PLANT RESEARCH INTERNATIONAL
WAGENINGEN UR

CLOSYS

Closed system for water and nutrient management in horticulture

Final report

J.A. Dieleman & L.F.M. Marcelis (eds.)

Report 98

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1. Summary

CLOsed SYStem for water and nutrient management in horticulture (CLOSYS)

Objectives

The primary objective of the CLOSYS project is zero nutrient pollution and minimum water use in greenhouse cultivation. This project aims 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. Pollution will be minimized by controlling the input of resources rather than by end-of-pipe measures. Besides aiming at sustainability, enhancing crop quality and safety, and controlling the timing of production are important aspects. The latter being increasingly important in order to produce at the right time what is requested at the point of sale. Within this overall objective, a number of other objectives necessary to reach its achievement are comprehended, which include development of mechanistic plant and substrate models with self-learning properties, non-invasive sensors for plant and substrate characteristics, improved growth substrate, real time process controller and expert system.

Results and Milestones

The project is carried out with 2 different crops (rose and sweet pepper) which are economically very important throughout Europe. As the system to be developed has a mechanistic basis, a generic structure and self-learning properties, it can easily be applied to other crops as well. The work is grouped into 5 themes:

1. Plant sensor
   Non-invasive on-line sensors measuring important parameters of the crop were developed. This includes UV induced fluorescence imaging to sense photosynthetic performance and plant stress, as well as reflectance measurements to sense leaf area.
2. Plant physiology
   Experimental and modelling research focuses on the development of a dynamic crop model that predicts the demand for and uptake of water and the individual ions by a crop. The model considers physiological processes, gets feedback from actual on-line measurements of crop status and contains self-learning features.
3. Substrate physics
   Multiflow computer fluid dynamics is used to develop a substrate model that predicts the strategy of fertigation to meet the demand of the roots. The substrate model is linked to the crop model and gets feedback from sensors in the rooting medium. Novel sensors for selective measurement of Mg and Na are being developed. The substrate for plant growth is improved such that it allows better control of water and nutrient fluxes in the root zone.
4. Systems integration
   The models and sensors are integrated in an expert system and a real-time control system for ion-selective nutrient and water supply. To realize total system integration, all subsystems will be implemented in a technical infrastructure consisting of a modular hardware platform.
5. Testing and dissemination
   In the last year the integrated system will be tested on a near-practical level and results will be disseminated to the horticultural industry, students and policy makers. Moreover, in 5 countries national workshops will be held for dissemination of results.

In Theme 1 ‘Plant sensor’, in a number of experiments the relation between plant status and the signals of the fluorescence imaging sensor was established. In order to obtain this relationship, the status of the plant was influenced by applying different stress treatments. Results showed that the fluorescence ratios were affected differently dependent on the type of stress applied. This indicates that fluorescence signatures can be used to detect the type of stress plants are subjected to. However, it was found that plants under greenhouse conditions are in such ‘optimal’ conditions that little disturbances that occur in practice do not cause the plants to be stressed and therefore cause no changes in fluorescence signals.

In this theme, a portable fluorometer for stress detection with UV light was constructed and tested. It proved to be a very user-friendly, compact and accurate system. Furthermore, a UV-LED array, an alternative to a Xe-arc lamp system was developed and tested successfully.

In Theme 2 ‘Plant Physiology’, mechanistic models for sweet pepper and rose were developed and self-learning capacity was introduced. Extensive experiments were conducted, quantifying the demanded and critical nutrient concentrations for the different plant organs and the time constants of nutrient demand and uptake, and cation uptake of rose and sweet pepper plants. The sweet pepper and rose models were calibrated with these data and were validated on the basis of extensive datasets of long-term experiments with rose and sweet pepper crops at four experimental sites in Europe.

In Theme 3 ‘Substrate physics’, an elaborate substrate model has been developed which can simulate water and nutrient contents in the slab at a detailed, three-dimensional level. It was used for the design optimization of the slab. According to the calculated optimal design, a new slab was manufactured, which was used in the CLOSYS system. The substrate model was coupled to the plant model to be used in the CLOSYS system. Furthermore, the management system for fertigation of the final test of the CLOSYS system was designed.

For an optimal control of a closed system, it is important that all individual major minerals can be monitored by on-line sensors for which a multi-ion sensor probe was developed and tested. It was found to be an accurate and stable sensor.

In Theme 4 ‘Systems integration’ all subsystems of the CLOSYS system were integrated into one entire system. An expert system and a real time controller (RTC) were developed in order to control water and nutrient supply. The expert system determines the irrigation schedule and the nutrient supply plan. Output of the expert system are fertigation plans, that will be applied to every weather forecast. The plans contain set-points for the RTC, which will combine information from plant and substrate sensors as well as the plant and substrate models to control the system to nullify nutrient and water losses. A technical infrastructure was developed whereby the different subsystems can work together and the tasks decided upon by the expert system and RTC can be executed.

In Theme 5 ‘Test and dissemination’ the CLOSYS system and a commercial sweet pepper growing system were compared in the final field test. The CLOSYS system consisted of the newly developed substrate, the plant and substrate models, the multi-ion sensor, the fluorescence sensor, the reflectance sensor, the expert system and the real time controller embedded in a specially designed technical infrastructure. Results showed a lower plant water use in the CLOSYS system than in the classical system, without affecting fruit production.

Results of the CLOSYS project were disseminated in five national workshops, organized in The Netherlands, Hungary, Spain, France and Greece.

Benefits and Beneficiaries

The main benefits of the project are zero nutrient pollution and minimum water use in greenhouse cultivation. This will diminish problems with water availability and will prevent pollution of ground or surface water with nutrients. CLOSYS will improve the possibilities for growers to control crop growth and product quality such that it meets the quantitative and qualitative demands of the consumers, which will minimize the production of products not requested by the market. The project results will contribute to the competitiveness of the European horticultural sector as it reduces costs of water and nutrients (2500-4000 Euro per ha per annum), it allows a better control of crop growth, product quality and production volume, and it appeals to consumers’ wishes with respect to production systems.

The main beneficiaries of the project results are the growers. Besides, companies selling horticultural supplies (control equipment, sensors, substrate) will benefit directly. The results of CLOSYS can be used by policy makers when developing directives for nutrient pollution of the environment and water use. Furthermore, the results are of interest to students, teachers, advisers and scientists.

2. 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 have to drain nutrients and water to the environment from time to time to prevent imbalances of the nutrient solution in the root zone. As in the present production systems nutrients and water are always supplied in excess, possibilities to control and to plan crop growth and product quality by a regulated water and nutrient supply are not used by growers. In greenhouse production systems approximately 120 kg N, 20 kg P and 2200 L water per ha are lost each year in North-western Europe, while in Mediterranean countries with more severe water shortage and salinity problems the yearly losses are approximately 300-350 kg N, 125-300 kg P, 600 kg K and 3000-3500 L water per ha. As an example, this means a total annual loss of 1,200 tonnes nitrogen for The Netherlands as a whole (total production area: 10,000 ha) and 16,000 tonnes nitrogen for Spain as a whole (total production area: 50,000 ha). 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. Losses of water and nutrients to the environment resulting from excess use of water and nutrients in horticulture can be avoided by:

- Independent control of the supply of water and nutrients
- Controlling the supply of individual minerals rather than total salt concentration
- Supply of water and individual minerals 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 CLOSYS project aims 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 project aims at minimizing pollution by controlling the input of resources rather than by end-of-pipe measures. Besides aiming at sustainability of crop production, enhancing crop quality and safety and controlling the timing of production are important aspects. The latter being increasingly important in order to produce at the right time what is requested at the point of sale.

The project is carried out for two different types of crops: cut rose and sweet pepper. These crops are representatives of vegetable and cut flower crops and both are economically very important crops throughout Europe. As the system to be developed has a mechanistic basis, a generic structure, and self-learning properties, the system can easily be applied to other crops as well.

For closed systems without losses of water and pollution of nutrients to the environment, cultivation on substrates is an important aspect. Nowadays, already a large fraction of greenhouse crops is grown on artificial substrate. In the Netherlands already more than 85 % of the vegetables are grown on artificial substrate, while in Southern Europe the use of artificial substrates is very rapidly increasing. Therefore, in this project we focus on a cultivation system in which plants are grown on artificial substrate. However, the properties of these substrates are still not optimum with respect to control of water and nutrient transport. Improvement of the substrate to allow a better water and nutrient management is also part of the project.

The activities of the CLOSYS project were grouped into five major themes:

1. Plant sensor
2. Plant physiology
3. Substrate physics
4. Systems integration
5. Test and dissemination

Re 1. Plant sensor

Under normal physiological conditions, the major part of light absorbed by the photosynthetic pigments, chlorophylls and carotenoids, is used for photosynthetic quantum conversion, and only a small proportion is de-excited via emission as heat or as red and far-red chlorophyll fluorescence. In contrast, under many stress conditions, the photosynthetic quantum conversion declines, with a concomitant increase in red and far-red fluorescence. Blue and green fluorescence also change under stress. A laboratory apparatus for high resolution detection of ultraviolet laser-induced fluorescence has been developed at the University of Karlsruhe, which allows whole leaf imaging of all four fluorescence bands: blue, green, red, and far-red. Even small fluorescence gradients are detected, permitting the early detection of stress. In the CLOSYS project, the set-up of this imaging system will be improved, after which the possibilities of this sensor in early stress detection will be investigated. In addition, reflectance of near infrared radiation has been shown to be a useful parameter for remote sensing of leaf area development of plants, an input parameter of great importance for calculating plant growth by the plant model. Relations between reflectance and leaf area will be established in this project.

This theme delivered the following results as described in this report:

1. Fluorescence imaging sensor
2. UV-LED array
3. Portable fluorometer

Re 2. Plant physiology

In the CLOSYS project, dynamic mechanistic models for rose and sweet pepper will be developed that predict crop growth and demand and uptake of water and individual nutrients. Emphasis will be on the development of simulation modules for nutrient and water relationships of the plant, while for dry matter production and transpiration existing simulation modules will be used. The model will have self-learning properties by feed-back from on-line sensors that measure important parameters of the plant model and by use of historical crop production data. The concept of the plant model for simulating the water and nutrient relationships will be verified and quantified in a series of experiments with rose and sweet pepper. The models will be validated with extensive data sets of experiments with rose and sweet pepper performed at different sites in Europe having different climate conditions.

This theme delivered the following results as described in this report:

1. Water and nutrient demand of rose
2. Water and nutrient demand of sweet pepper
3. Plant/substrate model

Re 3. Substrate physics

Until recently, artificial substrates used in horticulture were considered as black boxes in which only input and output were studied. However, recent studies have shown that the unbalances between crop demand and water and mineral transfers in the substrate were responsible for large saline variations of concentrations around the roots, which stress the plants and give rise to large production losses (mainly quality), particularly in the summer period. This is a reason for growers to drain water and nutrients to the environment. In the CLOSYS project, experimental studies as well as modelling will be conducted in order to develop a model that simulates the dynamics and heterogeneity of water and mineral flows in the substrate in dependence of root absorption and convective and diffusive transfers in the slab. With this substrate model, substrate properties for an improved substrate will be defined. Based on these properties, a new type of substrate will be produced and used in the final test of the closed system.

For an optimal control of a closed system, it is important that all individual major minerals can be measured by robust on-line sensors. In the CLOSYS project, sensors for Na^+ and Mg^{++} will be developed and integrated in the complete on-line multi-ion sensor unit, which will then be used in the final test of the closed system.

This theme delivered the following results as described in this report:
1. Substrate characterization and models
2. Improved substrate
3. Substrate sensor

Re 4. Systems integration

The software and hardware developed in this project will be integrated into an integrated system for closed water and nutrient management and will be finished as a research prototype. The control of the water and nutrients comes from an off-line expert system that defines daily decision plans, while an on-line real-time controller operates the irrigation and fertilization system. These activities will produce new algorithms for the management of irrigation and fertilization, with feed-forward capabilities and optimized schedules for water and nutrient supply in the closed system. These schedules are continuously adapted to the evolution of the plant demand, to the constraints of the system, operational costs, environment protection, and to the goals of the grower who will be able to control the behaviour of the crop by tuning water and mineral supply.

This theme delivered the following results as described in this report:
1. Expert system
2. Real time controller
3. Technical infrastructure

Re 5. Test and dissemination

In the last year of the CLOSYS project, all subsystems developed will be integrated into a CLOsed SYStem that will be installed at an applied research station in the north of France. A comparison will be made between sweet pepper plants grown in the CLOSYS system and plants grown in a system which is now commercial practice in sweet pepper growing. The CLOSYS system will consist of the following subsystems: a new substrate, the multi-ion sensor, the fluorescence imaging sensor, the plant and substrate models, the expert system and the real time controller embedded in a specially designed technical infrastructure. Results of the CLOSYS project will be disseminated in five national workshops, organized in The Netherlands, Hungary, Spain, France and Greece.

This theme delivered the following results as described in this report:
1. Closed system

3. Material and methods

3.1 Fluorescence imaging sensor

A laboratory apparatus for high resolution detection of ultraviolet (UV) laser-induced fluorescence has been developed at University of Karlsruhe, which allows whole leaf imaging of the major fluorescence bands of green leaves: blue, green, red, and far-red (Buschmann & Lichtenthaler, 1998; Buschmann *et al.*, 2000; Langsdorf *et al.*, 2000; Lichtenthaler *et al.*, 2001, 2005). Even small fluorescence gradients are detected, permitting the early detection of stress. In addition to the fluorescence signals, reflectance of near infrared radiation has been shown to be a useful parameter for non-destructive, non-contact sensing of leaf area development of plants, an input parameter of great importance for calculating plant growth (Bouman *et al.*, 1992). Image analysis has the advantage of a) a high local resolution, it shows b) the distribution of signals inside a sample, c) the localization of specific signals, d) the pattern of signals, and e) gives statistical confidence.

A multispectral fluorescence imaging system for monitoring plants and vegetation existing at the Botanical Institute II of the University of Karlsruhe was further developed for the purpose of the CLOSYS project by integrating the reflectance measurements into the fluorescence measurement routine. In particular the light source (pulsed Xe-arc lamp) has been newly constructed by the University of Budapest who developed the ignition electronics and lamp power supply. This light source was manufactured to suit the use in a greenhouse within an IP-65-box shielding against external humidity. Filters have been chosen which makes it possible to determine the fluorescence and reflectance parameters needed for the detection, specification and quantification of different stress types of the sweet pepper and rose plants.

The system now established at the Botanical Institute of the University of Karlsruhe is recommended as a plant sensor for the purpose of the CLOSYS project. It consists of the following components:

Light Source

Xenon-arc lamp (pulsed, PERKIN-ELMER FX4400) with parabolic mirror and lens
  Pulse energy: 0.25 J, effective energy between 350 and 370 nm: 10-2 J
  Pulse duration: 2.5 µs, frequency: 50 Hz (controlled by the computer), jitter + 15 µs
  Power: 220V, VA
Spot size at a distance of 0.5 m: diameter 200 mm (lens focal length: 50 mm)
Filter wheel in front of the Xe lamp with
  bandpass filter with maximum transmittance at 340 nm (half bandwidth: 120 nm)
  (DUG 11, SCHOTT, Mainz, Germany)
  Neutral density filter with 1% transmittance
Light shutter: by means of TTL signal
Housing: closed, sealed (humidity Class IP 65), cooling with internal air-ventilation

Rotary indexing table for sample sequences

A rotary indexing table was installed which allows to take images of different leaf samples or pot plants in a sequence. Thus the number of fully automated measuring sequences is enhanced to six instead of only one. The turning of the rotary indexing table is controlled by the computer.

Camera

Intensified camera for ('Camille' camera, OPTRONIS, Kehl/Germany)
Lens for collecting the image (NIKON, focal length: 50 mm)
  focused on the entrance of the intensifier

Filter wheel in front of the camera (controlled via the RS232 interface) with the following filters:

- bandpass filter at 440 nm (half bandwidth of 10 nm, ORIEL, France),
- bandpass filter at 520 nm (half bandwidth of 10 nm, ORIEL, France),
- bandpass filter at 550 nm (half bandwidth of 40 nm),
- bandpass filter at 690 nm (half bandwidth of 10 nm, ORIEL, France),
- bandpass filter at 740 nm (half bandwidth of 10 nm, ORIEL France),
- bandpass filter at 800 nm (half bandwidth of 40 nm),
- block

Gated image intensifier tube (Micro Channel Plate (MCP)-type, PHILIPS XX1414M/E, photocathode Type S25, diameter 18 mm) connected to the camera (controlled via a RS232 interface by the synchronizer), adjustable gain with a factor of 3000 (set between 300 and 880 V), gated time 320 µs, 50 Hz

Detector: CCD-array of 565 x 754 pixels, image digitized on 8 bits

CCIR video output to the PC interface

Accumulated pictures: 50 per second

Synchronizer

Synchronization of pulses to the gating of the image intensifier is solved by a microprocessor controlled trigger system, which allows jitter-compensated detection of pulses which was newly developed and manufactured by partner 10 (TUBUD).

Computer

For centralized image acquisition controlling, data storage and data treatment a PC with WINDOWS system software is used together with a PCI interface for 'Camille' camera and a Video frame grapper (transferring the images from 8 to 16 bit).

A new imaging software which is user-friendly and suitable for automated routine measurements could be purchased which fits the demands of the project. With this software one is able to control the camera (start/stop, filter wheel), the light source (Xe pulse ignition, filter wheel), the rotary indexing table and the image intensifier (gain of the micro channel plate amplifier). The acquisition parameters can be set for choosing the fluorescence and reflectance bands, the number of accumulated images, the gain of the image intensifier, and the definition of an imaging sequence. The acquisition parameters are stored in a separate report file. The raw images are then ready for data processing and image analysis, i.e. corrections for background light, uniformity of the illumination light source, gain of the intensifier and differences in filter transmittance. The image analysis also comprises scaling (transformation to a common scale), masking the region of interest, calculation of parameters (ratios) which can be freely defined and statistics (including histograms and profiles). The software is also able to carry out the data handling including report of the sample displayed and stored, display and printing of images (b/w, false colour, life image, zoom), storage of images (on the hard disk and on CD) and erase of unwanted data.

Alternative light source

An UV-LED array with extremely high output power was developed (paragraph 3.2) and successfully tested as an alternative to the Xe-arc lamp implemented in the Karlsruhe fluorescence imaging system.

3.2 UV-LED array

Within the CLOSYS project, different types of UV light sources were developed to allow induction of blue and green fluorescence (Broglia, 1993) in leaves and alternatively in whole small plants.
Prior to the realization of the final, high intensity UV-LED array system, a new pulsed Xe-lamp source has been designed, manufactured and tested for fluorescence imaging system. The lamp, typed FX4400, is based on the latest technology of PerkinElmer. Power supply, ignition electronics synchronization and housing are developed

by TUBUD. Synchronization of pulses to imaging is solved by a newly developed, microprocessor controlled trigger system, which allows jitter-compensated detection of pulses. The lamp and all electronics are placed into a greenhouse-conform (Class IP-65) housing with movable, flexible holders in order to enhance plant illumination conditions. Housing of the Xe-arc flash-lamp is mounted on an arm that is able to rotate ±90° around the box (Figure 3.2.1). The power supply is capable of generating high energy pulses up to 1 J (C=2 µF, U=1000 V).

The unit is equipped with a manually changeable interference filter set to allow alternative fluorescence or reflectance measurements. Pulse repetition rate is set to 50 Hz with energy of 0.25 J and duration of 2.5 µs. The spot size on the sample at a distance of 500 mm is in the range of 25-75 mm depending on the focal length of the lens. The lamp was installed at UNIKARL.

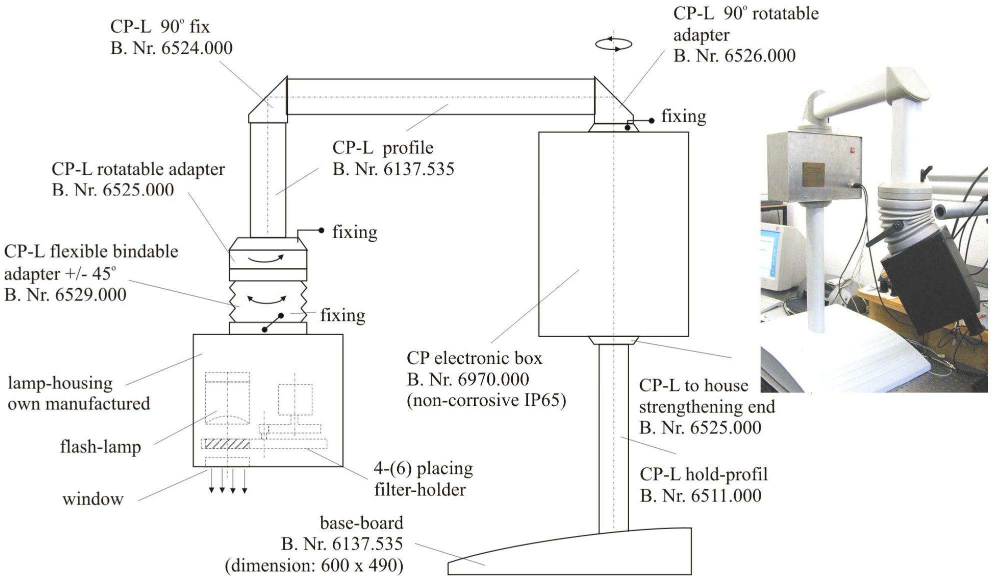


Figure 3.2.1. Construction of the UV lamp unit.

As an initial approach, two types of UV light sources were contructed based on a circular array of 10 UV-LEDs (Figure 3.2.2). The light heads are designed to deliver a maximum intensity to an approximately 1 cm^2 area of leaf samples. The two types differ in their radiation characteristics. This UV-array was incorporated into the portable fluorometer (Section 3.3, Figure 3.3.4).

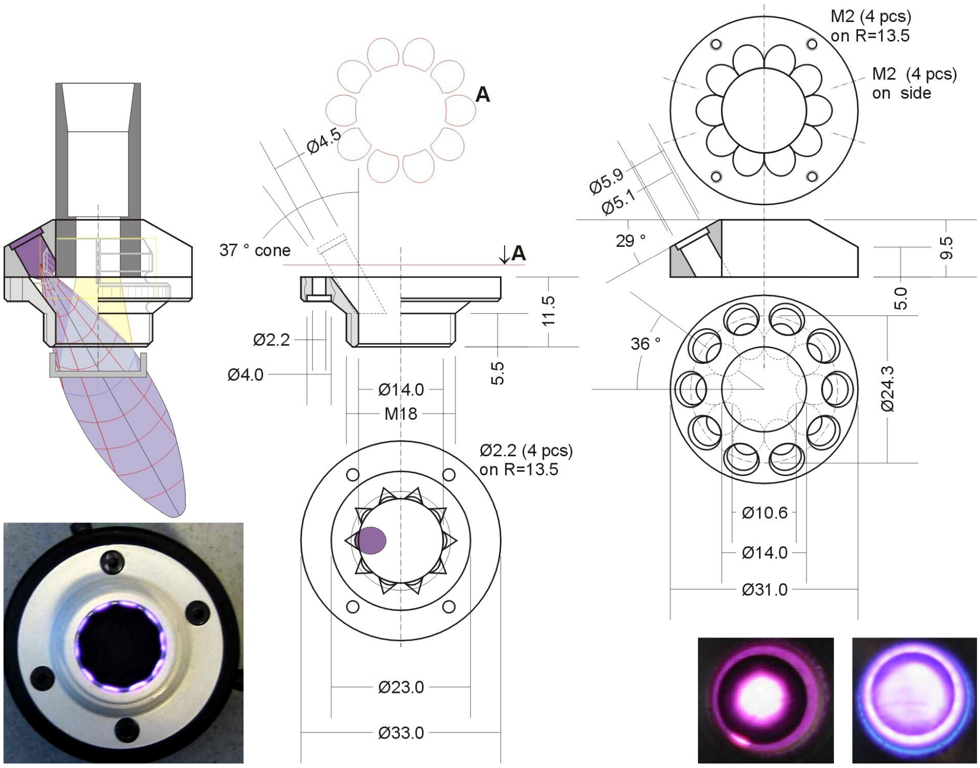


Figure 3.2.2. Optical and mechanical design of the UV light source based on a circular array of UV-LEDs.
Smaller spot: UVLED371-10 (370 nm, 0.75 W radiated power/LED, ±5° divergence).
Larger spot: LED375-04 (375 nm, 2.5 W radiated power/LED, ±17° divergence).

Based on the above experiences, a UV-LED array based, extremely high output power illuminator was developed and successfully tested – as an alternative to a Xe-arc lamp based system. An LED array has a main advantage of requiring a low driving power. Furthermore, the pulse repetition rate can be significantly increased without any jitter effect when triggering. Its peak wavelength is at 370 nm with a narrow bandwidth of ~20 nm, so it is well suited to induce blue and green fluorescence. Because of its relatively low radiated power (compared to a UV lamp) and wide viewing angle, however, an accurate optical design was necessary.

