrients according to the plant needs. This prototype includes: substrate and plant models incorporated in an expert system, using substrate and plant sensors, and a real time controller.

In 2003, an evaluation of the plant model was carried out at the Ctifl Carquefou centre in France. In 2004, the components of the prototype were assembled and the various system modules were tested. This paper presents the development and the evaluation of the prototype, comprising all the different modules, in comparison with a classical closed system for a sweet pepper (*Capsicum annuum*) crop in 2005 at the Ctifl Carquefou centre, with a goal to control production and quality as well as to reduce nutrient accumulation or shortage in the root zone in a closed system and to avoid pollution of the environment.

MATERIALS AND METHODS

General Conditions

The experiment took place in two 4.20 meters high heated experimental Venlo type glasshouse compartments (250 m^2) with the same climate conditions.

The cultivar 'TRIPLE 4' (Enza Zaden, the Netherlands; harvested as green fruits) was sown on October 29th 2004, planted on December 16th 2004 on Grodan Master Grotop rockwool slabs, and harvested once a week from March 2nd to October 12th 2005.

The sweet pepper plants were grown in an integrated pest management system, with two stems per plant and a stem density of 6.25 stems.m^{-2}. The nutrient solution made of Substrafeed fertilizers (Yara France) was recycled without disinfection.

Two experimental treatments in 4 blocks (4 replicates per treatment and 12 plants per replicate) were compared from the planting date:
- Classical closed fertigation system (CLASSICAL treatment)
- Fertigation with the CLOSYS integrated system (CLOSYS treatment).

Analysis of variance followed by Newman and Keuls test (α=5% and 10%) were used in order to statistically compare both treatments.

Main Modules of the Automated Fertigation Management Prototype

1. Plant Model. This mechanistic model was developed by Plant Research International Wageningen (Marcelis et al., 2005; Marcelis et al., 2006). It consists of modules 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 the plant organs (roots, stems, leaves and individual fruits), fruit harvest, nutrient demand and uptake. Inputs to the model are the global radiation outside the greenhouse and the inside climate (temperature, air humidity and CO_2 concentration). Greenhouse radiation transmission, radiation interception, photosynthesis and transpiration are calculated with time intervals of an hour. The time step of the modules for dry matter production, dry matter partitioning, fruit harvest, nutrient demand and uptake is 24 hours. Finally, a sensor (Cropscan, Inc., USA) measuring the light reflection of the canopy was used to estimate the Leaf Area Index (LAI) of the crop, in order to adapt the parameters of the plant model, thus creating a system with self-learning capacities.

2. Substrate Model. The substrate model was developed by INRA Avignon. It consists of reduction functions for the various plant model outputs according to relative water content and electric conductivity in the substrate slabs.

3. Expert System. This system, developed by INRA Avignon, automatically calculates a fertigation strategy to optimize the crop production, in quantity and in quality, according to fruit fresh weight, transpiration and Blossom End Rot rate (Dieleman and Marcelis, 2005). A fertigation strategy is considered as a set of average slab states (relative water content and electric conductivity) to which the crop responds. The optimization uses the information about crop state and crop behaviour, as given by the coupled plant-substrate model, which is used both to assess the current crop state from historical weather and slab data, and to predict crop development under future weather. The expert system also calculates the water and the individual nutrient uptake of the crop for each day of the fertigation strategy.

4. Real Time Controller (RTC). The RTC is a multivariable predictive controller of the slab status, used to satisfy the expert system set points (slab relative water content and electric conductivity), while maintaining a daily drainage rate between 30 and 40% (Brajeul et al., 2005). To achieve this goal, the RTC fine-tunes irrigation frequencies and doses every ten minutes, as well as electric conductivity of the supplied nutrient solution. Input data of the RTC model are global radiation, volume and electric conductivity of the irrigation water. Output data are slab relative water content and electric conductivity measured with three WCM (Water Content Meter) Grodan sensors (developed independently from the RTC), as well as the drainage rate.

Experimental Protocol

1. Plant Model Calibration/Validation. It required:

- climatic data acquisition every ten minutes (outside temperature, global radiation, inside temperature, air humidity, CO_2 concentration, pipe temperature);
- plant development measurements once a week, to estimate the number of nodes and the fruit load;
- plant destructive measurements five times a year, to estimate LAI, dry matter production and partitioning, and plant nutrient concentrations (total, fruits, leaves, stems);
- harvest data, to estimate fruit yield and quality.

The model was calibrated in 2004 and in 2005 by using data from a Cropscan sensor (reflectance to LAI estimation), development measurements, destructive and harvest measurements. The model was validated by comparing generic/2004/2005 model results with 2005 CLOSYS treatment experimental data. The generic model is a model with nominal set of parameters without any calibration.