The light source is based on 5 parabolic mirrors with a single chip LED array of 60 InGaN UV diodes (Roithner, 2003) in each mirror focus. These LED-mirrors are arranged so that their light spots form an overlapping rosette on the planning plane. Positioning the LED-mirrors in radial direction results in different types of light spots ranging from large (180 mm diameter) and homogenous (within 80 %) to smaller and more inhomogeneous, but with a 2.5-fold brighter central (60 mm) region. It works in pulsed mode similarly to the Xe-lamp system. The features of the UV-LED array design are the following (Figure 3.2.3):

- *Mechanical design:* The LED-mirror units and the camera were mounted on an aluminum-plane with three adjustable legs (LED/mirror focal length vs. planning plane/leaf distance: 450-1000 mm). The LED-mirror units are adjustable in radial direction so that different spots can be created on the sample. The mirrors are made of diamond-tool lathed aluminized half brass-rod with mirror size of 11*12 cm^2.

- *Electrical design:* It works in pulsed mode similarly to the Xe-arc lamp system (repetition rate: 50 Hz). For increasing the radiated effective power to the level of the Xe-arc lamp system, the pulse duration was extended from 20 µs to 200 µs. The radiated power may be further increased e.g. by longer pulse duration or increased repetition rate (e.g. 500 Hz): the limits (maximum ratings vs. lifetime) of this LED source are undocumented so it would require additional tests.

- *Optical design:* Off-axis arrangement is realized with a parabolic mirror and a LED-array in its focus. This concept minimizes absorption loss (compared to lens focusing optics) and beam-shielding loss (compared to an axial configuration with a spherical mirror). A single LED-array (type LED370-66-60-110 (Roithner, 2003)) possesses a viewing angle of ±60° and an output power of 20 mW/chip. The focal distance of the parabolic mirror is 21 mm. The angle between the mirror axis and LED normal is 79.5°. The angle of the LED-mirror system axis and the planning plane (sample) is 71.5°.

The assembled UV-LED array light source is shown in Figure 3.2.4.

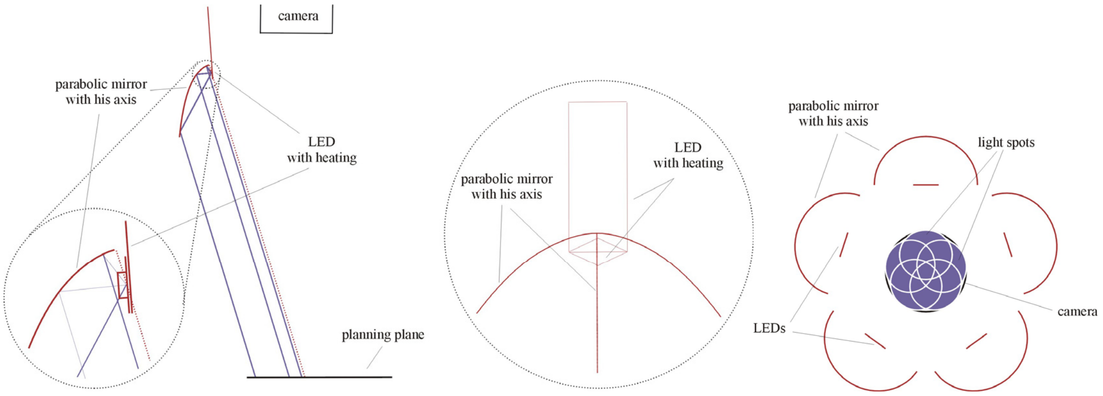


Figure. 3.2.3. Side view of the UV-LED array system with the central and Θ1/2 beams (left), rear view of a single LED with its heating (middle) and top view of the LED-mirrors and the generated spot (right).

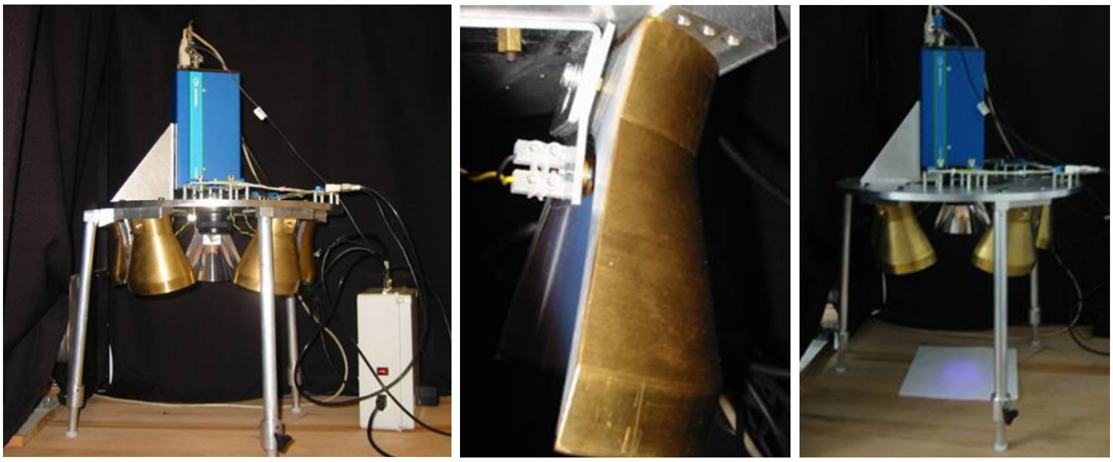


Figure 3.2.4. View of the assembled UV-LED array light source (left) with the parabolic mirror (middle) and the generated spot (right).

3.3 Portable fluorometer

An existing portable, time resolved, laser induced chlorophyll fluorometer (CFM, developed in cooperation with TUBUD for plant stress detection (Barocsi *et al.*, 2000, 2003)) is equipped with new light sources, additional wavelength detection channels and new measuring methods of plant physiological parameters in order to enhance the stress detection capability of such fluorometers on greenhouse grown plant (Buschmann & Lichtenthaler, 1998; Gustafsson *et al.*, 2000). This new generation device (Figure 3.3.1) is applied for detection of stress symptoms in sweet pepper plants. For measuring the fluorescence signal of the leaves, the leaf is excited with UV light at a wavelength of 375 nm. Detection is made at 4 wavelengths, 440, 520, 690 and 735 nm. For recording UV induced fluorescence, a simple leaf-clip is designed that holds the external UV light source and keeps the leaf in position during a measurement. Data from the CFM can be downloaded for further evaluation using a serial cable and the provided evaluation programme FluorMeas+ running under Microsoft Windows.

Figure 3.3.1. The complete CFM portable fluorometer operated at Plant Research International.

The basis of the new device is a fully documented version of a CFM-636973 type, two-wavelength CFM, in which extensions were implemented according to the following concepts:

- *Mechanical design:* The instrument electronics consist of a stack of PC/104 form factor boards (PC/104 Embedded Consortium, 2001) (Figure 3.3.2, left) that are mounted with spacing larger than required by the PC/104 standard (15.4 and 28.0 mm instead of 15.2 mm). Reducing the board-to-board spacing, the additional 2-channel detector board could be fitted in the original housing (Figure 3.3.2, right). The spacing of the two detector boards were shrunk to 12.3 mm. The vertical dimension of the detector mounting side panel was expanded to accommodate all 4 detectors.

- *Electrical design:* The data acquisition board was capable, without changes, of receiving analogue signals on a total of 8 channels, of which 4 were used (zero and reference levels, and 690 nm and 735 nm signals). The remaining 4 channels could be connected to a second detector board. The internal supplies were capable of powering the extra board. The extra channels are placed on a 'half-sized' PC/104 board to save space for the heat sink of the internal laser (Figure 3.3.3).

- *Optical additions:* 2 extra detectors with edge and interference filters to separate the fluorescence wavelengths and eliminate back-scattering of the illumination. The UV illuminator is realized externally and mounted directly onto the sample holder clip (Figure 3.3.4). For proper detection and separation of the fluorescence signals, a 5-branch optical fiber bundle was developed that allowed also fluorescence induction using the built-in laser diode. The 5-branch fiber was assembled using elementary plastic (PMMA) fibers of ∅0.5 mm (Figure 3.3.5, left). Four of the 5 arms are identical with 36 individual fibers and used for fluorescence detection. The 5th arm with 28 fibers is used to guide the internal red laser light to the sample. The aperture diameters of the illuminating branch, the detection arms and the common end are ∅3.2 mm, ∅3.5 mm and ∅7.4 mm, respectively. The common end of the fiber groups the elementary fibers of the arms symmetrically so that detection of all 4 wavelengths be identical and maximum illumination intensity from the internal light source be achieved (Figure 3.3.5, right). The fibers were bonded into cords using a 4-component Araldite based epoxy (Durcupan). After assembling and curing (48 hours at 60 °C), the fiber ends were optically polished.

- *Software additions:* It was necessary to handle the signals of the additional detector channels and allow saving of the extra fluorescence data. The latter was done by saving the data in a separate file while keeping the existing format for backward compatibility. The internal control programme of the CFM is different for the red and UV induced measurements to avoid interference in controlling the optoelectronic hardware.

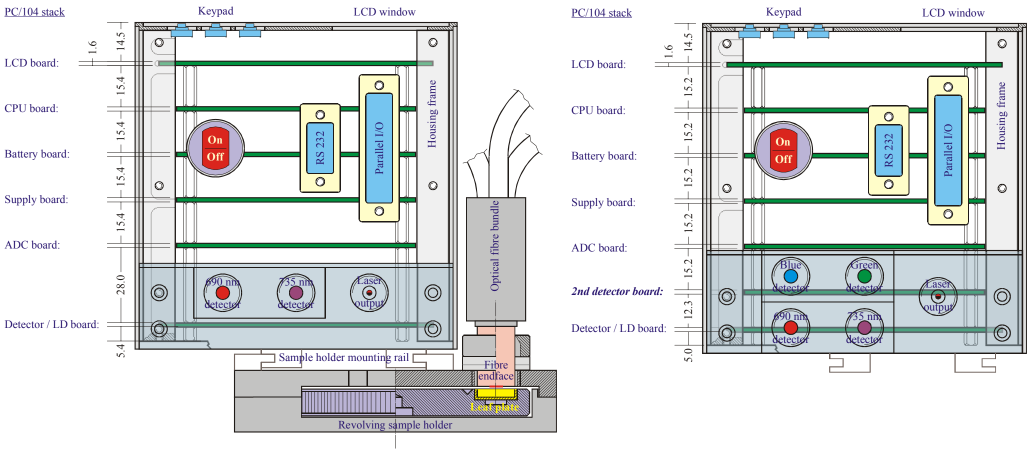


Figure 3.3.2. Side views of the original 2-channel (left) and the extended 4-channel (right) fluorometers.

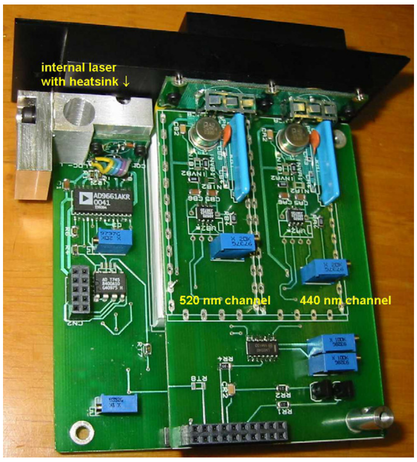


Figure 3.3.3. 'Half-sized' PC/104 board for the two additional detector channels.

Figure 3.3.4. Performing a UV induced measurement (right) with the sample holding clip containing the UV illuminating head (left).

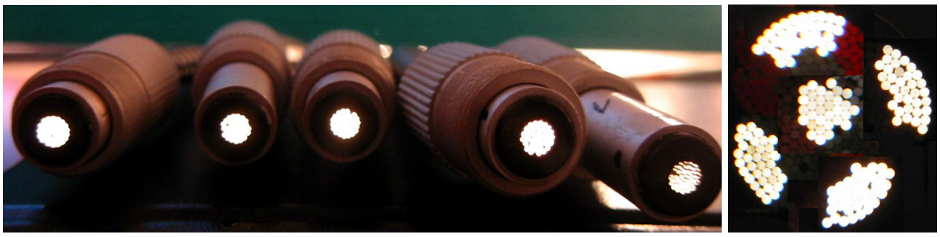


Figure 3.3.5. Branches of the 5-branch fiber (left) and its common end showing each illuminated section (right): middle is used for laser guiding.

As the measurement techniques are different for the red and UV illuminations, different accessories must be used. For recording UV induced fluorescence, a simple leaf-clip is designed that holds the external UV light source and keeps the leaf in position during a measurement. The UV head is based of an array of 10 circularly positioned LEDs (Section 3.2) and designed so as to allow connection of both the original and the new optical fiber bundle (compatibility issue). The UV induced measurements are easily made by this assembly and the new CFM control program. It is a quick test without any pre-darkening of the leaf samples. A single measurement takes only some seconds holding the clip according to Figure 3.3.4. This way, the slit of the holder as well as the backside of the sample is covered (shielded against ambient light).

The sampling is done according to the chart of Figure 3.3.6. The detector dark levels are measured 10 times prior to turning the UV light on, then averaged. Next, the UV source is on for 4 seconds. Three seconds are used to wait for plant relaxation and 1 second is used to sample the fluorescence signal 100 times, which is then averaged. Both raw and averaged data are stored for evaluation.

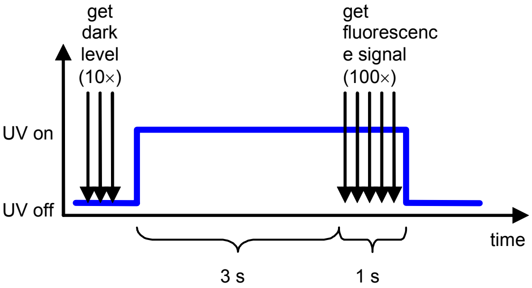


Figure 3.3.6. UV induction protocol chart.

3.4 Water and nutrient demand rose

In order to determine the nutrient demand of roses, measurements conducted on plant growth, plant nutrient uptake (by chemical analysis of nutrient solution and plant material), water uptake and transpiration, were performed in three series of experiments.

The first series of experiments concerned:

- the evolution of pH and EC as well as the evolution of the nutrient elements NO_3^-, NH_4^+, PO_4^-, K^+, Ca^{2+} and Mg^{2+} in the nutrient solution, and
- the determination of the transpiration rate of the plants during different climate conditions.

This work was realized in the experimental farm of the University of Thessaly, in Velestino near Volos at the coastal area of Greece, from 2/2/2001 to 26/10/2001. In a 200 m^2 glasshouse, a rose crop was cultivated on perlite bags, placed on plastic gutters at the ground level. A closed hydroponic system was used for fertigation, consisting

of a 800 liters nutrient solution tank, a 3 m^3 h^{-1} irrigation pump, a drip irrigation pipe network, and a recycling pump used to bring the draining solution back to the main tank. Initial pH and conductivity were adjusted to 5.5 and 1.7 mS cm^{-1} respectively. The solution was supplied to the plants for two minutes every hour from 6:00 to 21:00 and its pH was measured (pH meter) and regulated continuously (with addition of HNO_3) close to 5.5. The solution was completely replaced about ten days after its preparation. The concentrations of the nutrient elements were measured colorimetrically, using a Palintest photometer 7000. Measurements were taken every two days starting immediately after the preparation of the nutrient solution.
In order to determine the water needs of the rose crop, measurements of greenhouse air temperature and vapour pressure deficit (D, kPa), incoming solar radiation (G, W m^{-2}), rose crop transpiration (TR, W m^{-2}) and LAI (m^2 leaves m^{-2} ground area) were carried out during winter and summer period.

In the second series of experiments, long- and short-term experiments were realized.

During the long-term experiments young rose cuttings of the ‘First Red’ cultivar were installed in water culture in a glass-covered greenhouse of 200 m^2. The plants were pruned one week after their installation. Immediately after pruning a nutrient element was excluded from the solution provided in 2/6 of the plants (Depletion during shoot initiation), while the other 4/6 of the plants served as control with excessive nutrient concentrations. In 1/2 of the depleted plants (1/6 of the total plants) and 1/2 of the control plants (2/6 of the total) only one secondary shoot was left to develop (without competition) while on the other half of the depleted plants and of the control plants, all secondary shoots were left to grow simultaneously (with competition).
The time from cutting to shoot appearance, the dry weight increase and nutrient composition of the roots and the wood measured and climate variables were monitored. Shoot appearance corresponded to the time that the vegetative bud broke and the first leaves appeared. The nutrient content of the shoot buds was measured at shoot appearance.
In order to determine the effect of nutrients on shoot growth after shoot appearance, at shoot appearance nutrient depletion was applied to half of the control plants with and without competition (1/6 of the total). During this period leaf appearance rate (daily measurements), leaf area increase and root, wood, young shoot, leaf and flower, dry matter and nutrient contents were measured, until commercial maturation of the shoot (separation of at least two sepals). The tissue of the different organs (roots, shoots, leaves and flowers) from 504 control plants (supplied with commercial nutrient solution) was analyzed for the concentration of nutrients in order to determine the nutrient requirements for each plant organ in each developmental stage. Critical nutrient concentrations in plant tissues and in the nutrient solution were estimated for 10% reduction on plant growth. Under the same climatic conditions, tissue of the different organs (roots, shoots, leaves and flowers) from 1512 treated plants (after elimination in the nutrient solution each of the elements NO_3^-, NH_4^+, PO_4^-, SO_4^-, K^+, Ca^{2+} or Mg^{2+}) was analyzed in order to determine the critical nutrient concentrations for each plant organ in each developmental stage.

Seasonal repetitions allowed the study of the relationship between demanded concentrations and sum of temperatures and/or solar radiation. Given time and space shortages, effect of shoot charge (competition) on nutrient concentrations and growth was monitored only once. The duration of the long-term experiment was one year.

During the short-term experiments, young rose cuttings of the ‘Iceberg’ cultivar were installed in water culture in a glass-covered greenhouse of 200 m^2. The plants were pruned one week after their installation. Only one shoot per plant was left to develop.
Three repetitions (one for each season) of the experiments with elimination and recovery of nutrient elements NO_3^-, NH_4^+, PO_4^-, SO_4^-, K^+, Ca^{2+} or Mg^{2+} were completed in order to determine the time constant of the nutrient uptake. In these experiments, water uptake was measured and the tissues of the different organs (roots, shoots, leaves and flowers) from 2016 plants were analyzed. The time constant was estimated for 10% reduction of plant growth separately from the elimination of each nutrient. Critical concentrations of the elements in nutrient solution and tissue were affected by the growth rate and climatic conditions in the greenhouse.
The regulation of cation and anion uptake was measured daily in 15 repeated experiments (5 repetitions for each season). The uptake of cations and anions was correlated with water uptake (transpiration) and/or with climatic

conditions. Transpiration rate seemed to affect the Ca and Mg absorption strongly, since K, NH_4, and most of the anions were strongly affected by the climatic conditions (temperature and solar radiation).
The duration of the short-term experiments was 3 weeks and the experiments were repeated 3 times in order to study the influence of the different nutrient supply and climatic conditions.

In the third series of experiments, experiments were performed to yield data sets for the validation of the plant model. For this, equipment and plants were installed. Two different rose varieties, cv. Iceberg (204 rose plants in block 5) and cv. First Red (408 rose plants in blocks 1-4) were installed in the same greenhouse chamber. Two different irrigation rates, high rate = 0.2 mm per irrigation (corresponds to a total of 47 J/cm^2 for Rg_{out}) and low rate = 0.4 mm per irrigation (corresponds to a total of 94 J/cm^2 for Rg_{out}) were applied to the First Red plants, while only high irrigation rate was applied to Iceberg plants. Guard plants were placed at the side rows of the canopy. Grodan FL was used as substrate for this cultivation. All plants of the canopy were trained applying bending. Weekly measurements concerning plant growth were taken after bud appearance. After bending, blind, lower and upper shoots of each plant were marked. Number, length, leaf area as well as dry and fresh weights and inorganic nutrient concentrations of each part (leaf, stem, flower) of the harvested flowers (three harvests a week) were measured. Continuous measurements of the EC, temperature and humidity levels at different depths of the substrate were taken. In addition, during the experiment, climatic conditions (inside air temperature and humidity, and outside solar radiation) were recorded with a data-logger.

3.5 Water and nutrient demand sweet pepper

To determine the water and nutrient demand of sweet pepper plants, three types of experiments were performed:

1. Short-term experiments: Nutrient depletion (every 2 days, up to 14 days) and recovery (6 days after the starvation period) of N, P, K and Ca were studied (location: Madrid).
2. Long-term experiments: Water and nutrient demand were studied in spring and autumn growing seasons (location: Madrid). A complete change of the nutrient solution took place every three weeks and water was added regularly to replace losses from transpiration. Water used during plant growth was determined by measuring its volume added to the pots. Six plants (replicates) were harvested 0, 3, 6, 9, 12 and 15 weeks after transplanting.
3. Validation experiment: Water and nutrient demand related to plant density and irrigation frequency were studied in a commercial greenhouse (location: Murcia).

Plant growth conditions

The plant material used was sweet pepper (*Capsicum annuum* L.) cv. Ziggy (Lamuyo type) in experiments 1 and 2, and cv. Requena (California type) in experiment 3. Seedlings were transplanted to pure hydroponic cultivation (Experiments 1 and 2) or to rockwool slabs (Expert, Grodan; experiment 3). In all cases the nutrient solution used was a modification of the solution described by Hoagland (1951). Glasshouses were equipped with outside and inside climatic sensors of temperature, relative humidity and global radiation and inside PAR and CO_2 concentration. Climatic values were recorded hourly and stored in a Data Logger (DL2e Delta-T Devices Ltd.). An adequate temperature range was kept (20-30 °C) by air warming and cooling when necessary. Relative humidity was 60-80%, and CO_2 concentration ranged between 350-400 ppm. The solution pH was adjusted to 6. A randomized block design was used in experiments 1 and 2, whereas a systematic block design was used in experiment 3.

Growth and chemical analysis

Immediately before the beginning of the experiments, six plants were sampled to determine the initial biomass. In each sampling period, plants were divided into leaves, stems (including petioles), roots and fruits before weighing. Leaf area (LA) was measured by scanning all leaves and then area was integrated by using analysis software (Foliarea Program and LICOR area meter). All parts of the plant were then oven-dried at 70 °C for 48 h and weighed separately for dry mass and growth parameter determinations. Samples were ground and stored for subsequent chemical analyses. Ground plant material (100 mg) was wet-combusted in concentrated H_2SO_4 (96-98%) and

500 mg of a mixture of metal Se (2 g) and Li_2SO_4 as catalyst. The concentrations of N and P in plant material were colorimetrically determined by flow injection analysis (Lachat 800) and K, Ca and Mg concentrations by atomic absorption spectroscopy (Perkin-Elmer 4000).

Statistical analysis

Analysis of variance (ANOVA) was performed on all data sets. Means were separated by a test for the least significant difference (LSD) with a probability of 0.05 (Bender *et al.*, 1989). Linear regression and correlation analysis were also performed. Levels of significance are represented by * at $P < 0.05$; ** at $P < 0.01$; *** at $P < 0.001$ and ns: not significant. The statistical analyses were carried out using the SPSS PC 11.5 package.

3.6 Plant/substrate model

Dynamic mechanistic models for sweet pepper and rose were developed. The development of a model that predicts crop growth and demand and uptake of water and the individual nutrients followed a number of steps:

- Existing simulation modules were used for the simulation of dry matter production and transpiration.
- Prototype modules for the simulation of nutrient and water relations of the plant were developed on the basis of existing data and literature information.
- Modules that enable self-learning by utilization of historical data sets and feed-back information from sensors were developed.
- Existing and new modules were integrated into a plant model.
- A sensitivity analysis was performed.
- The plant model was complemented by a water uptake module.
- The effects of water and nutrient shortage on crop growth were introduced.
- The sweet pepper model was validated against experiments that were conducted in 2003 in Carquefou, France, and in Murcia, Spain. The rose model was validated against experiments that were conducted in 2003 in Aalsmeer, The Netherlands.

3.7 Substrate characterization and models

Water and mineral movements within the slab: characterization and modelling

Water movement in a porous medium satisfies the conservation equation of matter and for an incompressible fluid in a rigid porous media. The combination of this equation and Darcy's equation is described by the classical Richard's equation for a porous unsaturated medium. This formulation accounts for the aptitude of the porous medium to release or to store water under the effect of a pressure gradient. Solving this equation requires determination of the system boundary conditions, its initial conditions together with the values of the substrate hydraulic properties: hydraulic conductivity (K), differential water capacity (C) and sinks terms (S) representing water and mineral absorption by roots. These various parameters were experimentally characterized, then determined for roses and sweet pepper crops for two rockwool slab types: Expert ® and Floriculture ® manufactured by Grodan.
Special attention was paid by Brun *et al.* (2004) to the characterization of the distribution of water in rockwool slabs, by Bougoul and Boulard (2004) to the characterization of the hydraulic properties of the slabs and by Longuenesse and Brun (2004) to the distribution of root density and root activity within the slabs. Knowing these various substrate-plant parameters, the Richard's equation giving the water movement was solved (see boundary and initial conditions of the growing medium in Figure 3.7.1 and the results compared with the results of the experimental characterization.

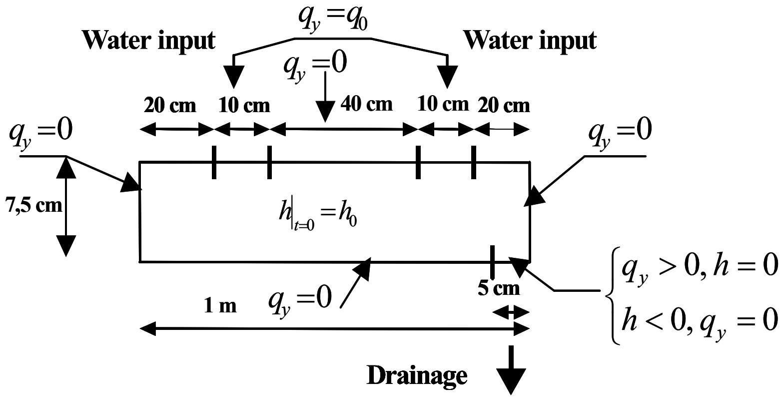


Figure 3.7.1. Geometry of the growing media and boundary conditions.

Characterization of the hydraulic properties

Humidity variation inside the substrate was deduced from the resolution of the Richard's equation with appropriate values of the hydraulic properties (suction (*h),* hydraulic conductivity (*K*), differential water capacity (*C*)), particularly with respect to its volumetric water content (θ). Conductivity versus suction for both steady state and transient regimes in evaporation and humidification were experimentally determined for Floriculture® and Expert® slab (Figure 3.7.2). Different results were experimentally determined for different regimes corresponding to various ranges of suction (Bougoul *et al.*, 2005). Water retention characteristics $\theta(h)$ in sorption and drying were also experimentally determined for the Expert® and Floriculture® types of rockwool slabs (Bougoul *et al.*, 2005) and the differential water capacity was deduced from the characteristic curve of water retention.

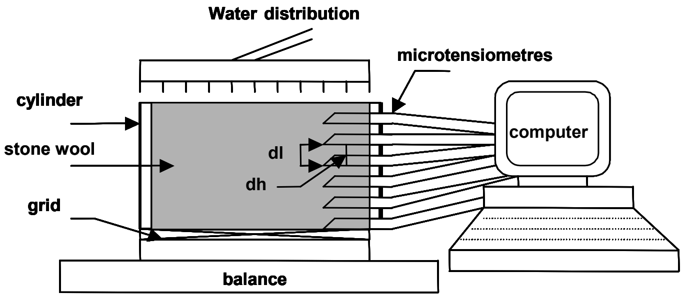


Figure 3.7.2. Schematic representation used for the determination of hydraulic conductivity in infiltration non stationary mode).

Characterization of the distribution of water in rockwool slabs and root activity

Two experiments, one with a rose crop *(Rosa hybrida* 'Pretty woman' Meilland) located at INRA - Sophia Antipolis and one with a sweet pepper crop *(Capsicum annum* 'Twingo' F1) located at INRA - Avignon were realized in 250 m^2 glasshouses. Four similar experimental treatments, combining two irrigation frequencies, a low irrigation frequency (noted LF) and a high irrigation frequency (noted HF), the nutrient solution was given to plants for every 0.4 mm (LF) or 0.2 mm (HF) of potential transpiration estimated by the global radiation received by the crops and two rockwool slab types, Grodan's product for flowers FLORICULTURE® a high-density rockwool with fibres horizontally oriented (noted FL) and Grodan's product for vegetables EXPERT® a low-density rockwool with fibres vertically oriented (noted EX), were applied at these two locations.

The daily solution amount received was the same for the two frequencies. A daily drainage ratio of more or less 40% of this quantity was maintained, the drainage was recirculated. Each rockwool slab (100 x 15 x 7.5 cm L x l x h) received six plants and six drippers for rose crop and two plants and two drippers for pepper crop.

Characterization of the distribution of water in rockwool slabs

Non-destructive measurements of water content (WC) were realized using Grodan® water content meter device (De Groot, 1993, 1995) on one half of a whole rockwool slab divided into 40 (pepper) or 24 (rose) parts during several days (Figures 3.7.3 and 3.7.4). The sensor carries out digital measurement of instantaneous water content (% v/v), electro-conductivity (mS cm^{-1}) and temperature (°C). WC was measured at several dates on four slabs one for each treatment and at different times of the day (5 or 6 measurements between 8:00, before the first irrigation, and 20:00, after the last irrigation).

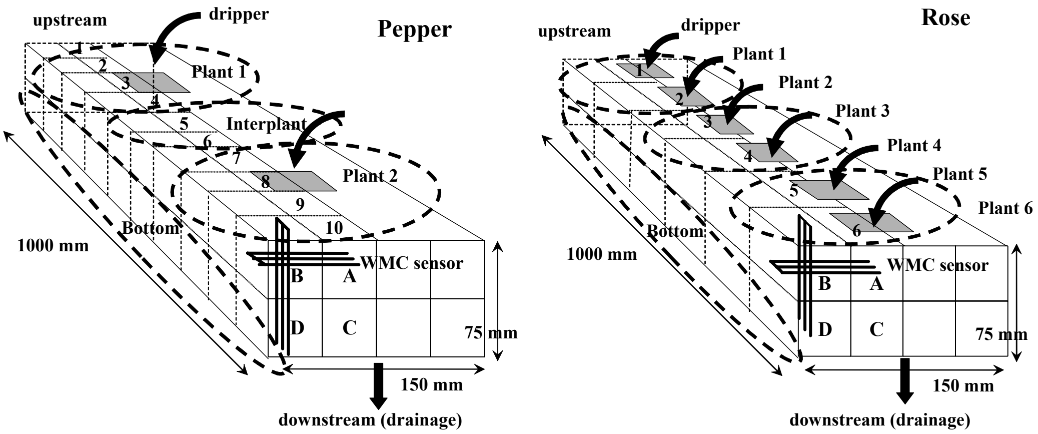


Figure 3.7.3. Experimental design for water content measurement in the case of pepper (left) 40 points of measurement A1, B1, C1, D1... A10, B10, C10, D10 and rose (right) 24 points of measurement A1, B1, C1, D1... A6, B6, C6, D6. To obtain a visual representation of the WC repartition in the slab (Figure 4), values measured were combined in four groups:

- *For pepper: plant 1 = mean of parts 2, 3 and 4 of the upper part of the slab, interplant = mean of parts 5 and 6 of the upper part of the slab, plant 2 = mean of parts 7, 8 and 9 of the upper part of the slab, bottom = mean of parts 2 to 9 of the lower part of the slab.*
- *For rose: plant 1-2 = mean of parts 1 and 2 of the upper part of the slab, plant 3-4 = mean of parts 3 and 4 of the upper part of the slab, plant 5-6 = mean of parts 5 and 6 of the upper part of the slab, bottom = mean of parts 1 to 6 of the lower part of the slab.*

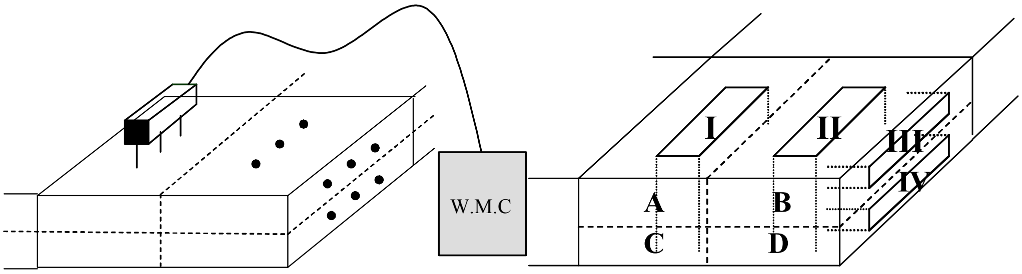


Figure 3.7.4. Positioning of the WCM sensor (left) and calculation realized for the different measured parts of the slab.
For each part of the slab (parallelepiped 1 I, 1 II, 1 III, 1 IV, 2 I, 2 II...) WCM sensor measures mean water content in a volume of about 7.5 x 7.5 x 7.5 cm. To obtain the WC on parts A, B, C and D we have solved these equations: x = (I + III) / 2, y = (II + III) / 2, z = (I + IV) / 2 and t = (II + IV) / 2. To validate these recombinations we have compared the I, II, III and IV values measured to the x, y, z and t values calculated using the equations I = (x + z) / 2 ; II = (y + t) / 2 ; III = (x + y) / 2 ; IV = (z + t) / 2. We applied iterations by adding a corrective term equal to the difference between the calculated and measured values to x, y, z and t until the difference between the calculated and measured values was less than 1%.

Characterization and modelling of root activity within the slabs

Root distribution in rockwool slabs

At several dates during crop growth, one slab from each treatment was sampled and cut up in two parts along its main axis. One half was discarded, assuming that root distribution is symmetrical; the other half was further cut up into 40 parts (sweet pepper) or 24 parts (rose). The parts were then placed in phosphoric acid (1 mol/L) for 30 minutes to dissolve the rockwool and then rinsed under flowing water over a sieve to collect the roots. Excess water was then carefully blotted out and the fresh weight of the roots was measured.

Water tension in the slab and root absorption

In a second experiment, we used an experimental system kindly provided by GRODAN Company. Propagation cubes with young sweet pepper plants, or slab parts with whole rose plants from experiment 1, were placed over a capillary mat on a tray placed over a tank (50 x 30 x 20 cm L x l x h) filled with nutrient solution. The mat overlaps the sides of the tray and dips in the solution to the bottom of the tank. By adjusting the level of the solution, and thus the height between its surface and the tray, water tensions from -6 cm (whole substrate submerged in solution) to 15 cm were applied to the base of the substrate. After two to three days of equilibration, the plants' water uptake was then evaluated during three days by measuring the amount of solution needed to maintain the level in the tank.

Solving numerically the Richards' equation in 3 dimensions

Richards' equation is a non-linear equation, solving of which requires the use of a numerical method. It was implicitly solved using commercial Computer Dynamics software: CFD 2000® (1999), based on a control volume method which can solve in 3 D convection–diffusion equations with convection, diffusion and source terms. However, for water movements described by a variable of suction, h (cm), deep modifications of the Richards' equation are needed to match with the convection diffusion equation solved by the CFD software. When compared to the classical convection diffusion equation solved by the CFD, we have been obliged i) to modify the solving algorithm (customization of the source programme of the software) by setting the convective term to zero, ii) to rewrite the non stationary, diffusion and source terms (Bougoul *et al.*, 2005), and iii) to solve the equation on the domain described in Figure 3.7.1 with the hydraulic properties and sink term characteristics deduced from the characterization phase.

3.8 Improved substrate

The goal of this part of the CLOSYS project was to develop a substrate with improved physical/chemical properties to allow better control of water and nutrient fluxes in the root zone or in other words: better controllable substrate properties, fitting in a closed system, adapted to the specific demands of that system. The method used to realize this goal was mainly based on the fact that extensive research was performed at substrate characterization and modelling of the substrate properties (see paragraph 3.7).

The method of the hydraulic conductivity was discussed between the partners Grodan and INRA. At both labs the method was performed and compared, the test prescriptions were compared, literature was taken into account and it was that there were some very strange results reported in the literature which could not be confirmed by the results of the methods used both at Grodan and INRA. In the end, INRA and Grodan concluded that their own figures were correct and could be used as input parameters for the simulation models and product property characterization.

Regarding the water retention by measuring the pF-curve of the substrates a strange unknown phenomenon, i.e. a non-closed pF-curve, was noticed. Although certain indications for the cause of this exist, the exact cause is not fully understood and needs further research. In the mean time we proceeded with understanding more of the relevant product properties.

3.9 Substrate sensor

To develop a working ion-selective, pH independent, sensor for Na^+ with on-line measurement capability, the following steps were undertaken:

- A literature survey on pH-independent ionophores for measurement of Na^+ was performed.
- From the possible fit ionophores, membranes were produced and implemented in sensors for further testing.
- The independence of pH was tested.
- Durability tests were performed with the selected ionophores in different membrane matrix compositions.
- Finally, complete pH-independent Na^+ sensors were implemented in the Hydrion-line multi-sensor probe.
- In greenhouses in the Netherlands and in France, tests with the multi-ion sensor were executed.

Furthermore, a working ion-selective sensor for Mg^{++} with on-line measurement capability was developed. After literature research, 6 commercially available Mg ionophores were chosen to be further investigated in practice. Interference and sensitivity for Ca^{++} ions is the main problem to overcome for the implementation of Mg^{++} sensitive membranes and sensors in the Hydrion-10 sensor unit. Especially the ratio of appearance of Ca and Mg in greenhouse environments enhances this problem. By changing the amount and types of anionic sites in the membranes and using different types of membrane materials, attempts were made to increase the selectivity for Mg^{++}. Furthermore, attention was paid to the life span and durability of the sensors.

Steps in the development of a Mg^{++} selective sensor were:

- Testing of the 6 different ionophores.
- Possible additions and changes in the anionic sites and the composition of the membrane matrix to improve selectivity for Mg^{++}.
- Testing of PVC en polysiloxan membranes.
- Testing of different plasticizers.
- If possibel implementation of ionophores in ceramic membrane matrix instead of plastic matrix

3.10 Expert system

The problem is to automatically generate a fertigation strategy to optimize crop production, in quantity and in quality. A fertigation strategy is considered as a set of slab states to which the crop responds. The optimization will use the information about crop state and about crop behaviour, as given by a 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. Because of the complexity of the model, of the numerous interactions and also to take into account the uncertainty of the weather forecasts, direct inversion of the model to find the best controls has not been considered. A simulation-based method seems much more appropriate and a machine learning algorithm has been chosen.

The problem can be seen as an MDP, a Markov Decision Process (Bellman, 1957). An MDP is defined by the property of *independence of path* which states that all that is needed to determine the next system state are the current state and action taken (plus a forecast of the environment in case of a system also driven by external disturbances). In other words, no matter by which path the system has arrived at its current state, the current state contains all the necessary information to determine the next evolution. Reinforcement learning uses this property and the Bellman principle (Bellman, 1957) to solve an optimization problem under uncertain environment. The Bellman principle states that *at any intermediate state* x_i *in an optimal path from* x_0 *to* x_f, *the policy from* x_i *to goal* x_f *must itself constitute optimal policy.* This principle allows determining from the best final state *backwards on* the path coming from the initial (or current) state. The decision problem is then defined as a *sequential* decision problem, the system evolving step by step under the influence of the decision taken at each step and under the influence of uncontrolled disturbances varying from step to step. Formally, a reward can be associated to each step, measuring the profit resulting from the association of the current state and the decision taken. The final state can also be associated to a reward measuring the value of this final state. The Markov property also states that these rewards are additive, i.e, the final reward is also the sum of all rewards accumulated along the path followed by the system.

The fertigation problem fulfils the Markov property, the current crop and slab states contain enough information to determine the dynamics of the system from this point on. This property, which is the base of the optimization method chosen, is also a computational asset. The current crop state, as defined by the model of the system, cannot be fully determined by measurements and has to be estimated using the model itself by running it from the last-measured state which is generally the state of the crop at plantation. Therefore to estimate the current crop state, a full run of the model from plantation to the current day is necessary. Because of the Markov property, this run is only needed once per day; the number of runs necessary to determine the best fertigation strategy over the next coming days however, is large. All that is needed is a mechanism to store and reload the current state so that the model can be started again from this stored state.

The optimization problem can be stated as follows. We want to find the combination of slab states (relative humidity and electrical conductivity) for the next days so that the response of the crop to these conditions, under the forecasted weather, fulfils (maximizes) a given goal. Although the basic time step of the model is hourly (because of the nonlinear response of the crop to temperature and PAR), the computation of the crop response to slab humidity and slab EC is only done at a daily time-step. Therefore the decisions about the slab states will also be made at a daily time step and the slab states will represent daily average values. Varying the slab states during the day, according to the evolution of the solar radiation or of the temperature cannot be determined without a more detailed coupled crop–substrate model. The problem is then to find daily slab relative humidity and electrical conductivity that will elicit the appropriate response from the crop.

A criterion must be defined to measure this crop performance. Growers do not have one single measurement of the crop performance but use several indicators which may have varying relative importance. Of course the total harvest, measured by weight, is a paramount factor because the harvest is paid proportionally to its weight. But the quality of the harvest also comes into play, through different aspects like size (in the case of fruits or vegetables) or visual aspect or sanitary state. In the case at hand, the production of green pepper, the absence of BER, Blossom End Rot, is an important quality indicator. This sanitary and visual quality indicator has been retained, with harvest weight, as a measure of crop performance. The total water transpired by the crop has also been retained as a third element in the assessment of the performance of the crop because insuring a high water flow through the plant has been shown to be a key element in a proper nutrient transport in the plant and is often associated with a vigorous crop able to withstand short stresses. As mentioned above, these elements may have varying relative importance in time. Moreover, they are not comparable in the sense that they are expressed in different units. To define a single performance index the following approach has been defined. A reference fertigation strategy is defined. This strategy is fed to the crop model which gives its estimation of the crop harvest (H_r), fraction of BER in the harvest

(BER_r) and crop transpiration (E_r). Any candidate fertigation f strategy will be evaluated against this reference: the candidate f is also fed to the crop model which gives the associated estimation of crop harvest (H_f), fraction of BER (BER_f) and crop transpiration (E_f). Each of these elements is compared to the reference value and the performance index J is built as the weighted sum of these ratios:

$$J = \frac{1}{\alpha_E + \alpha_H + \alpha_{BER}} \left[\alpha_E \frac{E_f}{E_r} + \alpha_H \frac{H_f}{H_r} + \alpha_{BER} \frac{1 - BER_f}{1 - BER_r} \right]$$

The coefficients $\alpha_{E,H,BER}$ allow the user to change the relative importance of each of the elements in the criterion. It must also be noted that while the optimization goal is to maximize crop transpiration and crop harvest, it is to *minimize* the fraction of BER in the harvest. Hence the criterion does not use the fraction of BER but the fraction of healthy fruits (1-*BER*) as a value to maximize. Any strategy that yields a J bigger than one performs better than the reference strategy. If all possible candidates yields one or less, then the best solution is the reference strategy (because the reference strategy is also a candidate strategy). Crop performance is measured at the end of the optimization horizon only. No local rewards are associated to the daily steps (null local rewards).

The horizon over which the optimization takes place is limited by the weather forecasts availability and reliability. In greenhouses, the only useful forecast is solar radiation, when the hypothesis can be made that the control devices have enough power to achieve the climate decided upon by the greenhouse manager. On the other hand, the horizon must be long enough to allow the outcome of the decision taken to be visible. If the crop responds with a long time lag or at a slow pace to the fertigation strategy, then a longer horizon is needed. In the case at hand, the maximum number of days available for weather forecasts is 5 and this has been chosen as the optimization horizon length.

Not all values of the slab relative humidity and electrical conductivity are possible at a given time. First, the user may impose lower and upper limits (U_{min}, U_{max}) for safety reasons. Second, the daily rate of change of these parameters (ΔU^+, ΔU^-) depends on the physical properties of the fertigation system and also on the climate because crop water and mineral uptake also depend on the climate. From the current state onwards, the range (Un – Ux) of slab relative humidity and electrical conductivity is built using this information, absolute limits and rates of change (see Figure 3.10.1):

$$Ux_{j+1} = \min\left(U_j + \Delta U^+, U_{\max}\right) \quad \text{and} \quad Un_{j+1} = \max\left(U_j - \Delta U^-, U_{\min}\right)$$

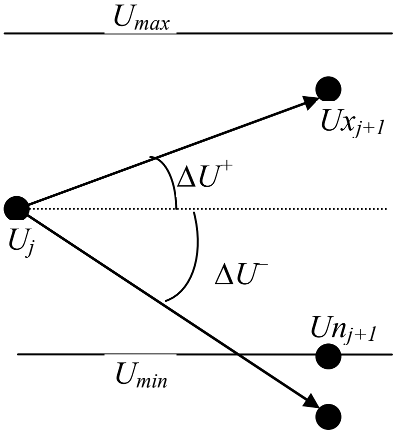


Figure 3.10.1. Range of possible slab states as a function of maximum change rates and absolute limits.

Over the complete optimization horizon, daily ranges are built using this simple algorithm. Because of the digital nature of the controllers installed in the greenhouse and because of the limitations of the sensors measuring the slab relative humidity and electrical conductivity, it has been chosen to consider these variables as discrete rather than continuous (although they are continuous in nature). Daily grids of relative humidity and electrical conductivity are built which give all the possible slab states. Because these grids are built from the range of possible values, they cover all possible fertigation strategies that can be designed from the current slab state.

Using these grids, all possible fertigation strategies are evaluated and measured against the reference strategy. After doing so, it is possible to choose the strategy that yields the highest performance criterion. Such an exhaustive approach has been used because the computational cost of determining the gains or rewards associated to all possible strategies is not very high. Moreover, the expert system runs only once a day and there is a lag of a few hours between the last weather forecast update and the next morning when the greenhouse manager can review the proposed solution before putting it into action.

Because of the stochastic nature of weather forecasts and because updates are available daily, a receding horizon scheme has been adopted. The expert system is run daily with the most recent weather forecasts and crop state estimation. It provides a solution for the next 5 days, but only the first day is applied and a new run is made the next day with updated values. This ensures that the system always takes advantage of the available knowledge rather than ignoring some recent measurements.

The expert system works along three steps. First, a run of the crop model is made on historical climate and fertigation data to evaluate the current crop state. From this point a reference run is made over the optimization horizon using forecasts of global radiation, the greenhouse set-points for the temperatures, and the reference irrigation strategy. Third, the optimal strategy is searched using a method derived from the forward dynamic programming one. A strategy is composed by a set of daily mean slab humidity and mean slab ECs.

The algorithm works as follows. First, for each day in the optimization horizon, the limits of feasible slab humidity and EC are determined. The user indicates the maximum changes in these variables that his system can achieve (or the maximum changes he agrees to). Different values for humidification, drying, salinity increase or decrease can be given. Maximum and minimum allowable values for these variables are also used, according to the user indication (the user may, e.g., set a low limit for slab humidity of 50% although the rates of change would allow a lower value). For each day the intervals of possible slab humidity and slab EC are discretized. This yields a grid of daily slab humidity and EC. The second main step is to compute the cost-to-go for all strategies that can be elected within these grids. The cost-to-go is the change in the criterion from day d to day d+1. At this point it is considered that the forecasts are reliable because the computational burden of exploring variations around the available forecasts is too heavy. At the end of this cumbersome task, which requires several model runs, a set of final crop states and associated criterion values is available. The final step is to select the crop state with the highest criterion value and to determine the path that leads to it while minimizing the cost of reaching this point.

The expert system then runs the model a final time with the selected strategy to also produce the individual nutrient uptake of the crop. From this information, the ion balance of the solution is computed and the expert system then calculates, for each day of the optimization horizon, mean slab humidity and EC, and solution composition.

3.11 Real Time Controller

The methodology developed for this study is generic. Two fundamental steps were considered:

- model simulation, and
- command rules.

Model

To be able to command a process, we need a model that can predict its dynamic behaviour. This prediction is needed around a steady state in order to know how to act on control variables. Therefore, we do not need a complex non-linear mathematical model, and use classical transfer functions applied to numerical signals. However, the choice of the 'good' inputs and outputs is crucial.

We have chosen a classical representation in transfer function by means of the z transform (z^{-1} is a delay operator and is depending on sampling time Ts) for sampled signals.

If we suppose that we have a process with p inputs and m outputs, each output y_k is given as a function of every input u_i by the following generic expression:

$$y_k = \frac{\sum_{i=1}^{p} \left(z^{-rki} \sum_{j=1}^{nnki} b_{kij}\, z^{-j}\, u_i\right)}{\left(1 + \sum_{j=1}^{ndk} a_{kj}\, z^{-j}\right)} \qquad \left\{ \begin{array}{l} k = 1 \text{ to } m \\ i = 1 \text{ to } p \end{array} \right.$$

nd_k = degree of denominator of the output k
nn_{ki} = degree of numerator of output k and input i
r_{ki} = delay between input i and output k (in sampling time Ts units)

The complete model will be defined by the determination of the coefficients a_{kj} and b_{kij}. They are identified using the minimization of the quadratic error criteria (non-linear) between the predicted and measured outputs. In addition, choosing $nd_k = nn_{ki} = 1$ is generally sufficient. Every delay is set equal to zero, except the delay between the input solution Vi and the drainage (see Annex I for definitions) which can be taken between 0 and 12 (always in Ts units). The adopted configuration is described in Figure 3.11.1.