2. Real Time Controller Identification/Validation. Model identification (RTC parameter adaptation) required irrigation and drainage volumes, irrigation and slab electric conductivity, slab relative water content and global radiation to be recorded every five minutes. The RTC was optimized in a closed regulation system, on-line with the Hortimax climate and fertigation computer. The RTC was validated by comparing the values realized by the multivariable controller (slab water content, slab electric conductivity and drainage rate), in feed-back with the desired set points generated by the expert system.

3. Comparison between CLASSICAL and CLOSYS Experimental Treatments. The comparison was made according to:

- slab relative water content and electric conductivity measured by six WCM Grodan sensors (three per treatment);
- drainage rate, water and nutrient consumption in the recycling systems;
- nutrient concentrations in irrigation and drainage;
- plant fresh and dry matter production/partitioning, and nutrient concentrations evaluated during destructive measurements;
- fruit yield and quality.

RESULTS

Plant Model Calibration/Validation

The plant model was calibrated throughout the experiment in 2004 and in 2005, according to the experimental data, by fine-tuning the following parameters concerning:

- node appearance rate;
- LAI;
- assimilation rate;
- assimilate partitioning between vegetative and generative parts;
- abortion rate;
- physiological age of fruit to harvest.

The plant model was validated by comparing generic/2004/2005 model results with CLOSYS treatment experimental data.

Contrary to the 2004 experiment when the Cropscan sensor predicted LAI rather well up to 3, the leaf area development was only properly evaluated in 2005 by the

Cropscan sensor up to LAI one, then it was largely under-estimated. However, the Cropscan sensor allowed to calibrate the model in 2005 and to obtain a LAI simulation as good as in 2004.

The harvested fruit number was also properly evaluated by the plant model. The model calibration performed in 2005 even contributed to improve the results in comparison with the same model in 2004.

The cumulative plant and fruit dry matter was properly evaluated by the plant model (Fig. 1). The model calibration performed in 2005 also contributed to improve the instantaneous dry matter (present on plant) simulation in comparison with the same model in 2004 and with the generic model (Fig. 2).

The leaf dry matter was also properly evaluated by the plant model. The poor stem dry matter simulation in 2005 was due to the model calibration at the whole plant level, which favoured the dry matter partitioning towards fruits and leaves.

Plant nutrient concentration simulations were really good for Ca (Fig. 3). The concentrations of N, P, K, S and Mg were fairly well simulated, though initial plant nutrient concentrations of N, P and K were under-estimated by the plant model.

In the 2005 experiment, plant nutrient uptakes were properly evaluated by the model for Ca (Fig. 4), Mg and S, but need some improvements for N, P and K, which could be linked to the poor initial plant concentration simulations for these nutrients.

On the contrary, the plant water consumption was under-estimated by the model in 2005, which tends to prove that no water savings can be expected from a lower crop water uptake.

As a conclusion, although the plant model is still imperfect, plant nutrient and water parameters were relatively well simulated. The differences between the plant nutrient uptakes measured and simulated by the model could be explained by:

- imprecisions in plant nutrient consumption measurements, which were evaluated as supply minus drainage,
- plant nutrient uptake estimation errors by the model.

Expert System Reliability

The expert system uses the weather forecasts (global radiation and outside temperature) to optimize slab relative water content and electric conductivity set points, as well as to calculate the nutrient equilibrium of the fertigation strategy. On three days, the average daily difference between weather forecasts and real climate is low, and similar from one day to the other (between 5 and 12% for the global radiation, between 19 and 20% for the outside temperature). That means the weather forecasts are not an important limiting factor for the expert system calculations, and there is no advantage in updating the fertigation strategy daily.

In 2005, the slab set points given by the expert system were always default ones (relative water content = 80% and electric conductivity = 2.5 $mS.cm^{-1}$). However, this relative water content set point was higher than what was physically possible in the substrate in late spring and summer, which means that default values had to be adapted according to the substrate characteristics and the climate.

Real Time Controller Identification/Validation

Different parameters were optimized for the RTC management.

To ensure a proper functionality of the system, the drainage rate, which suffers from an important inertia due to time delays in the flux measurements, should not be a driving element. As a consequence, the drainage rate parameter has to be under-weighted in comparison with the slab relative water content and the electric conductivity ones. For the same reason, the drainage rate set point increase with time during the irrigation period has to be frequently adapted.

The slab relative water content set point also has to be adapted according to the substrate characteristics and the climate.

Moreover, the command levels should give the system sufficient possibilities, particularly for the input electric conductivity (minimum and maximum commands) and the irrigation dose.

Finally, the sensors used for the RTC management have to be reliable and precise, and frequently checked.