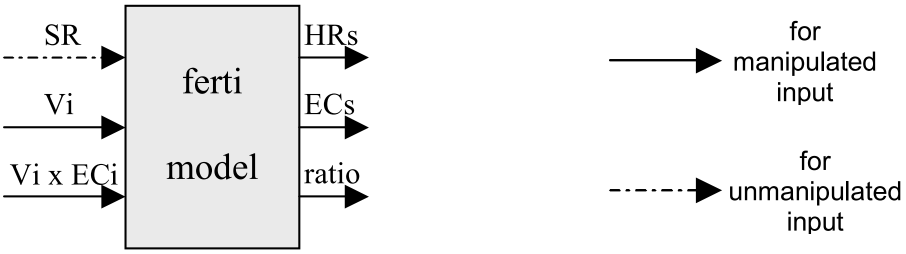


Figure 3.11.1. Model structure (choice of inputs and outputs).

This model structure (inputs and outputs choice) has been determined from process analysis and from mathematical model structure. Model parameters have been obtained from an identification procedure, based on the output error method implemented in MATLAB: experimental data from process operation during several weeks have been used to compute the model after a suited pre-treatment. The three graphs from Figure 2 show simulated (results of identification) and measured data during one month for the three output parameters . It can be noticed that the very satisfactory identification results validate the chosen approach based on a MIMO ARX model.

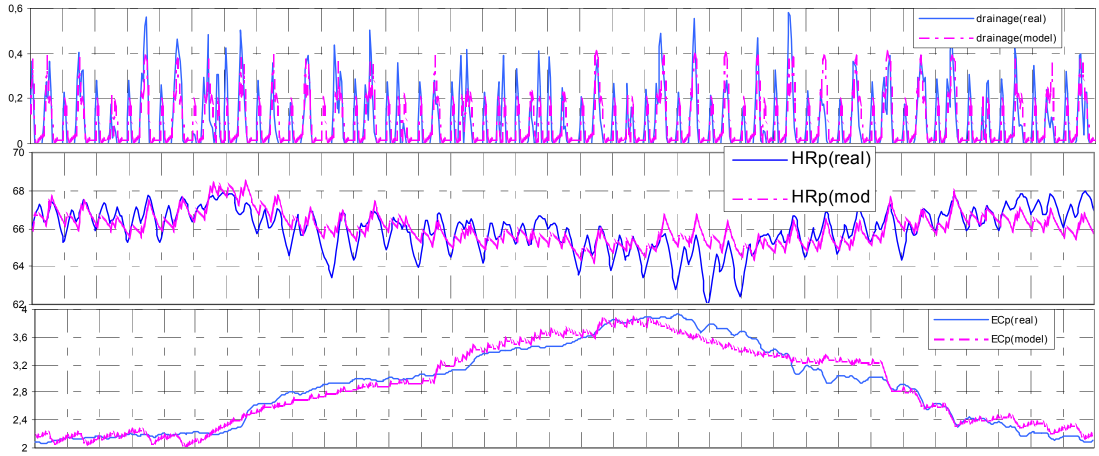


Figure 3.11.2. Identification results (fertigation control).

Predictive commands

To find command rules, predictive commands are used. This methodology has many advantages, especially:

- efficiency for process with delays,
- ability to take into account set-point variations,
- robustness (available responses with noise on signals).

Predictive commands require a model, and are based on the following principles. At a given time t, inputs and outputs (measures) of the process are known and, if a future command strategy U_1 is applied, the future outputs Y_1 can be predicted through the model, and so on for U_2.

The strategy which minimizes a given criterion ρ will be selected.
This criterion can relate to:

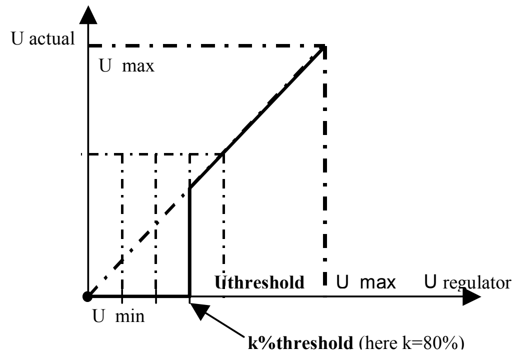
- the output errors (differences between set-points and measures),
- the cost of the generated commands,
- the relative variations of the commands (to minimize sudden variations of the actuators).

Each of the terms in the criterion can be weighted by a coefficient the value of which depends on the importance of the related term.
The quadratic form selected in this study is as follows:

$$\boxed{\rho = \underbrace{\Sigma_i \, \boldsymbol{\lambda_i} \, [\Sigma_j (y_j\text{-}SP_j)^2]}_{\text{‘performances’}} + \underbrace{\Sigma_i \, \boldsymbol{\nu_i} \, [\, \Sigma_j \, \Delta u_j^2 \,]}_{\text{command variations}} + \underbrace{\Sigma_i \, \boldsymbol{\mu_i} \, [\, \Sigma_j \, u_j^2 \,]}_{\text{command ‘costs’}}}$$

Constraints on the actuators

Some actuators do not allow low command levels, indeed it is the case for the supply solution volume in fertigation. It is then necessary to determine a minimum threshold value under which no command will be sent. Thus, the level determined by the regulator is not the same as the level sent to the actuator, and the relation between the command given by the regulator and the actual command is as mentioned in Figure 3.11.3.



$$\text{For} \begin{cases} U_{threshold} < U_{reg} & \Rightarrow U_{actual} = U_{reg} \\ \frac{kthreshold}{100} * U_{threshold} < U_{reg} < U_{threshold} & \Rightarrow U_{actual} = U_{threshold} \\ U_{reg} < \frac{kthreshold}{100} * U_{threshold} & \Rightarrow U_{actual} = U_{min} \end{cases}$$

Figure 3.11.3. Relation between real command and regulator value.

The complete list of the used parameters is shown in the following table.

Symbols	Size	Regards	Depends on
λi	{m,1}	performances weighting	user's choice
μ_j	{p,1}	costs weighting	user's choice
Umin Umax	{p,1}	absolute command values	process
Uthreshold	{p,1}	threshold values for commands	user's choice
Kthreshold	{p,1}	min threshold coefficient	user's choice
H_{deb} H_{fin}	2	daily watering starting hour and closing hour	user's choice

Fertigation control experiment

This experiment took place in 2004 at the CTIFL research station in Carquefou, France, in two 4.20 m high heated glasshouses (250 m^2) with both roof side vents. In 2003 we used the cultivar 'Triple 4' (Enza Zaden), sown on October 31th 2002, planted on December 17th 2002 with Grodan FL rockwool slabs, and harvested once a week from March 5th 2003. In 2004, we also used the cultivar 'Triple 4' (Enza Zaden), sown on October 31th 2003, planted on December 17th 2003 with Grodan Master rockwool slabs, and harvested once a week from March 3rd 2004. As a cultural system we used 2 stem-plants, with a plant density of 3.125 plant/m^2 and integrated pest management. The average inside temperature set-point was about 20°C and the average inside measured temperature about 21°C. Roof sprinkling was used in order to optimize greenhouse climate. We managed 2 different irrigation/drainage valves by controlling both supply/drainage volumes and electro conductivity of the nutrient solution. Drainage was recycled without disinfection. We also controlled substrate relative humidity and electro conductivity within the substrate with 3 different Grodan sensors.

3.12 Technical infrastructure

The objective for the technical infrastructure is to integrate all developed subsystems into one complete functional system. The system should be modular to allow for a flexible choice of which subsystems to include and which ones not to include based on the requirements of a specific grower. For easy use during the final field test, it was also required that the different subsystems could be easily accessed by the developers of each subsystem, so that fine tuning and maintenance could easily be carried out during the final field test.

In order to fit all these requirements, it was decided to extend the functionality of the present Multima process control hardware platform and the PC-based Synopta SCADA package, two products which are commercially used for greenhouse control at the moment.

Three specific links needed to be made between the HortiMaX process control equipment and submodules:

- Water contents and EC data from Grodan water content measurement devices needed to be included in the historical data database, because the Real Time Controller needed these data to be able to exert control over the water content In the substrate slab.
- The expert system needed weather forecast data and measured historical greenhouse data in order to be able to predict new set-points and to evaluate the performance of the plants over the past hours.
- The Real Time Controller needed data regarding the slab water contents and slab EC, and calculated new irrigation set-points, irrigation EC's and irrigation start times. This is the only submodule which not only needed data from the central Synopta database, but also needed to be able to actually send control actions back into the HortiMaX system.

It was decided to make it possible to connect the water content measurement devices from Grodan directly to the Multima process computer. The main reason for this was twofold:

- the data were available in an analogous format and the Multima process computer was already well-equipped to register analogous data;
- the data were measured continually and needed to be stored continually too.

For the interfaces between the expert system and the real time controller with the HortiMaX process computers it was decided to put all submodules on different PC's, but to include them all in the same network. In this way the central control loop for irrigation will be operated by the Multima/Synopta without being influenced by any disturbances of bugs in the software of the submodules. Also since all the computers are kept in the same network they can communicate with each other via a special interface programme, for this purpose written by HortiMaX.

3.13 Closed system

In the last year of the CLOSYS project, all subsystems developed were integrated into a CLOsed SYStem, installed at the CTIFL, Carquefou, France. A comparison will be made between sweet pepper plants grown in the CLOSYS system and plants grown in a system which is now commercial practice in sweet pepper growing. The CLOSYS system gradually built up from the following submodules:

- Improved substrate (December 2003)
- Real time controller (May 2004)
- Ion-selective sensor (May 2004)
- Expert system (June 2004)

The real time controller, ion-selective sensor and expert system needed testing and optimization before they contributed fully to the closed system. Therefore the CLOSYS system was fully implemented in July 2004.

On 17 December 2003 sweet pepper plants (variety Triple 4) were planted in 2 glasshouse compartments at CTIFL, Carquefou, France in order:

- to compare the CLOSYS system and the standard system in 4 blocks,
- to run and calibrate both plant and substrate models (prediction of plant growth and development, plant water/nutrient demand and consumption) integrated in the expert system, including reflectance and fluorescence sensors,
- to make identification of the real time controller (RTC) and to run and validate the RTC,
- to evaluate multi-ion sensor unit.

From December 2003 to May 2004, the CLOSYS system was identical to the standard system except for the type of substrate. The sweet pepper plants in the CLOSYS system were planted on Master Grotop substrate (Grodan), whereas in the standard system the substrate was Master Classique (Grodan). From May, in the standard treatment, the standard fertigation strategy was used, whereas in the CLOSYS system the integrated system fertigation was used. In both systems, nutrient solution was recycled without disinfection. The sweet pepper plants were grown in an integrated pest management system with two stems per plant, leading to a stem density of 6.35 stems m^{-2}. Fruits were harvested from 3 March until 13 October 2004.

During the experiment, the following measurements were performed:

- Climate (global radiation, air and pipe temperature, hygrometry, CO_2 concentration).
- Irrigation, drainage and substrate (EC, humidity and temperature).
- Non-destructive measurements (number of nodes and fruit load) of the plants.
- Destructive measurements (LAI, fresh weight, dry weight, dry matter content, nutrient concentrations in the different plant organs) of the plants.
- Fruit quality (% of class I /II, % of BER/fissures) and yield (number of fruit m^{-2}, total weight m^{-2}).
- Slab humidity, conductivity and temperature by 6 WCM sensors (Grodan; 3 per treatment),.
- LAI; reflectance by 1 Cropscan sensor.
- Hydric and mineral stresses by the CFM sensor (fluorescence).
- Mineral composition of irrigation and drainage water by the multi-ion sensor (2 automatic measurements for irrigation, 2 for drainage, 1 manual input for different water quality measurements).

4. Results

4.1 Fluorescence imaging sensor

Parameters for stress detection

The imaging parameters that are most suited for stress detection have now been specified as follows:

- Fluorescence ratio F440/F740 (blue fluorescence divided by the far-red fluorescence).
- Fluorescence ratio F690/F740 (red fluorescence divided by the far-red fluorescence).
- Excitation ratio ChlF-UV/ChlF-Blue (chlorophyll fluorescence excited with UV divided by the chlorophyll fluorescence excited by blue light).
- Reflectance ratio R550/R800 (reflectance in the green divided by the reflectance in the far red).
- Reflectance at 460 nm.

These parameters have repeatedly been applied for detection of nutrient stress (in particular nitrogen deficiency). However, for the detection of water deficiency (water stress) these parameters showed a significant effect only rather late, i.e. when the symptoms could also be detected by the eye.

Stress effects

Under conditions of nitrogen depletion, visible symptoms in sweet pepper occur after approximately 8 days. Approximately 2 days earlier, photosynthesis rates of the nitrogen-depleted plants were found to decrease. Fluorescence measurements on the nitrogen-depleted plants were done with all 3 fluorescence sensors described in this report. Both with the sensor of the University of Karlsruhe and the CFM meter (University of Budapest) higher blue/red (F440/F690) and blue/far-red (F440/F740) ratios compared to the control treatment were detected after 6 and 3 days, respectively. The other fluorescence ratios did not change due to the nitrogen depletion. These findings are largely in accordance with the table above.

Under drought stress, the decrease of water content alone does not lead to a change of the fluorescence signatures. This could be clearly shown by the experiments with the rapid water loss by detaching the leaves from the plants. Fluorescence signatures seem to change only when the plant adapts within days to the drought stress by impairing the photosynthetic apparatus and changing the quantity of blue and green fluorophores. Our experiments do not reveal clearly which parameters could be used for drought stress detection. Results between treatments were not unequivocal, especially for rose and to a lesser extent for sweet pepper.

Oxygen stress in the root zone was found to have severe effects on sweet pepper plants. Plants lost their turgescence within 1 day, resulting immediately in a strong reduction in photosynthesis rates and growth rate. In rose, the same occurred, but only after approximately 6 days. Fluorescence signals of 440, 520, 690 and 740 nm were found to be lower for the oxygen-stressed plants than for the controls from day 4 on. However, since photosynthesis rates decreased dramatically after 1 day of oxygen stress, red and far red fluorescence were expected to increase. The reason for this discrepancy between expected and observed results remains unclear. In conclusion, the relation between oxygen stress in the root zone and fluorescence imaging signals needs further clarification.

When sweet pepper plants were submitted to heat stress, fluorescence in all spectral ranges detected was found to increase. In sweet pepper, the ratio F440/F690 decreased slightly due to the heat treatment but this effect was not detected in all experiments that were performed. The fluorescence ratios F440/F740, F440/F520 and F690/F740 remained more or less unaffected by the heat treatments. Rose plants did not react strongly to the heat treatments applied, and results on the fluorescence images were therefore not unequivocal.

Using a plant sensor to establish a relationship between reflection and leaf area index (LAI) appeared to be very promising. Experimental results show an exponential relationship between R460 and LAI, indicating that LAIs up to approximately 2-2.5 can be accurately measured by means of reflectance.

4.2 UV-LED array

Spot measurements

The spot of a single LED-mirror unit as well as the resulting spots were measured at a distance of 450 mm using a Coherent Laser Mate Q with UV detector head (sensitive area: 25 mm^2). Spots at four different radial positions of LED-mirror units are shown in Figure 4.2.1. In summary, two types of spots can be created:

- a homogenous, less bright spot with a diameter of about 180 mm, and
- an inhomogeneous spot with a 2.5-fold brighter region in the centre (about ∅60 mm).

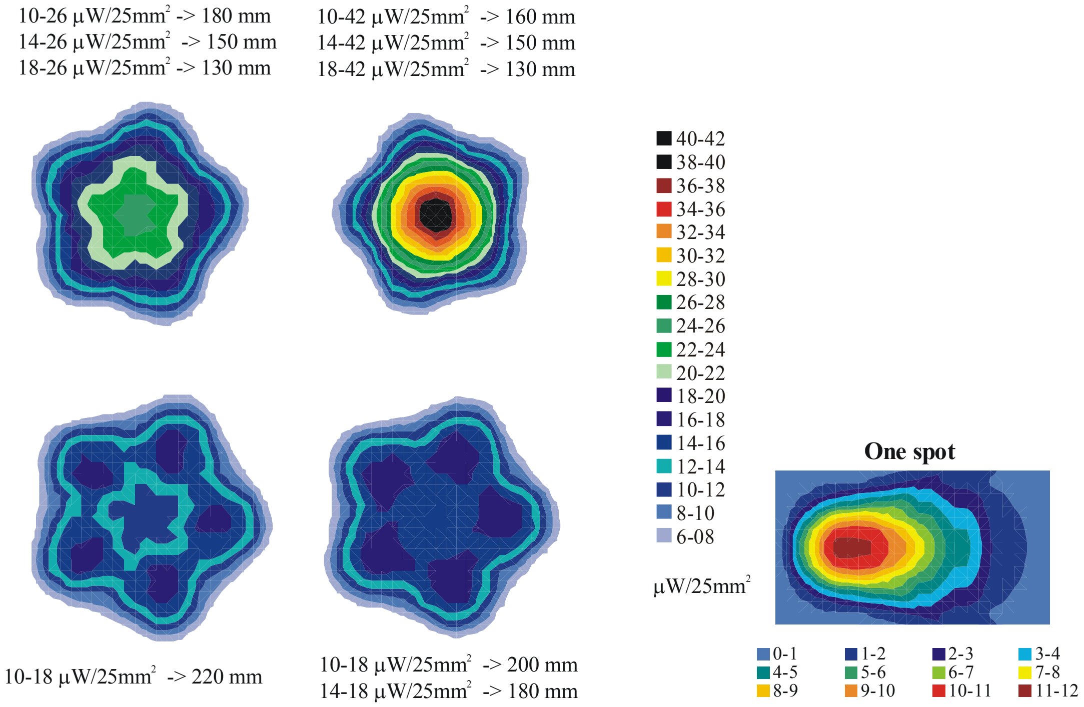


Figure 4.2.1. Left: spots generated at 4 different radial positions. Right: spot diagram of a single LED-array. All intensity values are in µW/25 mm^2.

Fluorescence imaging trials

Some images were picked up with the Xe-arc lamp and with the LED-array on the same leaf with the same camera imaging parameters (gain: 800, number of loops: 1000) at four wavelengths (440, 520, 690 and 740 nm) shown in Figure 4.2.2.

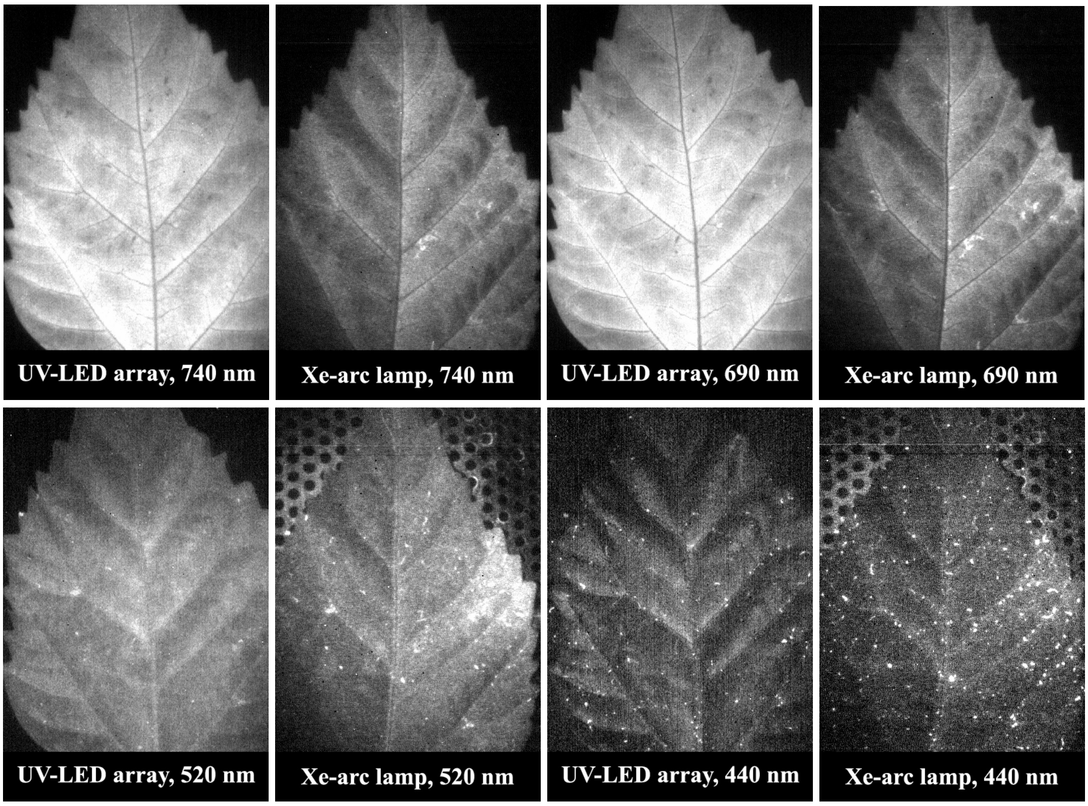


Figure 4.2.2. Comparative fluorescence imaging with the XE-arc lamp and UV-LED array sources at 4 wavelengths (grey scale is 0-1023 for 690 and 740 nm, 0-511 for 520 nm and 0-256 for 440 nm).

4.3 Portable fluorometer

Verification experiment

A comparative experiment was carried out (see paragraph 3.1) to verify the sensitivity of the portable fluorometer (CFM) to nutrient-stress-induced fluorescence changes. Three test groups of sweet pepper were formed to study nitrogen and iron deficiencies (N– and Fe– groups) and compare them to the control (Ctrl) group. Each test group consisted of 6 plants making a total of 18 plants for the experiment. On each plant, the 4 fully developed top (younger) leaves were measured. The sampling sequence of leaves and plants in the course of the plants were fixed. The results of fluorescence samplings and visual observations are shown in Figure 4.3.1.

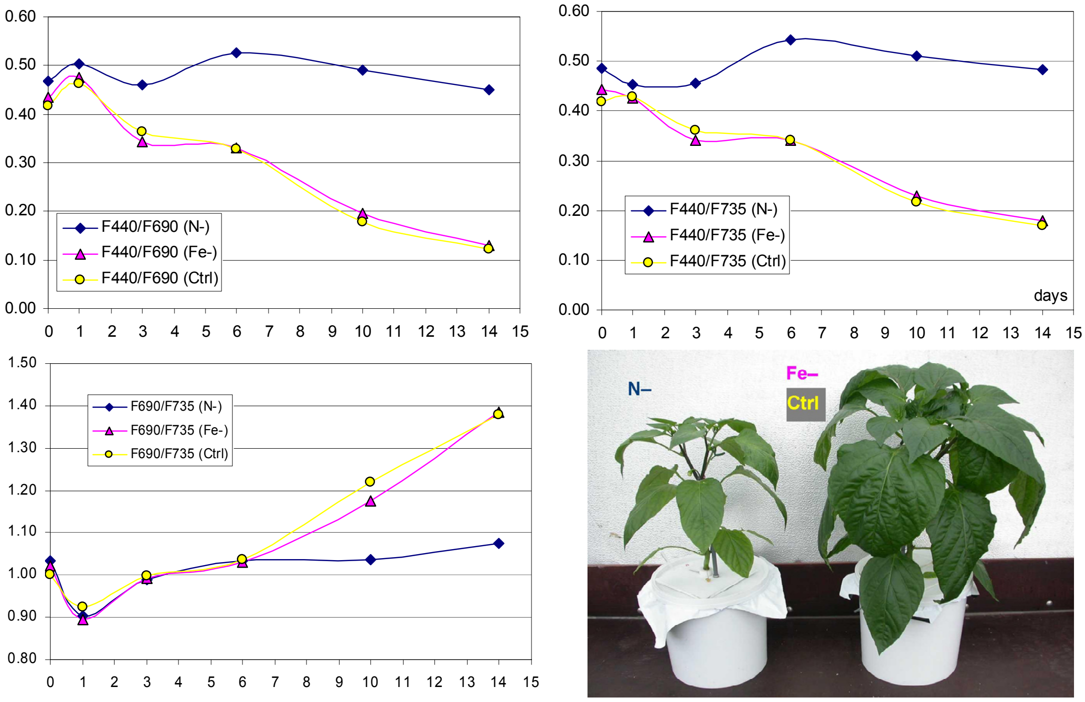


Figure 4.3.1. Fluorescence ratios for the different test groups. Visual symptoms (bottom right) show deterioration of N– plants and match with fluorescence signatures.

Final field test

The CFM portable plant sensor was also prepared to participate in the final test and calibration measurements at the experiments described in paragraph 3.13. A long-term measurement and monitoring strategy was agreed upon with the following key elements:

- Sweet pepper plants were fluorescence monitored.
- The 375 nm UV-light head of Figure 3.3.4 was used for fluorescence induction. Only UV-induced fluorescence signatures – at 4 wavelengths – were recorded using the protocol of Figure 3.3.6. Rational fluorescence values – rather than absolute data – were used for evaluation.
- The sampling period was selected so that at least one monitoring cycle took place every 2 weeks. During a monitoring cycle, all test groups were being fluorescence monitored according to Figure 4.3.2. The CLOSYS irrigation and fertilization (‘fertigation’) scheme was compared to the classical fertigation process. Each of the two schemes consisted of 4 test groups (blocks) located in 2 different greenhouse cells. One test group consisted of a set of 10 sampled plant replicates for statistical reliability.

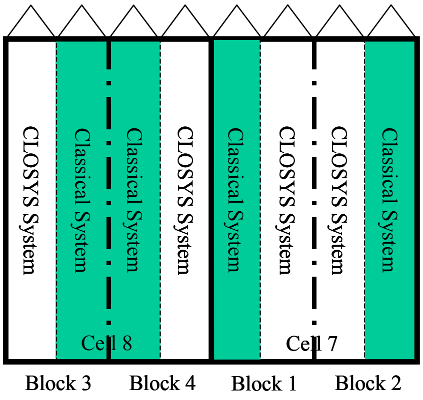


Figure 4.3.2. Schematic location of a total of 8 test groups (sketched by CTIFL).

The results of the long-term fluorescence monitoring of sweet pepper population were evaluated and compared to other monitored parameters, such as outside global radiation and irrigation volume. The temporal changes of rational fluorescence signatures (F690/735, F440/520, F440/690 and F440/735) are plotted in Figure 4.3.3 for each of the 8 test groups. Figure 4.3.4 shows the cumulative fluorescence signatures for the CLOSYS and the classical fertigation schemes.

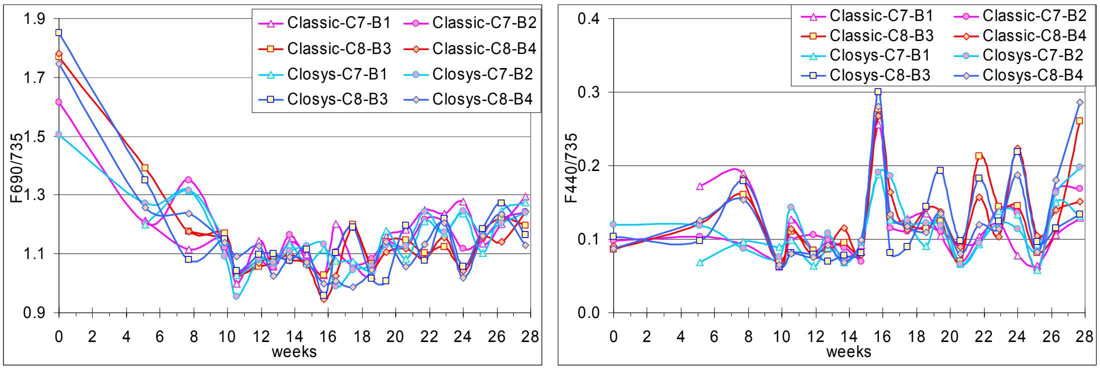


Figure 4.3.3. Rational long-term fluorescence signatures recorded with the CFM during the final test at CTIFL (Cn-Bm refers to Block m within Cell n).

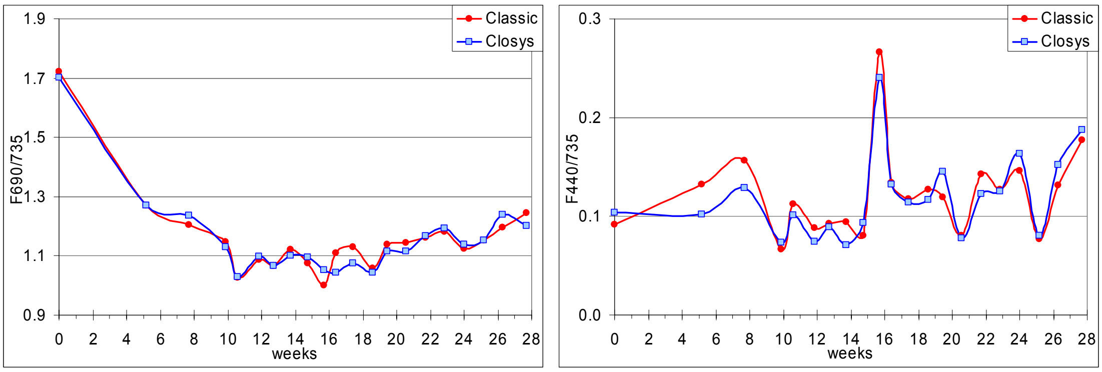


Figure 4.3.4. Comparison of long-term, cumulative fluorescence signatures of CLOSYS and classical fertigations.

4.4 Water and nutrient demand rose

The results of the long-term experiments show that:

- In the hot period of the year (May – September), the demanded NO_3 concentration was found to be higher for all plant organs. In contrast, in this period the demanded PO_4 concentration was lower for all plant organs. The same trend as for the demanded PO_4 concentration was found for the SO_4 concentration, but only for leaves and shoots. As expected, the demanded Ca concentration for leaves was higher during the hot period (May-September) and generally higher than for the shoots and roots during the same period. The demanded Mg concentration was higher and almost stable in all cases during the hot period (May-September). No clear picture was found for K, but in the case of leaves and shoots, no significant difference of the demanded concentrations were found between the hot (May - September) and cold (October - April) period.
- For some nutrient elements, the critical level (% DM) could be determined in different plant organs (leaves, shoots and roots) during the hot (spring and summer) and cold period (autumn and winter) of the year.

The results of the short-term experiments show that:

- The K^+/Mg^{++} ratio is more stable in leaves than in the other parts of the plant. The Ca^{++}/Mg^{++} ratio is unstable in plant organs. It is correlated to the K^+ concentration.
- The absorptions of Ca^{++} and K^+ are greatly affected by their initial concentrations in the nutrient solution.

The results from the validation experiments show that:

- The irrigation frequency affected cut flower fresh and dry weights since the total values of cut flower fresh and dry weight measured at the end of the experimental period were 1.22 and 0.35 kg m^{-2} for high and 0.88 and 0.25 kg m^{-2} for low irrigation frequency, respectively. As far as the number of cut flowers is concerned, the results showed that production increased with irrigation frequency since the total number of cut flowers measured at the end of the experimental period was 65 and 50 flowers per greenhouse m^{-2} for high and low irrigation frequencies, respectively. Finally, the results showed that the quality of rose flowering shoots was not affected by irrigation frequency.
- Numbers and fresh weights of the harvested flowers were also affected by the variety of the cultivated rose plants. Rose plants cv. Iceberg gave higher numbers of total cut flowers measured at the end of the experimental period (80 harvested flowers per greenhouse m^{-2}) than First Red plants (65 harvested flowers per greenhouse m^{-2}). The fresh weights of the harvested flowers were 1.48 and 1.22 kg m^{-2} for cv Iceberg and cv. First Red, respectively. In contrast, the dry weight of the harvested flowers was not affected by the variety of the cultivated rose plants. The dry weight of the harvested flowers was 0.38 and 0.35 kg m^{-2} for Iceberg and First Red, respectively. The variety of the cultivated rose plants also affected blind shoot production (15% and 30% of the produced shoots were blind for Iceberg and First Red, respectively).
- The nutrient solution in rooting media irrigated with high frequency had lower EC and pH values. In addition, the temperature of these rooting media was more stable and its value was lower than rooting media irrigated with low frequency.
- Irrigation frequency did not affect the concentration of K, Ca and Mg in the shoots and leaves. In contrast, the concentration of PO_4 and SO_4 was higher in shoots and leaves of rose plants irrigated with high irrigation frequency. In addition, the concentration of cations and anions were different for the two different cultivars, First Red and Iceberg, irrigated with the same frequency.

4.5 Water and nutrient demand sweet pepper

Short-term experiments

The results from the starvation and recovery experiments have been used to quantify critical concentrations of nutrients for the different organs of sweet pepper.

Results of the concentrations of nutrients during starvation are presented in Figure 4.5.1.

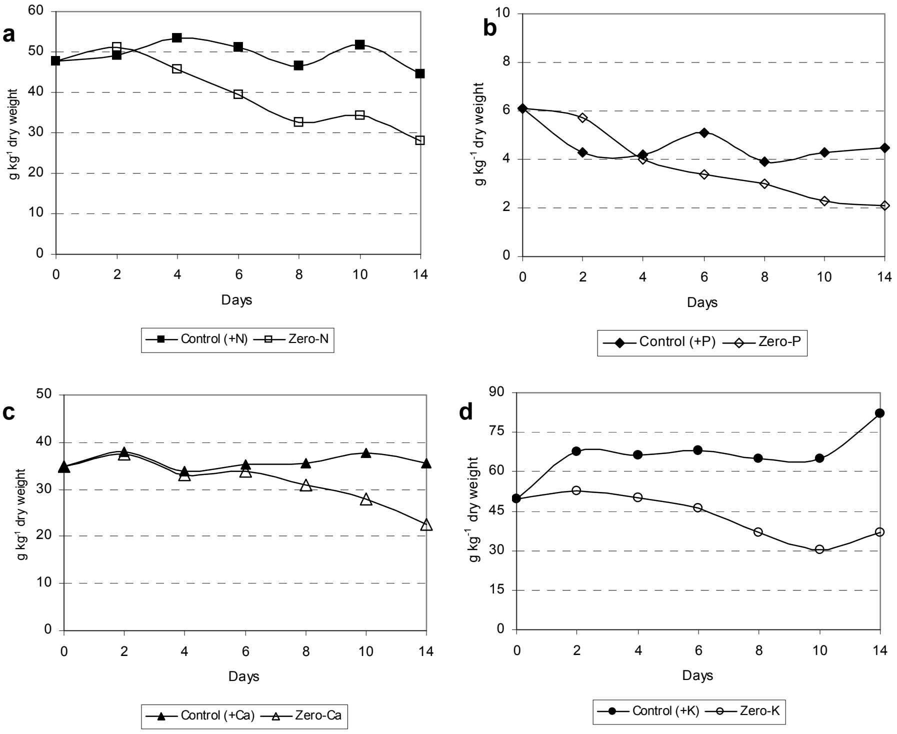


Figure 4.5.1. Leaf nutrient concentrations of starved and control sweet pepper plants. Plants were depleted of N (a), P (b), Ca (c) or K (d).

The nutrient uptake rate after six days of recovery of the starved and control plants (mg nutrient uptake per mg nutrient present after the starvation period) showed N, P and K uptake rates to be higher in recovered plants than in control ones. By contrast, the rate of Ca uptake in the recovered plants was higher only after 8 days of starvation.

Long-term experiments

The demanded nutrient concentrations for the different plant organs were determined with the results of the two long-term experiments organs. Cumulative radiation and total dry mass production was found to follow a parallel evolution with time along both experiments (Figure 4.5.2). Furthermore, from the sixth week of growth, radiation and total dry weight for the spring experiment were roughly (1.9, 2.3, 2.6) and (1.9, 2.1, 2.9) times higher than those in the autumn season, respectively.

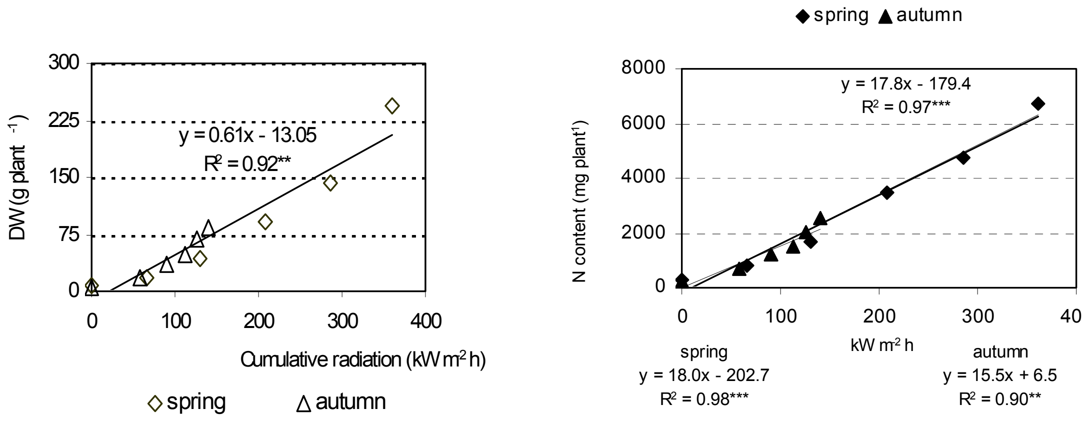


Figure 4.5.2. Effect of cumulative radiation on sweet pepper plant dry weight (A) and nitrogen content (B).

Validation experiment

The validation experiment included three treatments:
T1: high irrigation frequency, low plant density
T2: low irrigation frequency, low plant density
T3: high irrigation frequency, high plant density

Results show that the irrigation frequency did not affect fruit yield or total plant weight. However, higher plant density resulted in higher fruit production per m^2, but lower dry matter production per plant (Figure 4.5.3).

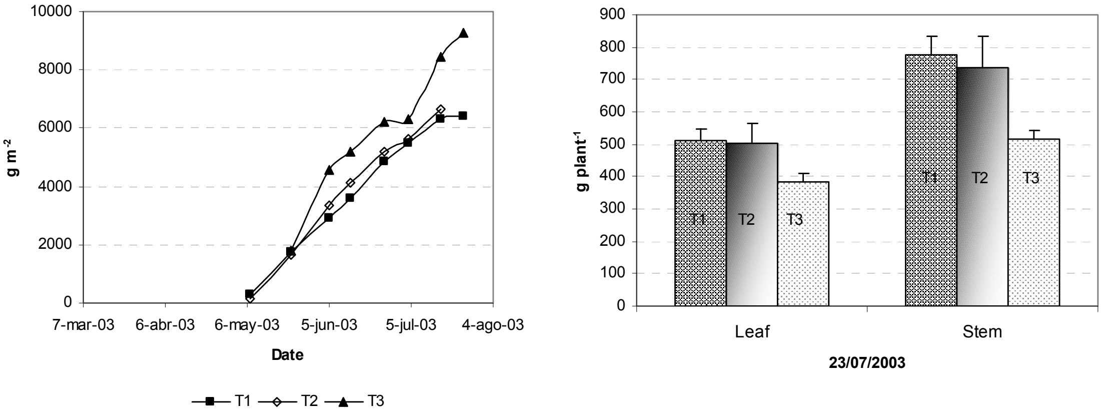


Figure 4.5.3. The effect of irrigation frequency and plant density on cumulative fruit yield (A) and cumulative dry matter production (B) of sweet pepper.

4.6 Plant/substrate model

Utilization of existing modules

Prototype models for sweet pepper and rose were developed. The starting point was a generic dynamic mechanistic model for the simulation of growth and development of greenhouse crops (Gijzen, 1992). The existing structure in the form of driver-routines that manage time and govern the sequential calls to various sub-modules was used. Existing simulation modules for photosynthesis, dry matter production and transpiration were used as well (Gijzen, 1994; Nederhoff, 1994). Existing modules regarding fresh weight and water uptake were made suitable for sweet pepper and rose, while existing sweet pepper modules for leaf area development, shoot development and fruit abortion were slightly revised.

Development of prototype modules for nutrient relations

New modules were developed for the simulation of nutrient demand and uptake for sweet pepper and rose. These processes were simulated along the following steps (Marcelis *et al.*, 2003):

- The demanded nutrient concentration (g g^{-1}) is computed per organ as a function of its temperature sum, thus introducing an ontogenic effect. The demanded nutrient content (g organ^{-1}) is computed.
- The demanded nutrient uptake rate (g m^{-2}) is computed from all demanded nutrient contents per plant minus the contents of nutrients already available in the organs, and plant density.
- A substrate model can assess whether the demanded uptake rate can be met. If not, the actual uptake rate will be lower than the demanded uptake rate.
- The actual amounts of nutrients allocated to each of the organs are determined from the total nutrient uptake rate, and the ratios of nutrient demands per organ.

An extensive literature search was conducted to obtain demanded (Figure 4.6.1) and critical nutrient concentrations.

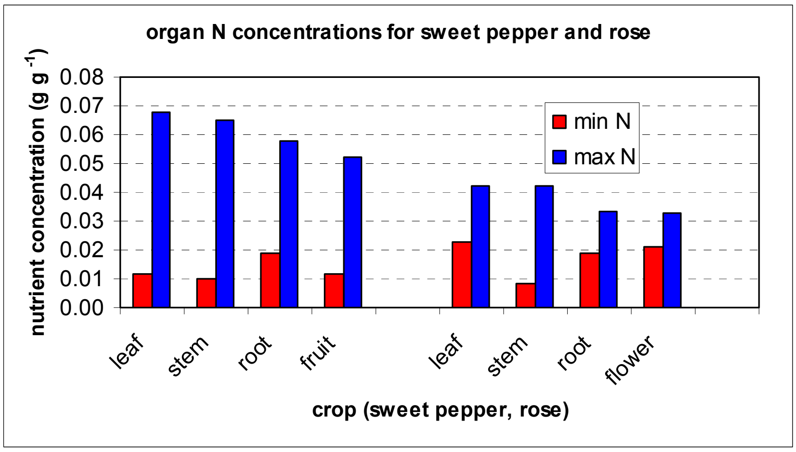


Figure 4.6.1. Demanded N concentrations for the various organs of sweet pepper and rose, as based on literature. Values for young organs (max N) and old organs (min N) are presented.

Self-learning properties

The process of self-learning of the model is based on feed-back from information from historical data and on-line plant sensors (Elings *et al.*, 2004). Historical data on climate and crop production were used to correct the model for the value of the greenhouse transmission, total production, and fruit abortion rate (sweet pepper) or shoot length increment (rose), and organ nutrient concentration. On-line sensor data were used for weekly auto-calibration during crop growth. A reflectometer measures light reflectance (from which LAI can be derived), and a plant stress sensor can measure photosynthesis characteristics.

Sensor	Plant property	Model parameter
Reflectometer	Leaf area	Leaf area index
Stress imaging	Photosynthesis	Light response parameters
Human count	Fruits per plant	Fruit abortion rate

Parameter optimization in the self-learning procedures is based on the 'random search' algorithm. This algorithm calculates the best performing parameter value by rerunning the model with randomly selected parameter values. Minimum and maximum values of the parameter are required as input, and have to be defined by the user. The random search parameter optimization can be performed on more parameters simultaneously.

Self-training capacity was first applied to the Carquefou 2003 validation experiment, and subsequently also to the Carquefou 2004 final field test. The 2003 data set in this manner serves as a historical data set for the 2004 experiment. In 2003, the above-mentioned processes were calibrated. The value of historical data sets (from 2003) was illustrated by the fact that in 2004, total dry matter production and organ nutrient concentrations were correctly simulated and did not require to be calibrated again. Yet, the parameters for leaf area development had to be corrected in 2004 relative to those calibrated for 2003, on the basis of measurements of leaf area by the Cropscan sensor. This resulted in a higher leaf area that corresponded very well to the values found for harvested plants (Figure 4.6.2). In order to simulate total dry matter production correctly, the higher leaf expansion (relative to 2003) had to be partly compensated for by a 20% decrease in leaf assimilation rate. Whereas fruit load was not calibrated in 2003, it was calibrated in 2004, resulting in a much more accurate fruit load and number of harvested fruits. As dry matter partitioning was substantially altered, the weight of harvested fruits remained under-estimated.

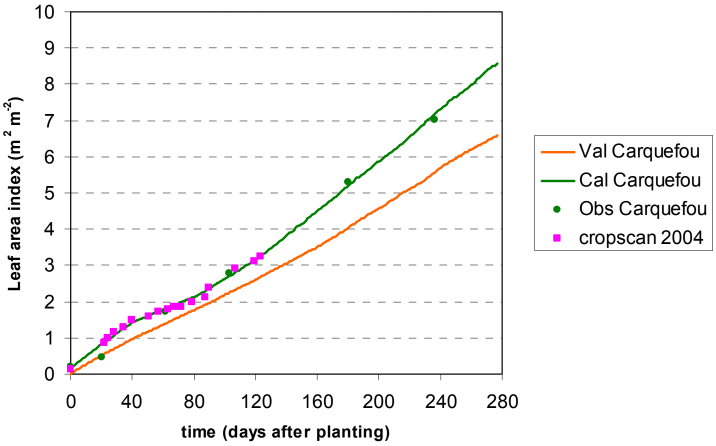


Figure 4.6.2. Course of Leaf Area Index (LAI) in the 2004 experiment in Carquefou. Val, validated on basis of 2003 parameters; Cal, LAI simulated after self-learning (calibrated); Obs, observed LAI of harvested plants; Cropscan is the on-line leaf area sensor.

It appeared in 2003 that minimum and maximum nutrient concentrations based on literature research caused incorrect simulations of organ nutrient concentrations. If minimum and maximum nutrient concentrations were calibrated for 2003, and used in 2004, then organ nutrient concentrations were adequately simulated. If, on the other hand, Carquefou 2003 data on nutrient concentrations were used for validation of Santomera 2003, organ nutrient concentrations were not adequately simulated. This calls for site-specific calibration.

On a fortnightly basis, calibrations were performed in support of the final field test, for which information regarding crop reflection (enabling calibration of LAI), number of harvested fruits and dry matter production were made available from France to The Netherlands.

Sensitivity analysis

Sensitivity analyses were conducted with regards to photosynthesis, transpiration, water uptake rate and nutrient uptake concentrations, in relation to outside global radiation, vapour pressure deficit (VPD), air CO_2 concentration, air temperature, and plant density. Global radiation was varied from 0 to 800 J m^{-2} s^{-1}, VPD from 0.5 to 1.5 kPa, air CO_2 concentration from 300 to 400 ppm, air temperature from 15 to 25 °C, and plant density was doubled from 3.1 to 6.2 plants m^{-2}. The effects of radiation and VPD on transpiration, and water and nutrient uptake were large in comparison with those of CO_2 concentration, air temperature and plant density. Average water uptake per unit radiation was simulated at approximately 2 mg H_2O m^{-2} / J cm^{-2}. Simulations for sweet pepper indicated that variation in cumulative N, P and K uptake was predominantly caused by the relatively low concentrations in the fruits at maturity, that variation in cumulative S and Ca uptake was predominantly caused by the relatively high concentrations in young leaves and that variation in cumulative Mg uptake was predominantly caused by the relatively high concentrations in young leaf and stem material.

The interaction between water and nutrient uptake was analyzed. With increasing global radiation and associated increased vapour pressure deficit in the greenhouse, both the uptake rates of water (mg m^{-2} s^{-1}) and nutrients (mg m^{-2} s^{-1}) increase. However, the nutrient uptake rate (mg [nutrient] mg^{-1}[water]) is relatively stable over a wide range of radiation levels (Figure 4.6.3).

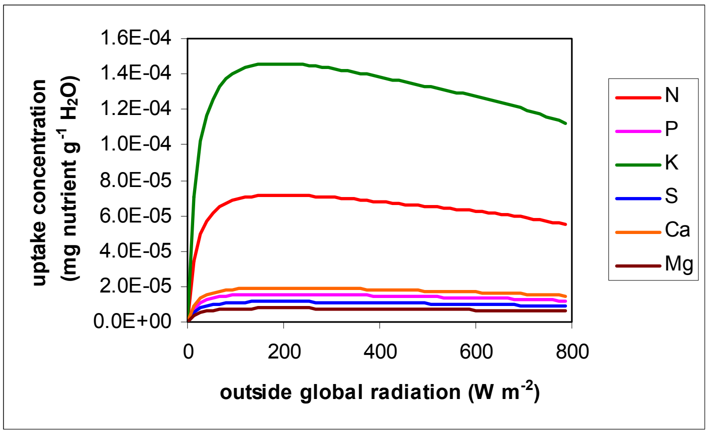


Figure 4.6.3. Simulated nutrient uptake concentrations for a sweet pepper crop under representative climate conditions in The Netherlands.

Water uptake

The plant model was coupled to a simplified substrate model (paragraph 3.7) that computes the fraction reduction in water and nutrient uptake from the humidity and EC of the slab. This, in combination with the demanded water and nutrient uptake rates as computed by the plant model, results in actual water and nutrient uptake rates. Reduced water uptake may result in stomata closure, leading to reduced transpiration, photosynthesis and crop growth.