When all of these conditions were met, the RTC allowed the slab relative water content and the electric conductivity to be controlled, while maintaining a daily drainage rate between 30 and 40%.

Comparison between CLASSICAL and CLOSYS Experimental Treatments

Apart from week 19 to week 25 when inappropriate parameters were set for the RTC, drainage rate, irrigation and drainage volumes were globally similar between both treatments. However, at the end of the experiment, irrigation, drainage and water consumption by plants were a bit lower for the CLOSYS treatment.

Moreover, from week 16 onwards, the slab set points given by the expert system were adapted and the average slab relative water content was lower for the automated system.

Finally, although irrigation electric conductivities were similar, the slab conductivity was very variable between both treatments, with a general trend towards a lower electric conductivity for the CLOSYS treatment.

From the planting date, the K/(Ca+Mg) ratio given by the plant model for the automated system was higher than the ratio used for the CLASSICAL treatment, which could be linked to a ratio increase in the drainage for the CLOSYS treatment.

Moreover, at the start of the crop, sodium and chloride concentrations in irrigation and drainage were similar between both treatments. From March, a relatively high increase of these concentrations was observed in the CLASSICAL treatment.

Finally, the supplied and drained quantities of N, P, Ca, Mg, Na and Cl were lower for the CLOSYS treatment. The quantities of N, P, Mg and S consumed by plants were similar between both treatments, slightly lower for K and slightly higher for Ca in the CLASSICAL treatment (Fig. 4).

The fresh and dry matter production were similar between both treatments, with a sigmoid growth with a threshold value in June for the dry matter present on the plant, and a continuous growth for the total dry and fresh matter.

Moreover, the dry matter partitioning was also similar between both treatments. However, the fresh matter partitioning towards leaves and stems was significantly higher for the CLOSYS treatment.

Finally, mineral analysis for plant organs drew no statistical difference between both treatments.

At the end of the crop, the harvested fruit yield was similar between both treatments, although the number of fruits was significantly higher for the CLOSYS treatments with α = 10%. However, following the inappropriate parameter set for the RTC from week 19 to week 25, the final commercial yield was significantly lower for the automated system with α = 10%.

DISCUSSION

Module Performances

First of all, plant development, dry matter production and partitioning are properly simulated by the plant model, thanks to its yearly calibration. However, potential plant nutrient and water uptakes are only simulated fairly well and would need some improvements, because the results are more heterogeneous.

Moreover, the expert system enables the coupling between plant and substrate models, thus ensuring the system to take into account the weather forecasts, thanks to the link with the Hortimax climate and fertigation computer. It generates suitable optimal set points for the slab electric conductivity, but the slab relative water content set points will have to be automatically adapted according to the substrate characteristics and the climate.

Finally, the real time controller manages to control relative water content and electric conductivity in the substrate slabs when appropriate parameters are set. It could be an alternative in the future for PID controllers.

CLOSYS System Performances

The CLOSYS system has been working with all of its modules since June 2004.

At the end of the crop, the harvested fruit yield was similar between both treatments. However, following an inappropriate parameter set for the real time controller, the final commercial yield was significantly lower with the automated system. This emphasizes the limits of the CLOSYS system in its ability to reduce water consumption. As a matter of fact, water supply has not to be reduced too much in comparison with the CLASSICAL treatment, in order to maintain the fruit quality by avoiding a too high Blossom End Rot rate due to water stress.

On an ecological point of view, the automated system offers some positive impacts. The slab electric conductivity is correctly managed, even with low drainage rates. In comparison with the CLASSICAL treatment, the supplied and drained quantities are lower for most of the nutrients. The sodium and chloride accumulation in the drainage is also lower, which also facilitates the reuse of drainage in a closed system.

Finally, the K/(Ca+Mg) ratio given by the plant model for the automated system is higher than the ratio used for the CLASSICAL treatment, which could be linked to the results of a survey carried out on a sweet pepper crop in a closed system by a Swiss team (Pivot and Gillioz, 2004). In this survey, the nutrient solution calculated according to the plant needs provided higher potassium concentrations, and lower phosphorus, magnesium and calcium concentrations in comparison with what was usually advised.

CONCLUSIONS

The CLOSYS system is validated for its use as an automated fertigation management prototype for environmentally sound production incorporating fruit quality goals. It has shown potential in practical use, but still some improvements can be made, especially about plant nutrient and water uptake simulations by the plant model, and about some expert system functionalities.

This EU project led to two improvements:

- the nutrient equilibrium calculations of the fertigation strategy according to the plant nutrient contents,
- the real time control of the fertigation process.