Nutrient uptake

The effects of nutrient shortage on growth of a sweet pepper crop were assessed on the basis of experiments conducted in Spain. These data matched existing knowledge concerning tomato. Therefore, combined knowledge, translated to equations, was introduced to the plant model for sweet pepper.
Time constants for nutrient uptake could not unambiguously be retrieved from the conducted short-term experiments. Effects in plant nutrient status were detected, but effects were not sufficiently consistent. As a result, it was decided to maintain the time constant for nutrient uptake at 6 hours.

Model validation

The sweet pepper model was validated on the basis of the 2003 validation experiment in Carquefou, France, which lasted 275 days. As existing equations for leaf area simulation resulted in a substantial overestimation, leaf area development was fully calibrated. Total dry matter production and dry matter partitioning were adequately simulated, with a slight overestimation of total dry matter, and stem and fruit weight during the middle part of the season. Because leaf area had been calibrated, and leaf weight was adequately simulated, also specific leaf area was adequately simulated. Simulated default node formation rate proved very satisfactory for the first 180 days of the season, after which observed formation rate reduced, while simulated formation rate did not. This resulted in a substantial overestimation of the number of harvested fruits and slight overestimation of harvested fruit weight towards the end of the season. Consequently, the weight per fruit at harvest was underestimated. It proved difficult to simulate the flushes in load number, and while observed load number increased to 25 fruits plant^{-1} at the end of the season, simulated values never exceeded 15 fruits plant^{-1}. Blossom-end rot was reasonably simulated, although it proved difficult to simulate the timing of peaks in BER. Default nutrient concentrations, based on literature research, did not result in acceptable simulations.

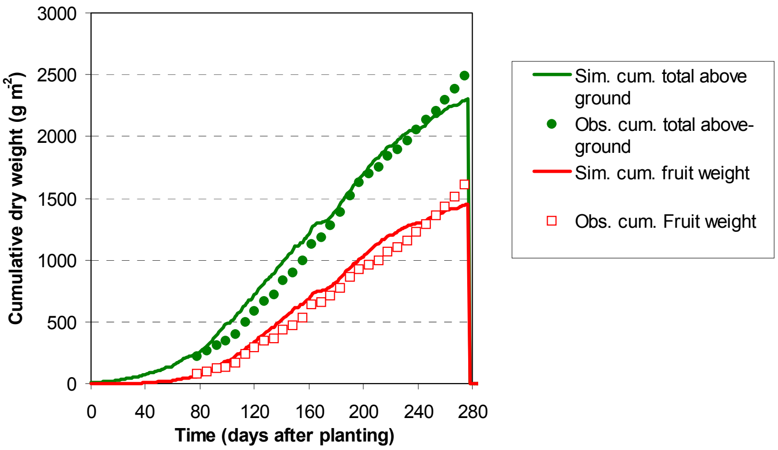


Figure 4.6.4. Validation results for sweet pepper cultivated in Carquefou, 2003: observed and simulated values of total above-ground dry matter and of dry fruit weight.

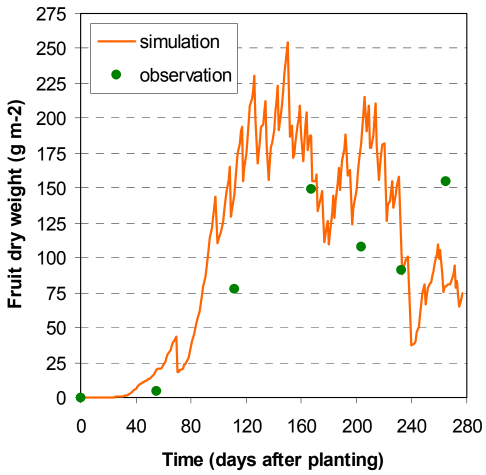


Figure 4.6.5. Validation results for sweet pepper cultivated in Carquefou, 2003: observed and simulated values of actual fruit weight (the fruit weight on the plant).

The sweet pepper model was also validated on the basis of the 2003 validation experiments at Santomera, Spain. The selected cultivar was characterized by a slightly shorter ripening duration of the fruits (600 d°C instead of the default value of 750 d°C. Observed leaf area index (LAI) was low, possibly because of low plant densities (1.6 and 2.4 plants m^{-2}). However, the effect of very low plant densities appeared not sufficiently well simulated by the model. It should be considered to incorporate the effect of plant density on leaf area development of an individual plant. If LAI was calibrated, then above-ground dry matter was simulated accurately up to 140 days after planting, and 10-20% overestimated at the end of the season. Cumulative above-ground dry matter was simulated very well for the entire season. The number of nodes was simulated correctly until 160 days after planting, but overestimated by 13-26% afterwards. This was also observed in case of Carquefou 2003. Apparently, node formation rate decreases towards the end of the season. The number of fruits (and flowers) on the plant was seriously underestimated (by 50%). This stresses the need of self-training with respect to fruit dynamics. The underestimation of fruit load caused overestimation of the weight of an individual fruit. Cumulative fruit dry weight was simulated well for all three treatments up to about 150 days after planting, which means that up tot this moment dry matter partitioning between vegetative and generative organs was also correctly simulated. Actual dry fruit weight, however, was sometimes overestimated and sometimes underestimated.

The rose model was validated on the basis of the 2003 validation experiments at Aalsmeer, The Netherlands and Volos, Greece. Cumulative shoot dry matter was slightly overestimated, indicating that dry-matter partitioning towards the shoots is a little too high. Shoot length is a cultivar characteristic for which a parameter must be specified. After this was done, shoot length over the growing season was well simulated. Shoot weight was well-simulated, except an underestimation towards the end of the season. Initial leaf area was overestimated, but leaf area during the productive phase was simulated correctly. The development duration of a shoot was slightly underestimated, causing a slightly earlier simulated harvest moment than observed. Finally, organ nutrient contents were simulated on the basis of literature characteristics. Results indicate that calibration on the basis of historical data sets is essential.

4.7 Substrate characterization and models

Substrate hydraulic properties

Conductivity versus suction for different regimes corresponding to various ranges of suction were experimentally determined for Floriculture® and Expert® slabs and their corresponding parameter values fitted on the Mualem-Van Genuchten model (Rathfelder *et al.*, 1994) (Figure 4.7.1). Water retention characteristics $\theta(h)$ in sorption and drying were also experimentally determined for the two studied types of rockwool slabs (Bougoul *et al.*, 2005) and the results (Figure 4.7.2) adjusted to the model of Van Genuchten (1983). The differential water capacity was also deduced from the characteristic curve of water retention.

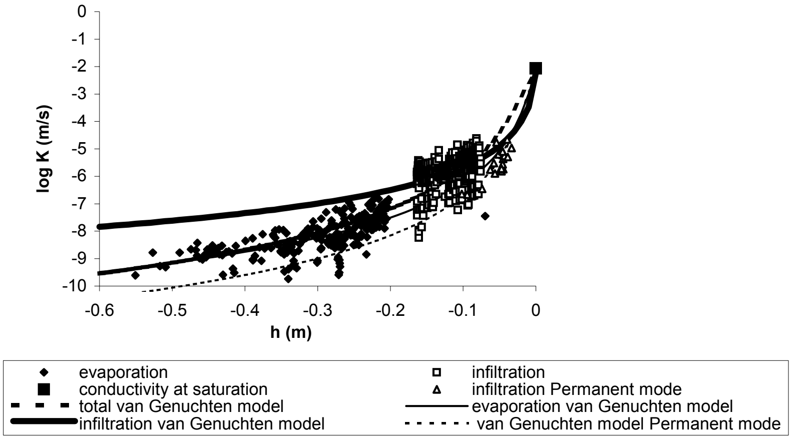


Figure 4.7.1 Hydraulic conductivity K(h) of Expert rockwool following the height of the substrate.

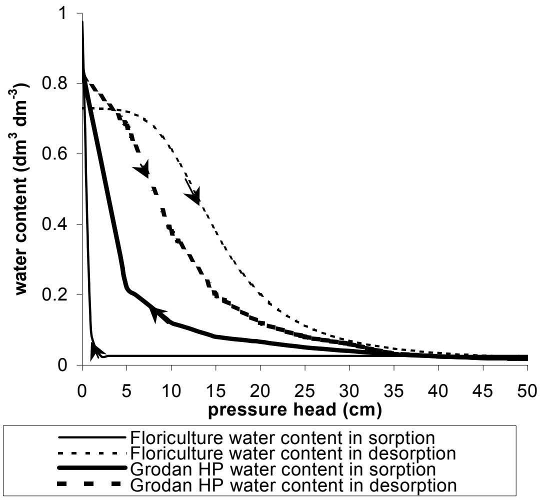


Figure 4.7.2 Comparison of the water retention curves for Floriculture and Grodan HP stone wool.

Distribution of water in rockwool slabs and roots activity

Water is not evenly distributed within the slab: water content is always higher in the bottom part of the slabs than in the top. This is due to the horizontal layer structure of the rockwool slabs and to the contact between the bottom part of the substrate and the polythene film. The movement of the solution in the slab is done according to two principles: one outflow following the drippers' axis through the gravity effect and one lateral way around it.

Along the length of the slab, there is no significant variation of water content in the case of rose crop. For pepper crop with two plants and only two drippers per slab there are two zones with higher water content under the two irrigation drippers and drier zones at both ends of the slabs and between the two plants.

The type of slab had an effect on the water distribution. The bottom part of the rockwool slab that represent 1/4 or less for EX and 1/2 or more for FL had a water content higher than 80% v/v for EX and often higher than 90% v/v for FL. The top part can range from 80% v/v for FL (with HF irrigation) to as low as 30% for EX (with LF irrigation). The bottom of the slab was always wet with a very close WC for FL and EX, the top was drier in EX than FL and under LF than HF. Mean WC in FL slab was higher than in EX slab, with a smaller vertical variability from the top to the bottom of the slab. These differences were increased by the LF irrigation. FL had a tendency to develop a high humidity in its bottom part especially under high-frequency irrigation. EX has such a high hydraulic conductivity that its top part is often too dry. On the other hand the high hydraulic conductivity of EX allows more variations in the water content solution and a faster turnover of the nutrient solution which may be useful to regulate the root environment.

As general rule for both rose and pepper crops, the slab is drier in the early morning, after a long period of leaching and plant absorption during the whole night. We have obtained a significant increase of the WC in the top and the bottom of the slab for the two slab types and the two irrigation frequencies after a few irrigations (one or two) at the beginning of the day. During the day, we noticed a relative WC stability. The change in WC due to the first irrigations is more significant for EX (increase of approximately 10% v/v WC) than for FL (approximately 5% v/v WC).

For both crops, the root distribution within the slab is strongly determined by the treatment applied. On EX substrate, the roots are located mainly in the middle part of the slab, while on FL, they are mainly found in the top part. These results are valid for both crops, although the rose crop, with six plants per slab, shows that there can be a high inter-plant variability.

The comparison of root maps drawn for the 4 treatments on sweet pepper shows two extreme situations: LF/EX, where roots have grown downwards and are mainly located under the drippers and below the slab (between the slab and the plastic bag); and HF/FL, where they are limited to the top centre of the slab, with very little lateral downward extension. Between these two situations, HF/EX and LF/FL show more even distributions.

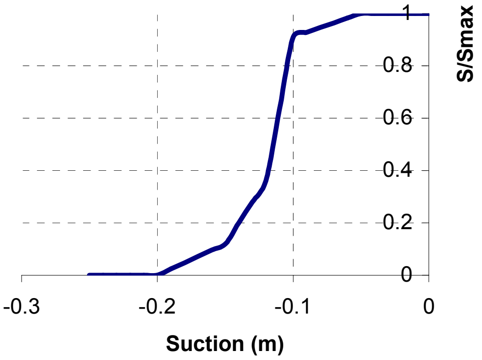
In the case of sweet pepper, sampling the roots at different dates during growth gives some information on how the roots settle in different parts of the slab. In FL the roots grow first in the top centre part of the slab, as can be expected; the colonization of the whole slab is better achieved under the LF irrigation regime. In EX, the roots grow very quickly to the bottom of the slab and below it; under LF irrigation they are unable to explore the sides of the slab; only under HF they are finally distributed in all 4 slab zones.

For both rose and sweet pepper, water absorption is more or less constant for low values of water tension (< 5 cm); it is strongly reduced for values higher than 10cm. The transition is steep in the case of sweet pepper, and more graduated in the case of rose. Moreover, for sweet pepper a treatment with a negative tension (i.e. roots totally submerged in solution) was applied. It also induced a strong reduction in root water absorption, very likely through the effect of anoxia.

Root absorption by sweet pepper can be considered as a sink of nutrient solution with an absorption rate depending on both root density and consequently root distribution (Brun *et al*, 2004) and substrate suction (Longuenesse & Brun, 2004). Knowing the potential absorption rate (S_{max}), the actual absorption rate (S) could be deduced by a simple relation:

$$S = \alpha(h)S_{max}$$

where $\alpha(h)$ depends on substrate suction (Figure 4.7.3) and EC. $S_{max,}$ the potential absorption rate (Longuenesse & Brun, 2004) depends on the relative density of roots in the substrate (measured values) and on atmospheric demand.



$$\alpha = 1 \ for \ -0.05m \le h \le 0m$$

$$\alpha = 1{,}8 * h + 1{,}09 \ for \ -0.10m \le h \le -0.05\,m$$

$$\alpha = 27{,}5 * h + 3{,}66 \ for \ -0{,}12\ m \le h \le -0{,}10m$$

$$\alpha = 8 * h + 1{,}32 \ for - 0.15\,m \le h \ \le -0.12\,m$$

$$\alpha = 2{,}4 * h + 0{,}48 \ for - 0.20m \le h \le -0.15\,m$$

$$\alpha = 0 \ for \ h < -0.20m$$

Figure 4.7.3. Variation of the absorption coefficient $\alpha(h)$ *according to the suction values.*

Modelling water and mineral movements within the slab

After rearrangement of the basic equation, nutrient solution movements in the substrate were determined by numerical solving of the Richards' equation using the CFD software together with the substrate hydraulic properties (Bougoul *et al.*, 2005).

Validation

Using the model with the identified parameters, numerical calculations were compared to the experimental measurements for the two substrate types (Floriculture® and Expert®) and two irrigation frequencies: a) high frequency (irrigation every 0.3 mm of atmospheric demand), and b) lower frequency (every 0.6 mm). The main results can be evidenced by examination of simulated water dynamics in the substrate over one day in July 2002, characterized by 12 irrigations for the high frequency regime and 7 irrigations only for the lower one.

Isosuction areas in the slabs (Figure 4.7.4) are represented with the same colours according to the scale of the legend (saturated zones in red and dry zones in blue) for both the numerical and experimental results. From a qualitative point of view, when comparing the computational and experimental results, one does observe similar repartition of humidity in the slab. Likewise, after watering the same dynamics were obtained both by modelling and experimentally for the two substrate types and the two irrigation regimes. Particularly, one can observe similar periodic humidity variations in the substrate.

Focusing on the water distribution at the end of the irrigation (Figure 4.7.4), the following remarks can be made for all studied treatments:

- for all treatments, the area located just above the drainage slot is always very dry, with suction values higher than –10 cm. Independent of the substrate physical properties, this zone seems mainly depending on the position of the drippers;
- the saturated zones (yellow and red colours in Figure 4.7.4) are always located just below the drippers and at the base of the substrate;
- comparing the two rockwool slab types, there is a greater extension of the saturated zones for the high density rockwool (Floriculture®) than for the lower density type (Expert®).
- high frequency irrigation rate also induces a larger extension of the saturated zones (see Expert® results).
- although it is hard to compare computed and measured values of water content in the slab because the measured values correspond to an average measured value corresponding to the whole width of the slab (TDR measurement) whereas the computed ones correspond to (almost) punctual value (over time) distributed along a vertical section passing by the drainage slot, one can observe similar dynamic tendencies concerning the slabs hydraulic behaviour:
    - a larger extension of the saturated areas for the high density rockwool (Floriculture®) than for the lower density slab (Expert®), and
    - a larger extension of the saturated areas for the treatment with the higher irrigation frequency rate.

Substrate optimization based on simulation studies

Simulated and experimental results both highlight the considerable extension of the areas with a very high humidity (>90%) for the Floriculture® slab (about 1/2 of the slab volume) whereas these areas are much less extended for the Expert® slab (less than 1/3 of the slab volume).

In order to design an optimal substrate, we have therefore proposed a composite slab, made up of two rockwool types, the density of each allowing for a closer control of hydraulic conductivity than of slab humidity. Thus, this 'optimum' slab was partly composed of a high density rockwool (Floriculture® type) in the first 1/4 upper part and of a lower density rockwool (Expert® type) in the remaining volume (lower part of the slab).

Simulation of the hydraulic comportment of this 'optimal' slab for the same boundary conditions and irrigation regime shows (Figure 4.7.5) that the extension of the dry zones decreases a lot in comparison with the Expert® slab, the wet zones (>90%) occupying now about 2/3 of the whole volume of the substrate (against less than 25% for Expert®). Figure 4.7.5 also shows that the enlargement of the wet zones allows for a much better exploitation of the slab volume by the plant roots, which is particularly important by the end of the day.

These wet and almost saturated conditions, however, must be periodic in order to avoid plants roots being kept under saturated conditions permanently. Such periodic drying can be systematically achieved at night, when irrigation is stopped and when the substrate dries up until the time of the first irrigation of the day.

Substrate humidity in the composite substrate (with low and high frequency irrigation rates) was therefore investigated at the end of the night, just before the first irrigation. The results were compared with Floriculture® slabs and Expert® slabs irrigated with low frequency irrigation rates (Figure 4.7.6). Simulation results for the 4 trials generally highlight an absence of water stagnation and of probable resulting risks of anoxia in the lower parts of the substrate. However, thanks to the hydraulic properties of the different rockwool types used in the 'optimized' slab, we observed that the composite substrate allows maintaining a larger extension of the wet zones without anoxia condition where root absorption conditions are improved.

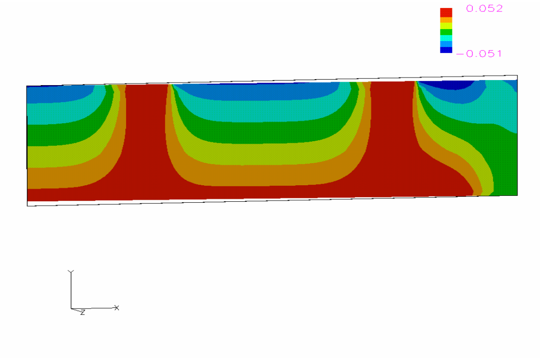
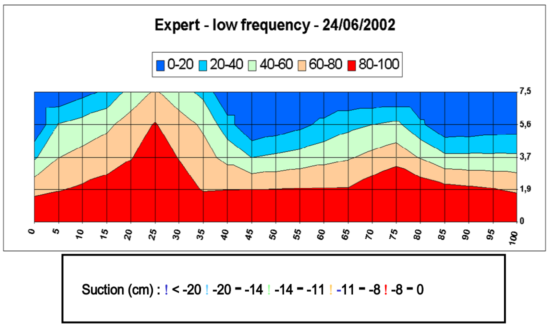
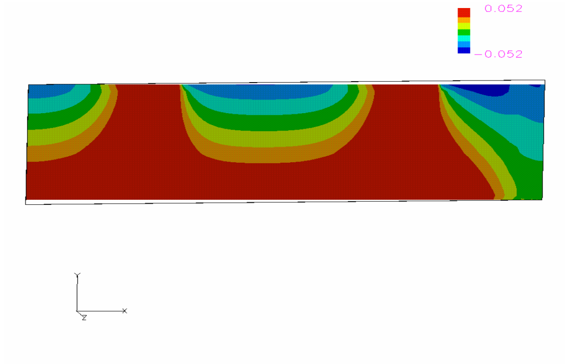
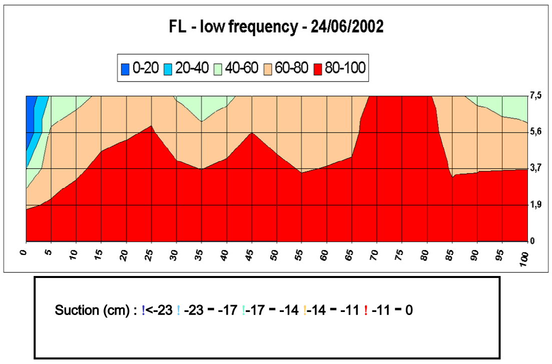
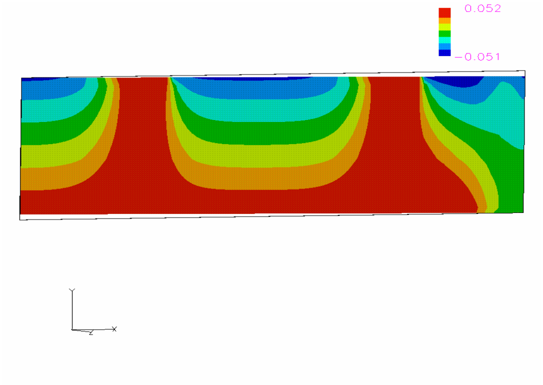
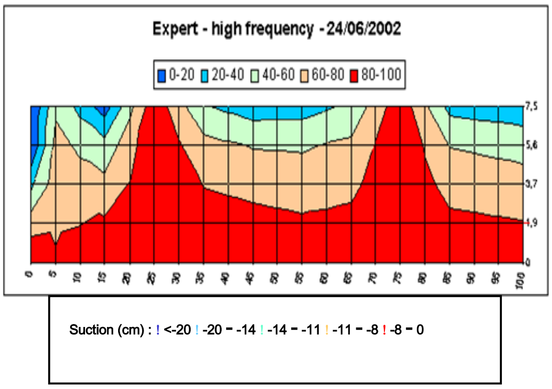
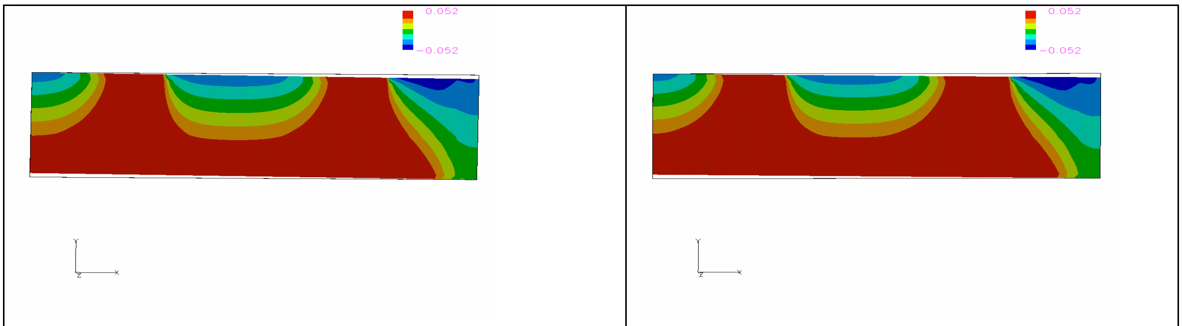
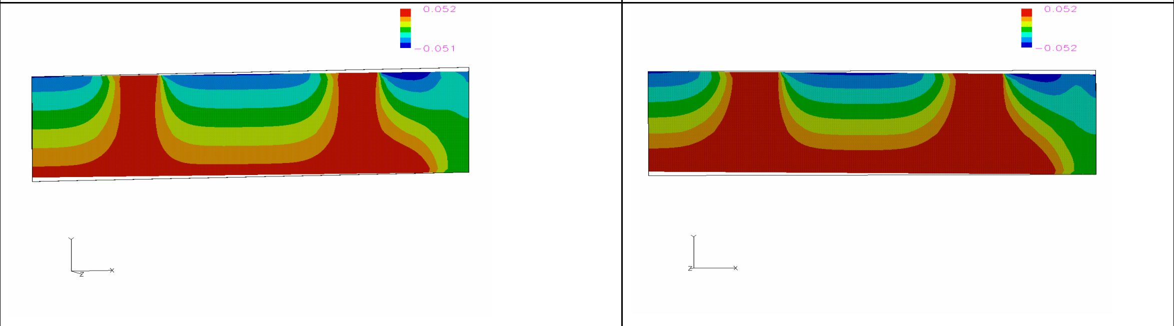
Numerical Results	Experimental Results
 *End of the irrigation Expert Low Frequency*	 *End of the irrigation Expert Low Frequency*
 *End of the irrigation FL Low Frequency*	 *End of the irrigation FL Low Frequency*
 *End of the irrigation Expert High Frequency*	 *End of the irrigation Expert High Frequency*

Figure 4.7.4. Distribution of water within the slab after irrigation.



Composite HF at the end of the first irrigation

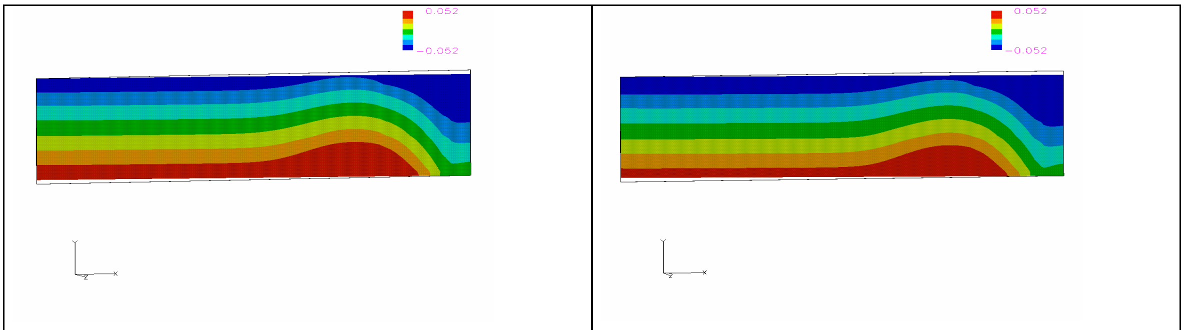
Composite HF at the end of the last irrigation



Expert HF at the end of the first irrigation

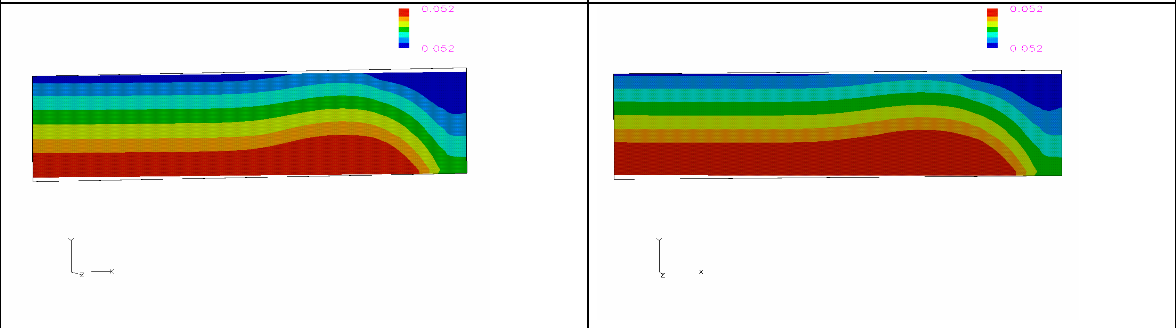
Expert HF at the end of the last irrigation

Figure 4.7.5. Distribution of water within the slab for wetting conditions and re-wetting.



Floriculture Low Frequency

Expert Low Frequency



Composite Low Frequency

Composite High Frequency

Figure 4.7.6 Variation in humidity for the two types of substrate at the end of the night.

4.8 Improved substrate

An improved mineral wool substrate was made which had new properties as regards:

- water distribution over height: better than former standard product,
- water retention curve: better than former standard product, and
- hydraulic conductivity: value between two former standard products.

Table 4.8.1. Physical properties of the improved CLOSYS slab.

Slab type	Grotop Master-1y
pF-10 drying	72%
pF-10 re-wetting	35%
Hydraulic conductivity (mm/s)	7.3

The result was realized with changes in density and other basic substrate parameters.

4.9 Substrate sensor

Sodium sensor

Literature research showed that the most suitable sodium ionophore was commercially available under the technical name 4-tert-Butylcalix[4] arene-tetraacetic acid tetraethyl ester. In the further experiments this Na-ionphore is used. The experiments consist of:

- testing pH independence,
- testing different membrane matrixes, and
- durability and life span tests.

Testing pH independence of the sodium sensor

For testing pH independence different Na-selective PVC membranes were tested in comparison with the classic pH-dependent glass sensors for sodium measurements.

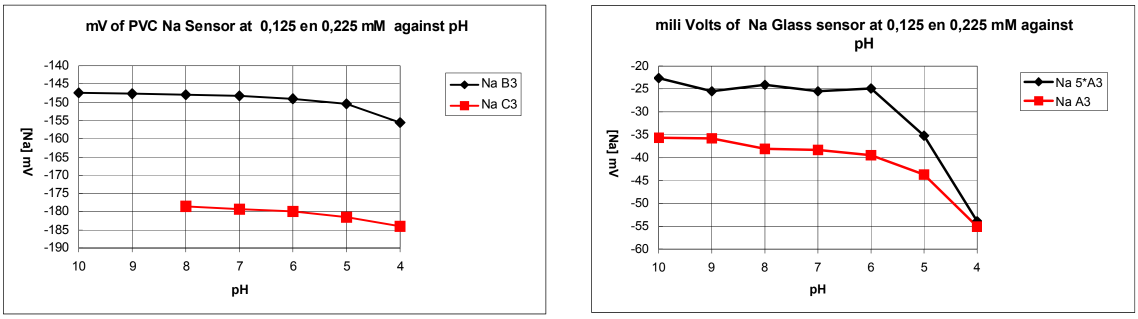


Figure 4.9.1 pH independency of the developed Na sensor compared to classic Na glass electrode.

Ceramic membranes

Testing of different types of ceramics included the following:

1. different pore sizes from the commercially available technical ceramics AKP 15 en AKP30, and
2. different compositions of PVC membranes with different amounts of ionophore.

The ceramics were impregnated with different Na-sensitive membrane compositions. The best working composition was found to be the standard membrane composition that was also used for normal PVC membranes excluding the PVC itself. One main problem remained: the membrane matrix was found to dilute from the ceramics with the result that the ionophore disappears and the signal diminishes. No solution was found for this problem.

Durability test

The conventional PVC membrane matrix was used for further testing. In practice, the life span of these membranes was up till 6 months; this is comparable to already existing PVC membranes.

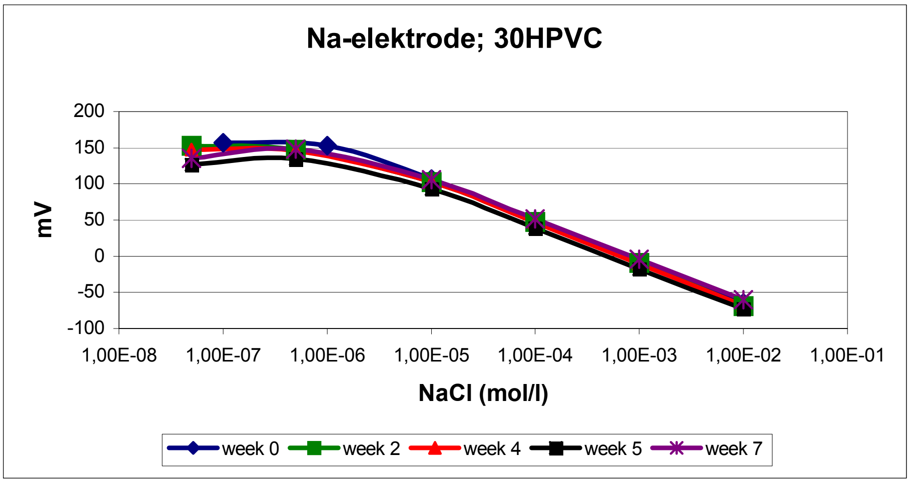


Figure 4.9.2. Durability test of the Na electrode.

The newly developed Na sensor was tested in the greenhouse. Figure 4.9.3 shows the stability of this sensor.

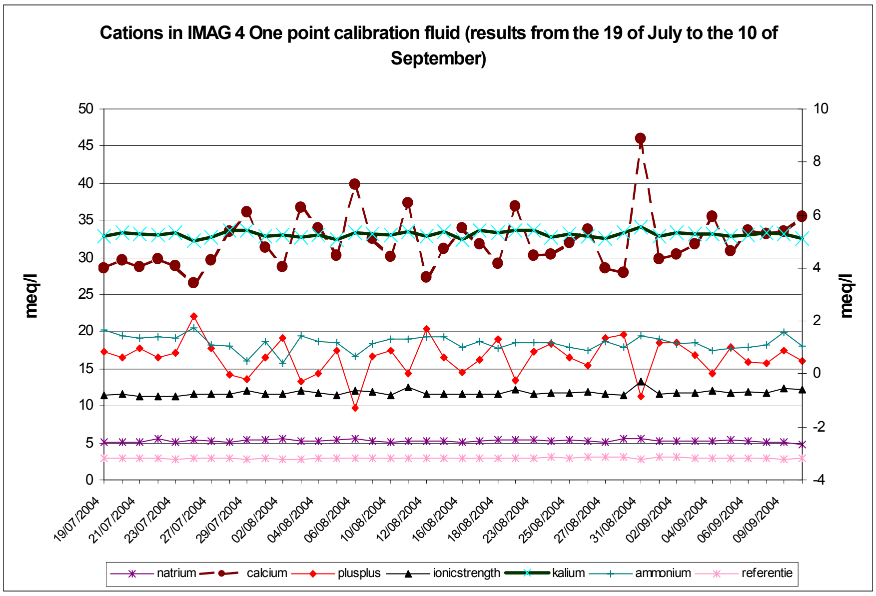


Figure 4.9.3. Stability of the Na sensor.

<u>Magnesium sensor</u>

Literature research and practical tests showed that ionophore I, II and III [1] (chemical names of Mg ionophores; Erne *et al.*, 1980; Hu *et al.*, 1989; Lanter *et al.*, 1980; Maj-Zurawska *et al.*, 1989) had insufficient selectivity for Mg^{++} in comparison to Ca^{++} and further testing was no option. Ionophore IV (Malinowsky *et al.*, 1999; O'Donnell *et al.*, 1993) were found to be more selective for Mg^{++} but the life span of the produced membranes was too short for practical use (less than 1 month).

The composition of the membrane matrix was changed in different experiments. Especially the amount of anionic sites and different plasticizers were tested. The produced membranes still proved to be more selective for Ca^{++} than for Mg^{++}. The application of different types of anionic sites neither improved selectivity. Literature research (O'Donnel *et al.*, 1993; Spichiger-Keller, 1999; Suzuki, *et al.*, 1995; Zhang *et al.*, 1998, 2000) showed that ionophores V and VI were most suitable concerning non-selectivity for Ca. Experiments proved the opposite. Another problem was that these ionophores were very expensive. In view of the disappointing results from these last experiments concerning the non-selectivity for Mg^{++} of ionophores V and IV, further research with these ionophores was cancelled. Ionophores were not tested in ceramic membrane matrices instead of plastic membrane matrices in view of the non-selectivity for Mg^{++} in former experiments.

4.10 Expert system

The plant substrate model has been extensively run on several historical climate data to assess the behaviour of the output variables that are used in the optimization criterion. These variables are actual plant transpiration, fruit harvest and percentage of blossom end-rot (BER) in the harvested fruits. The simulations have shown two noticeable facts. First, the BER indicator evolves slowly and a one-day change in the irrigation strategy has almost no significant effect on its value. Depending on the climate to which the crop is subjected, 3 or more days of a new EC are

---

[1] Ionophore I = N,N'-Diheptyl-N,N'-dimethyl-1,4-butanediamide (ETH 1117)
Ionophore II = N,N''-Octamethylene-bis(N'-heptyl-N'-methyl-methylmalonamide (ETH 5214)
Ionophore III = N,N''-Octamethylene-bis(N'-heptyl-N'-methylmalonamide (ETH 4030)
Ionophore IV = N,N',N''-Tris[3-(heptylmethylamino)-3-oxopropionyl]-8,8'-iminodioctylamine (ETH 7025)
Ionophore V = 7-[(1-Adamantylcarbamoyl)acetyl]-16[(octadecylcarbamoy;)acetyl]-1,4,10,13-tetraoxa-7, 16-diazacyclooctadecane (k22b1b5)
Ionophore VI = 1,3,5-Tris[10-(1-adamantyl)-7,9-dioxo-6,10-diazaundecyl]benzene (ETH 5506)

necessary to modify the value of this indicator. Second, sweet peppers are not necessarily harvested daily. In some cases the model has shown periods of 2 or more days without harvest.
Plant transpiration is therefore the only element with a fast high change rate that comes into play in the criterion. The direct consequence is that this element must always have a rather high relative importance in the criterion for the expert system to find a difference from the reference value. Indeed, if all strategies tested cannot elicit a change in the model response because of these low change rates of the elements in the criterion, all strategies will be equivalent and will be especially equivalent to the reference one which is preferred in such a case.

However, in situations of variable outside weather (more precisely variable outside forecasted radiation), the expert system gives solutions that are somewhat different from the reference one. At low irradiation levels it suggests higher electrical conductivity to increase the concentration of the absorbed solution so that the reduction of transpiration due to the climate does not limit nutrient uptake. The results of the application of the expert system solutions to the crop are given in paragraph 4.13.

4.11 Real Time Controller

Fertigation results
This methodology has been applied in real conditions at the CTIFL Carquefou site to control water and nutrient supply to the plants. To avoid discontinuity of the humidity in the slab and wrong drainage values, we have programmed particular set-points (SP) functions (Figure 4.11.1). t_1, t_2, t_3, HR, t'_1,t'_2 and r_{final} are programmed by the user.

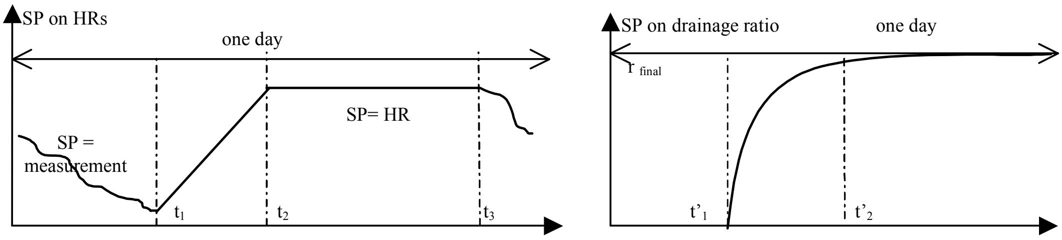


Figure 4.11.1. Set-point adjustment (fertigation control experiment).

Figure 4.11.2 summarizes the main results obtained between 7 and 13 June 2004.

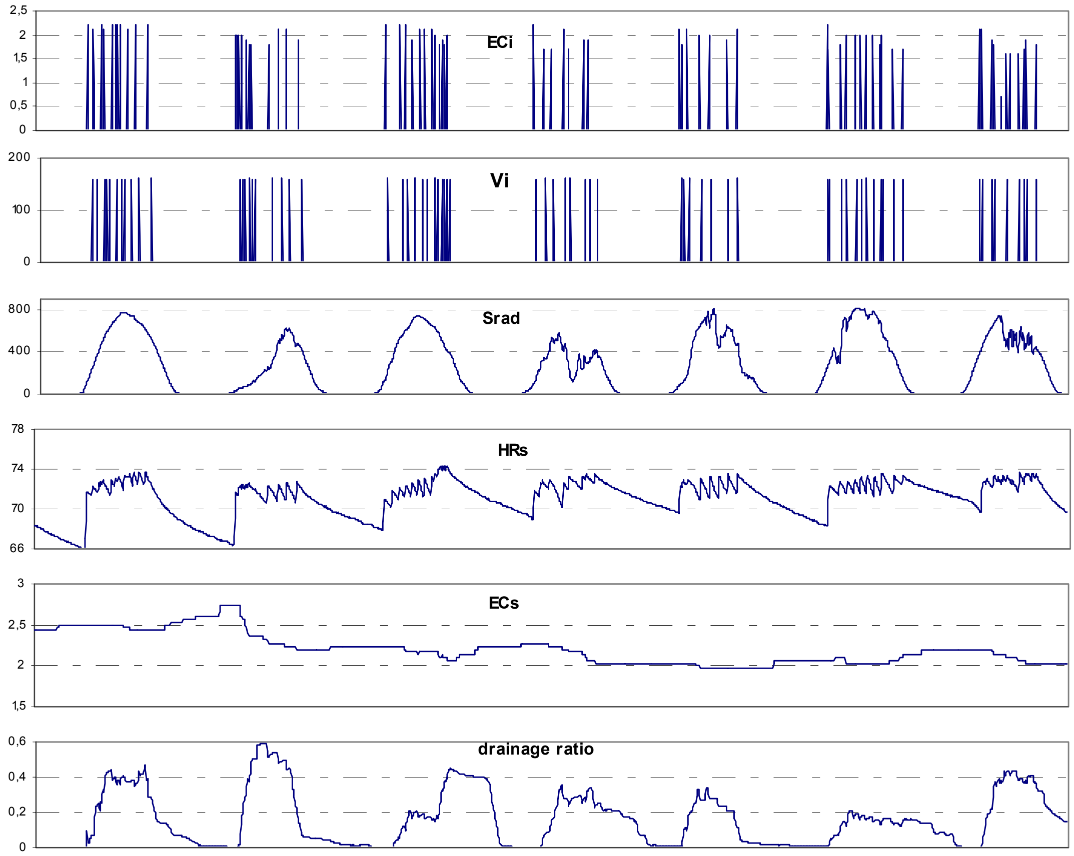


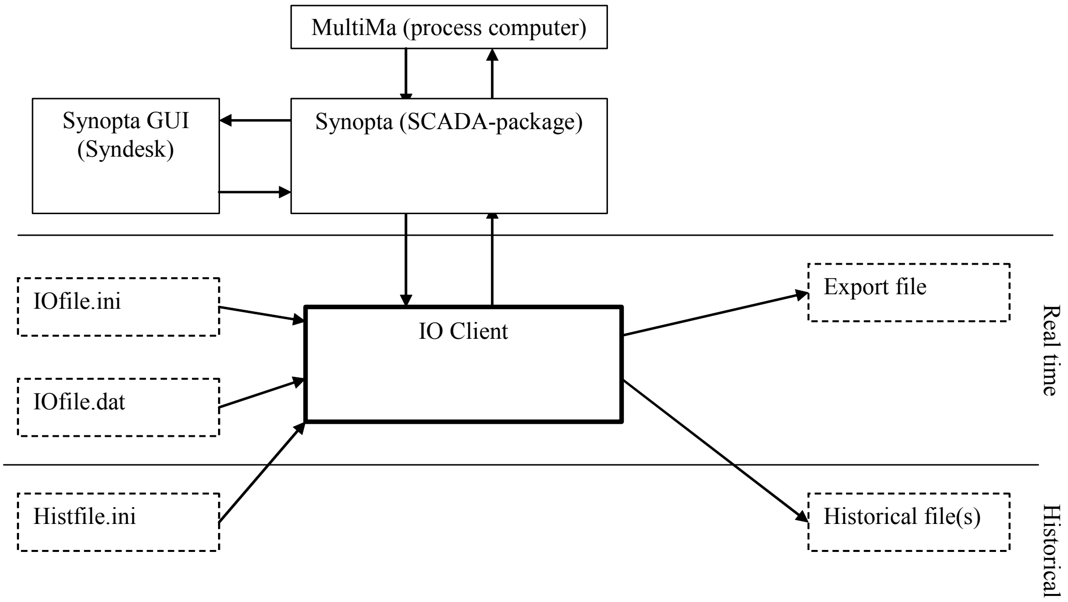
Figure 4.11.2. The 3 inputs (Vi, ECi, SRad) and the 3 outputs (HRs, ECs, ratio) in the fertigation control experiment. The selected parameters are given in Table 4.11.1.

Table 4.11.1. Experimental parameters and set-points in the fertigation control experiment.

Experimental parameters	Set-points		
H_{deb}=8H45 H_{fin}=19H15	HRs	ECs	Drainage ratio
Weighting parameters	t_1=7H35		t_1=9H30
λ_{HRs}=3, λ_{ECs}=3, λ_{ratio}=1, no costs	t_2=10H15	2.4 à 2.7	t_2=13H00
Threshold parameters and values	HR=72.5% à 75%		r_{final}=0.40
k_{Vi}=35 à 50% k_{ECi}=5% U_{vi}=160ml			

4.12 Technical infrastructure

The implemented software interface consists of the following modules:



The Multima process computer is the standard HortiMax process computer which controls the irrigation and climate processes. The Synopta SCADA package takes care of managing the user inputs, and stores the historical data. The newly developed IO Client is able to communicate actual or historical process data from the Synopta package to the different submodules such as the Real Time Controller or the Expert System. It is also able to take irrigation commands and set-points from the Real Time Controller and implement them via the Synopta/Multima process chain. Which commands are accepted and which data are communicated, is determined by the files Iofile.ini, iofile.dat and histfile.ini. These files have the following structure:

'hist ini file'

```
filename;{path}{filename}
intervaltime;{min}
var;{name specification};{address};{controllerid}
```

Example: 'histfile.ini'

```
filebase;c:\data\hist\identif
intervaltime;10
var;temp1;3433a001 bb432001 56500004;1
var;EC1; 3231b001 bc432001 16500004;1
var;EC2; 3231b002 bc432001 16500004;1
```

'Hist file'

- Name of the file: {filebase}_{filedate}.dat
- The first line is the 'header-line' that contains the variable names
- Lines are defined as: {Date};{Time};{Var1.value};{Var2.value};…;{Var'n'.value}

```
Date;Time;temp1;EC1;EC2
24/11/2004;00:00:00;34.34;2.1234;3.23
24/11/2004;00:10:00;32.34;2.12;12.23
……
```

Example: 'identif_24112004.dat'

'IOFile.ini'

The aim of this file is to define the needed variables in the RTC part of the IO Client so that self-defined variable names can be used instead of variable addresses.

Specifications:

- First line contains Outputfile name
- Definition of a line: var;{varname};{address};{controllerid}
- There can be defined x variables

Example of: 'IOFile.ini'

```
Outputbase;c:\data\export\RTD_export
var;temp2;3433a002 ba432001 56500004;1
var;temp3;3433a003 ba432001 56500004;1
var;EC10;343a2003 aa132001 12300004;1
var;EC11;343a2004 aa132001 12300004;1
```

'IOFile.dat'

- The 'IOFile.dat' contains the variables and corresponding times to 'get' or 'set' values in/out the defined variables.
- If a variable must be retrieved/set immediately; the date and time must be made zero; e.g. '00/00/0000;00:00:00'.
- The IOFlag defines whether a variable is been set(0) of get(1). When a variable is 'get', it is not necessary to give a Value.
- No header line needs to be given.
- A line has the specification: {Date};{Time};{VarName};{IOFlag}(;{Value}).

Example of 'IOFile.dat'

```
00/00/0000;00:00:00;temp2;1
00/00/0000;00:00:00;temp3;1
03/03/2004;12:25:00;temp2;1
00/00/0000;00:00:00;EC10;0;2.345
00/00/0000;00:00:00;EC11;0;2.445
```

The following remarks can be made regarding the example above:

1. Temp2 is gotten immediately (line1), and at 03/03/2004;12:25:00 (line3)
2. When there is a new file 'IOFile.dat' before 03/03/2004;12:25:00, line3 is not executed at that time.

Export file

The export file contains the values of the retrieved ('get') variables.

- The filename will be: '{filebase}_{filedate}.dat'
- The lines are containing the value of one specified variable. Line specification: {date};{time};{varname};{value}
- The first line holds the header.
- The output is appended, if there is no file available a new file is made.

Example of: 'RTD_export_24112004.dat'

```
24/11/2004;02:00:01;temp2;23.34
24/11/2004;02:45:01;temp2;23.34
24/11/2004;03:12:01;temp3;21.11
24/11/2004;03:12:01; EC10;1.11
….
```

4.13 Closed system

Comparison of the CLOSYS system, in which the plant and substrate models are integrated into an expert system, the real time controller, new slab type and the multi-ion sensor, with the system which is now commercial practice in sweet pepper growing showed a lower plant water consumption in the CLOSYS treatment than in the standard treatment (Figure 4. 13.1). The percentage drainage in the CLOSYS treatment was found to be higher than the standard treatment at the beginning of the experiment. After the RTC was added to the CLOSYS system, differences in drainage percentage were no longer found (Figure 4.13.1). The substrate humidity of the Grotop Master substrate of the CLOSYS treatment was found to be higher than in the Master classique substrate of the standard treatment (Figure 4.13.2).

In the beginning of the experiment, nutrient concentrations in the drainage water did not differ between the CLOSYS system and the standard system (Figure 4.13.3). However, when the expert system became active in the CLOSYS system, the ratio K/Ca+Mg was found to be higher in the CLOSYS treatment than in the standard treatment. Furthermore, at that time an accumulation of Na and Cl in the drainage water of the CLOSYS treatment was detected.

Plant growth and development between the CLOSYS treatment and the standard treatment was found to be very similar. No differences were detected in leaf area development, LAI (leaf area index), fresh and dry weights of the different plant organs (leaves, stems and fruits) or in dry matter contents. As can be seen in Table 4.13.1, fruit yield and quality did not differ between the CLOSYS and the standard treatment, although plant water consumption, substrate humidity, K/Ca+Mg ratio and the concentrations of Na^+ and Cl^- in the drainage water did differ.