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Figures

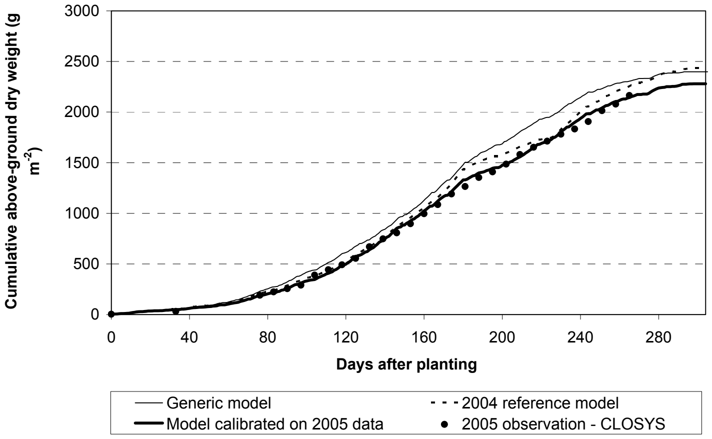

Fig. 1. Soilless sweet pepper crop under glasshouse – 2004 and 2005. Comparison between observed and simulated cumulative plant above-ground dry weight.

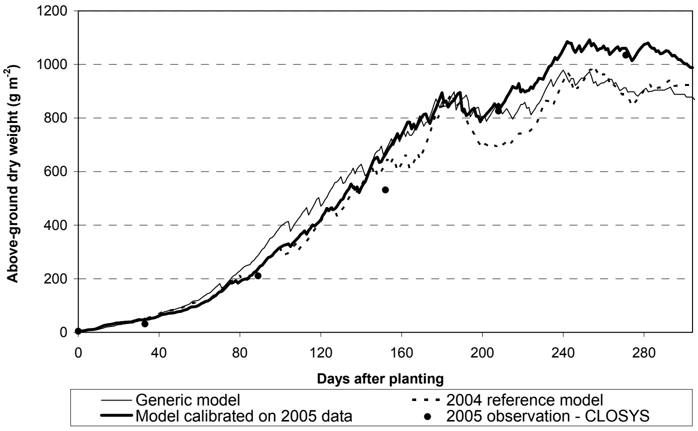

Fig. 2. Soilless sweet pepper crop under glasshouse – 2004 and 2005. Comparison between observed and simulated plant above-ground dry weight.

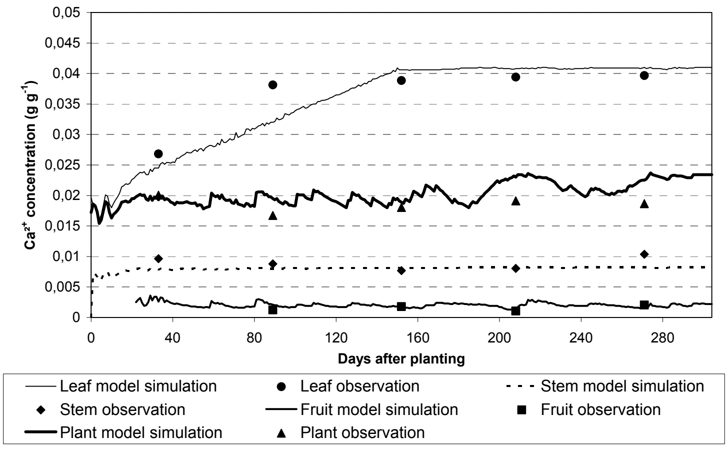

Fig. 3. Soilless sweet pepper crop under glasshouse – 2005. Comparison between observed and simulated plant calcium concentrations.

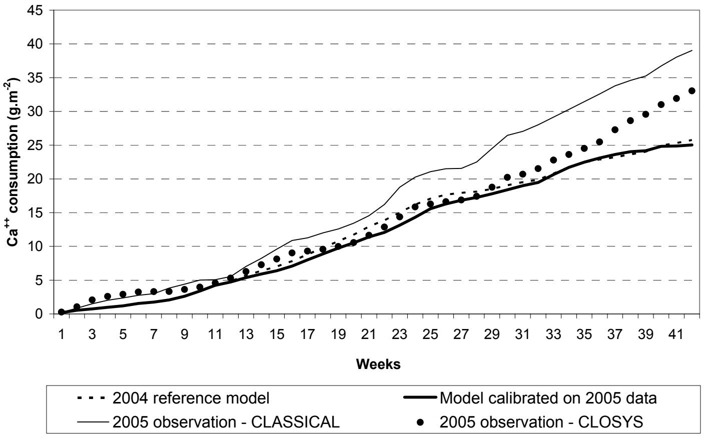

Fig. 4. Soilless sweet pepper crop under glasshouse – 2004 and 2005. Comparison between observed and simulated cumulated plant calcium consumption.