Table 4.13.1. Sweet pepper fruit yield and quality of plants grown in the standard treatment or CLOSYS treatment.

Treatment	Marketable fruit number (m^{-2})	Marketable fruit weight (kg m^{-2})	Average fruit weight (g fruit^{-1})	% in class 1
Standard	112.7	21.2	188	94.1
CLOSYS	116.3	21.3	183	94.1

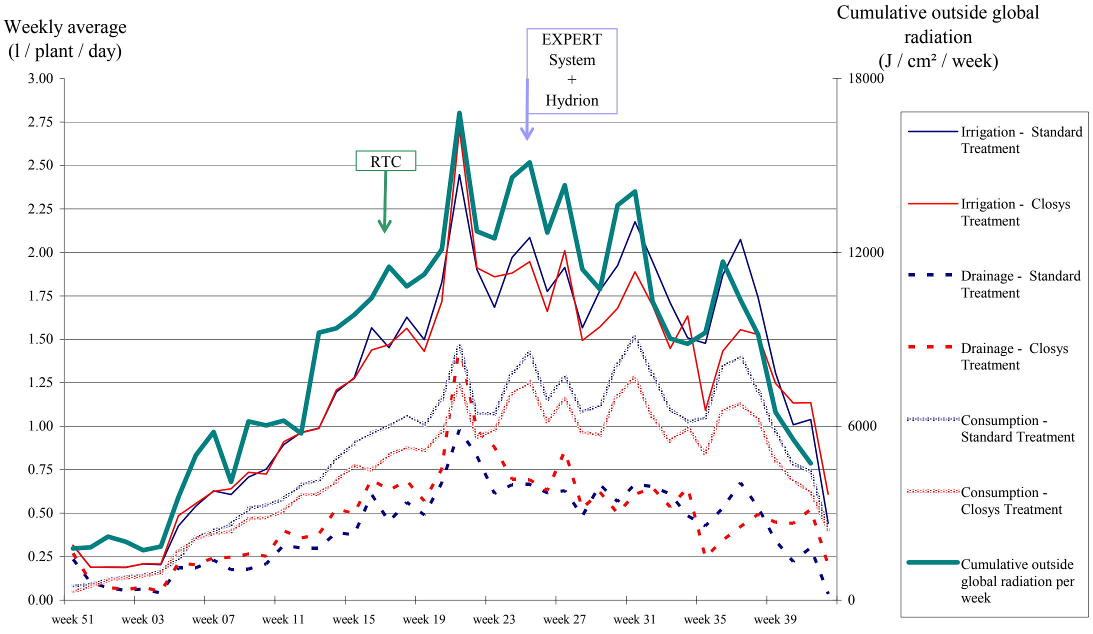


Figure 4.13.1. Course of irrigation, drainage and water consumption in the CLOSYS system and the standard system.

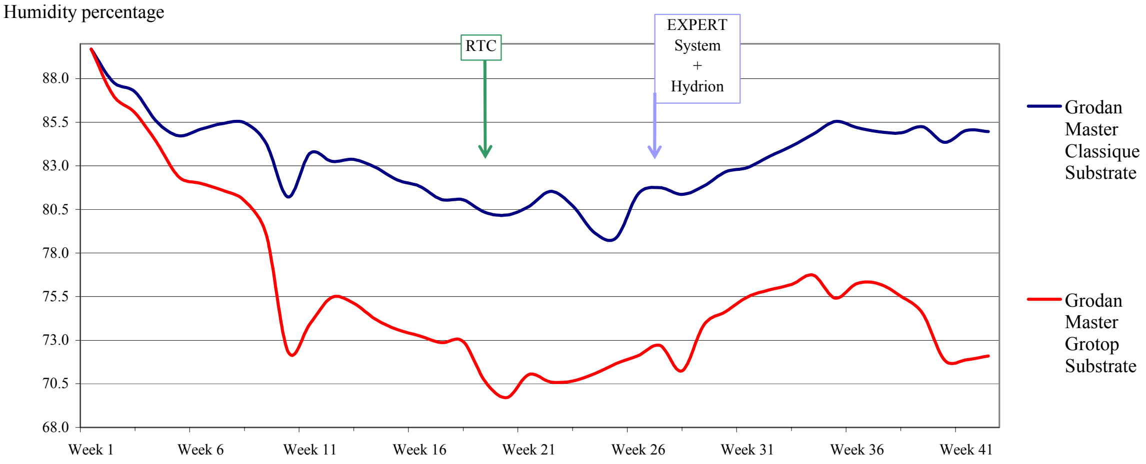


Figure 4.13.2. Course of the substrate humidity of the Grotop Master (CLOSYS treatment) and Master Classique (standard treatment).

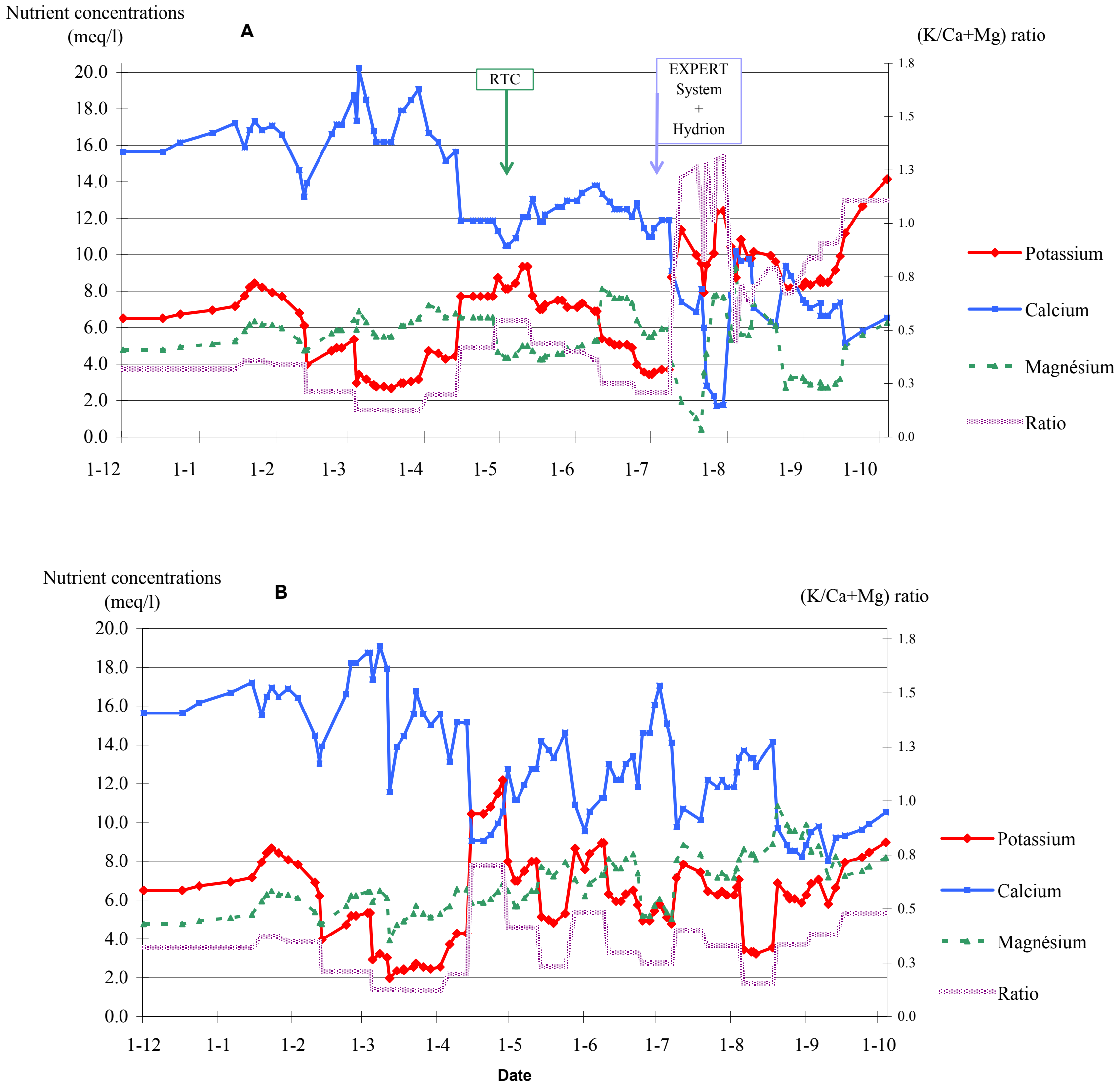


Figure 4.13.3. Course of nutrient concentrations in drainage water in the CLOSYS treatment (A) and the standard treatment (B).

The self-training properties of the plant model, being part of the expert system, were used in the Carquefou 2004 final field test. For this, first the self-training approach was applied to the historical data set of the Carquefou 2003 experiment. As a result of this self-training, a good agreement was found between simulated and observed values of 2003 of cumulative dry matter production, plant nutrient concentrations (except for S), and plant water consumption.

Subsequently the associated parameters for total dry matter production and organ nutrient concentrations did not require self-learning in the 2004 final field test again. On the basis of the online sensor on leaf area, self-learning of leaf area growth parameters was carried out in the 2004 field test, since considerable deviations occurred between measurement and simulation with the 2003 self-trained model (see paragraph 4.6). Apart from leaf area parameters, the model required self-learning for fruit abortion rate on the basis of the recorded fruit harvests. In 2003 it was already noted that the abortion parameter values changed with crop development. In the 2004 final field test this pattern was again slightly adjusted to simulate the wavy pattern of fruit production correctly.

In summary, the self-training in 2004 resulted in better modelling results with respect to LAI and harvested fruit number. The correction of LAI simulation resulted in an increased amount of simulated intercepted radiation. The resulting higher assimilation rates had to be decreased again in the self-learning process by decreasing model values on photosynthetic capacity.

As for the 2003 experiment, the self-learning model in 2004 showed good agreement between simulated and observed values of cumulative dry matter production, plant nutrient concentrations (except for S), and plant water consumption.

The Real Time Controller (RTC) was found to generate appropriate commands which satisfied Expert System irrigation set-points (substrate humidity and electric conductivity + drainage percentage). In order to avoid over- or under-irrigation, the weighting parameters of RTC set-points need to be carefully adjusted since the drainage percentage should not be overweighed in comparison to substrate humidity and electric conductivity. Furthermore, especially for the irrigation volume, command parameters have to be carefully adjusted to appropriate ones. Drainage percentage and electric conductivity set-points also have to be progressively adjusted with time. Finally, the irrigation dose has to be automatically adapted to the irradiation.

In the comparison of the CLOSYS system and the standard system, the multi-ion sensor performed continuous measurements of the irrigation and drainage solutions. From these measurements it became clear that the multi-ion sensor had a good measurement accuracy if the appropriate correcting calculations, maintenance and sensor recalibration were done. The sensor had a good measurement repeatability, which was better during the night than during the photoperiod, due to less temperature and process disturbances. The multi-ion sensor results were found to be very similar to laboratory analyses (Figure 4.13.4), which could enable growers to anticipate to drainage nutrient concentration changes and to make more accurate fertilizer calculations, rather than what is now common practice: adapting drainage nutrient concentrations mostly according to drainage electric conductivity.

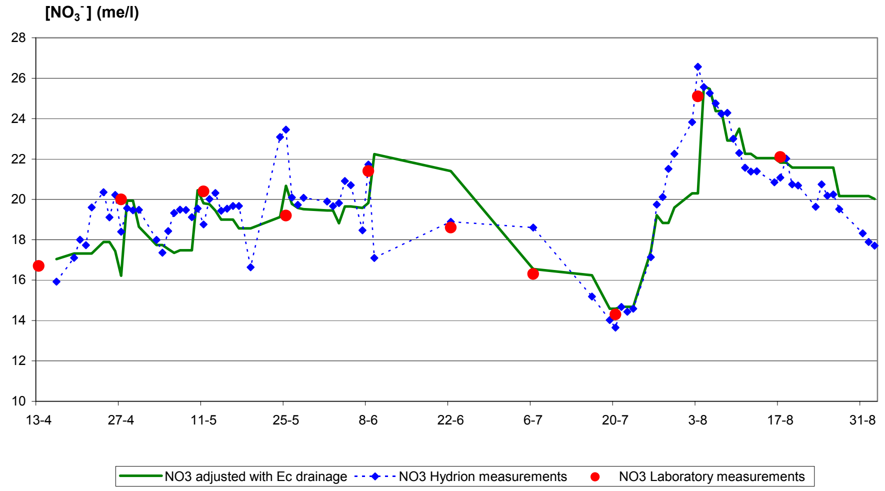


Figure 4.13.4. Comparison of NO_3^- concentrations in drainage water measured by the multi-ion sensor and laboratory analyses.

5. Discussion

5.1 Fluorescence imaging sensor

In greenhouses, plants are under constantly changing conditions. Light intensity, water availability, temperature, carbon dioxide level vary continuously. When these conditions come beyond critical levels, the plants will experience stress. Sensors that are able to detect the occurrence of plant stress in an early stage would be most useful to avoid stress conditions to last. Especially when this sensor would be able to indicate the type of stress from which the plant is suffering, a rapid adjustment of the greenhouse conditions would be possible, thereby avoiding long-term plant stress.

A promising sensor for this goal might be a fluorescence imaging sensor, as described in paragraph 3.1. Buschmann & Lichtenthaler (1998) have investigated the possibilities to use fluorescence imaging as a detection method for plant stress. They concluded that the fluorescence ratios blue/red (440 nm/690 nm) and blue/far-red (440 nm/740 nm) proved to be very early stress and strain indicators, since they change with the beginning of the stress or strain and long before damage of the photosynthetic apparatus is detectable. Furthermore, they state that the fluorescence imaging technique represents an excellent means to differentiate between certain types of stress. Some types of stress and their effect on the fluorescence ratios are indicated in Table 5.1.1.

Table 5.1.1. Changes of fluorescence ratios blue/red, blue/far-red, red/far-red and blue/green in leaves as indicators of strain or stress in plants (based on Buschmann & Lichtenthaler, 1998).

Conditions	F440/F690 blue/red	F440/F740 blue/far-red	F690/F740 red/far-red	F440/F520 blue/green
Photoinhibition	++	++	–	0
Water deficiency	++	++	0	0
Sun exposure	++	++	+	–
Heat treatment	–	–	0	-
N deficiency	++	++	+	0

++ = strong rise
+ = rise in fluorescence ratio
– = strong decrease
- = decrease in fluorescence ratio
0 = no significant change

In the sensor part of the CLOSYS project, we investigated whether these relationships, established for arable crops, also fit for greenhouse grown crops.

Under conditions of nitrogen depletion, visible symptoms in sweet pepper occur after approximately 8 days. Approximately 2 days earlier, photosynthesis rates of the nitrogen-depleted plants were found to decrease. Fluorescence measurements on the nitrogen-depleted plants were done with all 3 fluorescence sensors described in this report. Both with the sensor of the University of Karlsruhe and the CFM meter (University of Budapest) higher blue/red (F440/F690) and blue/far-red (F440/F740) ratios compared to the control treatment were detected after 6 and 3 days, respectively. The other fluorescence ratios did not change due to nitrogen depletion. These findings are largely in accordance with the table above.

Under drought stress, the decrease of water content alone does not lead to a change of the fluorescence signatures. This could be clearly shown by the experiments with the rapid water loss by detaching the leaves from the plants. Fluorescence signatures seem to change only when the plant adapts within days to the drought stress by impairing the photosynthetic apparatus and changing the quantity of blue and green fluorophores. Our experiments do not reveal clearly which parameters could be used for drought stress detection. Results between treatments were not unequivocal, especially for rose and to a lesser extent for sweet pepper.

Oxygen stress in the root zone was found to have severe effects on sweet pepper plants. Plants lost their turgescence within 1 day, resulting immediately in a strong reduction in photosynthesis rates and growth rate. In rose, the same occurred, but only after approximately 6 days. Fluorescence signals of 440, 520, 690 and 740 nm were found to be lower for the oxygen stressed plants than in the controls from day 4 on. However, since photosynthesis rates decreased dramatically after 1 day of oxygen stress, red and far-red fluorescence were expected to increase. The reason for this discrepancy between expected and observed results remains unclear. In conclusion, the relation between oxygen stress in the root zone and fluorescence imaging signals need further clarification.

When sweet pepper plants were submitted to heat stress, fluorescence in all spectral ranges detected was found to increase. In sweet pepper, the ratio F440/F690 decreased slightly due to the heat treatment; this effect, however, was not detected in all experiments performed. The fluorescence ratios F440/F740, F440/F520 and F690/F740 remained more or less unaffected by the heat treatments. Rose plants did not react strongly to the heat treatments applied, and results on the fluorescence images were therefore not unequivocal.

Using a plant sensor to establish a relationship between reflection and leaf area index appeared to be very promising. Experimental results show an exponential relationship between R460 and LAI, indicating that LAIs up to approximately 2-2.5 can be accurately measured by means of reflectance.

5.2 UV-LED array

Spot measurements

In summary, two types of spots can be created with the UV-LED array light source (Figure 4.2.1):

- a homogenous, less bright spot with a diameter of about 180 mm, and
- an inhomogeneous spot with a 2.5-fold brighter region in the centre (about ∅60 mm).

Fluorescence imaging trials

The first fluorescence imaging trials on plants showed very good results: the efficiency of generating fluorescence was the same as that of the Xe-arc lamp system.

5.3 Portable fluorometer

Verification experiment

Both the absolute fluorescence values at 690 and 735 nm (not shown here) and the fluorescence ratios (illustrated in Figure 4.3.1) clearly distinguished the different test groups of sweet pepper. The sensitivity of the measurements was high enough to observe differences as early as in 3 days – in case of strong N deficiency. However, the Fe and Ctrl groups turned to be almost identical suggesting that the condition of a serious Fe deficiency was not achieved. Later on, the visual observations verified this finding as shown in Figure 4.3.2. and verified the reliability of fluorescence signatures.

Final field test

Evaluation of the rational curves of Figure 4.3.3 shows that there is no significant difference among the groups. The cumulative fluorescence signatures of Figure 4.3.4 for the CLOSYS and the classical fertigation schemes again indicate that there is no significant difference between the two techniques. Both curves show an almost identical weekly fluctuation, suggesting that the greenhouse climatic conditions (e.g. solar exposure) have a more significant effect on the fluorescence signatures than any stress factors induced by the different fertigation schemes. To verify this hypothesis, we first investigated the trend of the temporal fluorescence, then correlated the temporal changes to the accumulated climatic and fertigation data.

According to a simple calibration model, the fluorescence signatures taken for the classical fertigation scheme is considered as a reference and the CLOSYS data is normalized to this reference. Such curves of all 4 fluorescence ratios are plotted in Figure 5.3.1. This shows that the normalized F440/735 signature displays a slight increasing trend. If, however, this was a result of the presence of any stress factors, the normalized F690/735 ratio should also change. This is not the case, however. The temporal trend for F690/735 remains constant, again proving that no stress factors were introduced with the new (CLOSYS) fertigation scheme.

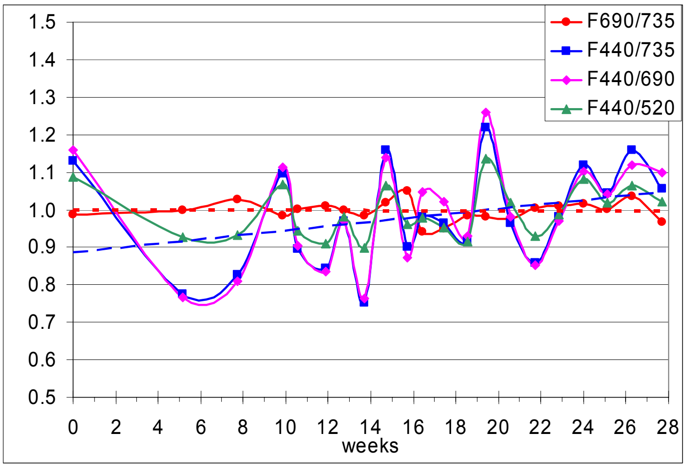


Figure 5.3.1. Temporal change of rational fluorescence signatures in the CLOSYS fertigation scheme normalized to that of the classical scheme with linear regressions for the F690/735 (red short dash) and F440/735 (blue long dash) ratios.

Temporal fluorescence changes were correlated to the accumulated climatic (solar radiation) and fertigation (irrigation volume) data. Only data pairs recorded weekly were compared, i.e., a total of 14 data pairs between calendar weeks 14-21. There is a week shift (uncertainty) between the data pairs, since a single day fluorescence data is compared to a weekly average of climatic and fertigation data. The irrigation volume is well correlated to the solar radiation with a coefficient of R^2>0.85 for both the classic and the CLOSYS treatment (not shown here). More interestingly, the fluoresce ratios F440/690 and F440/735 correlate strongest to the irrigation volume as shown in Figure 5.3.2 (with the convincing R^2=0.83 and 0.62 for the CLOSYS and the classic treatments, respectively).

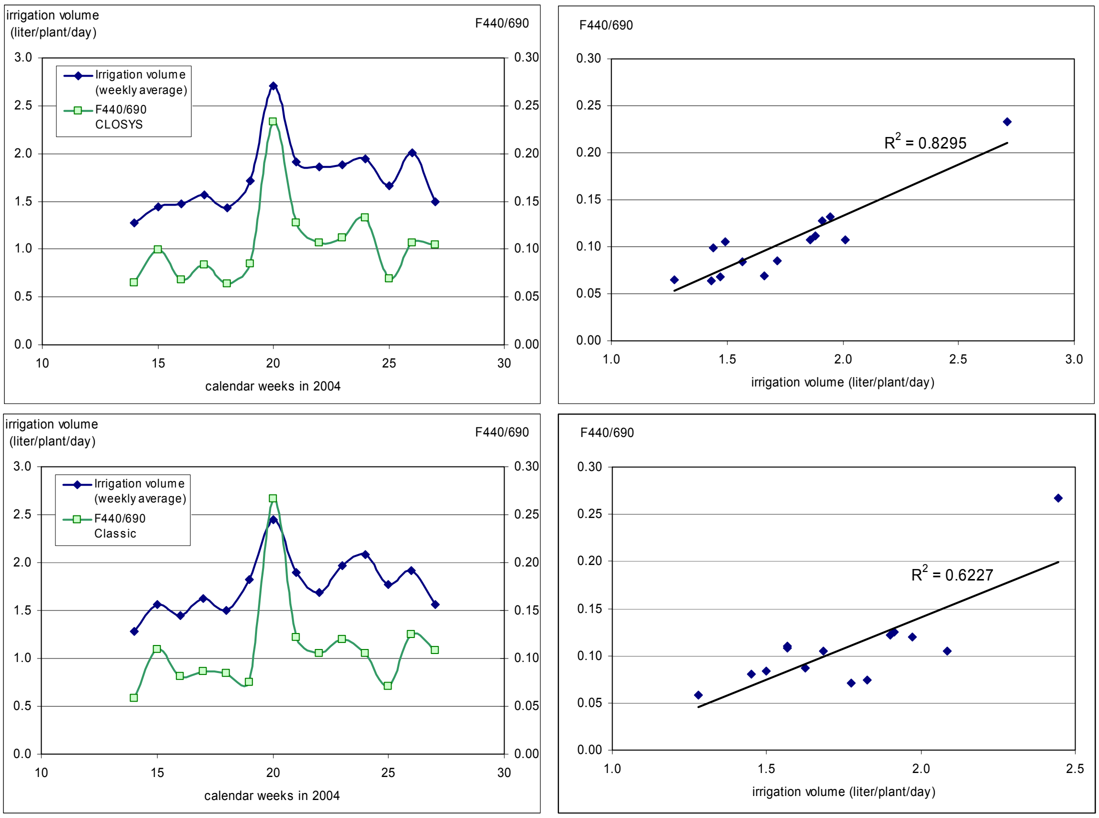


Figure 5.3.2. Comparison of the temporal F440/690 fluorescence to the irrigation volume (left) for the CLOSYS (top) and classic (bottom) fertigation scheme. Right: linear regression and correlation between the two parameters.

According to the results described in paragraph 3.1, the increase of F440/690 and F440/735 can be connected to both the water deficiency and high light stress of plants. This and the correlation data suggest that temporal water deficiency might occur in the plants in case of elevated outside global radiation.

5.4 Water and nutrient demand rose

Long- and short-term experiments

The uptake process of NO_3, PO_4 and SO_4 is actively regulated by the plant (Epstein *et al.*, 1963; Forde & Clarkson, 1999). This active absorption enables the plant to absorb the necessary amount of these elements even when their concentrations in the nutrient solution are lower than the optimum (Adams & Grimmett, 1986; Masey & Winsor, 1980; Draw *et al.*, 1984). Different demanded concentrations of NO_3 and PO_4 were measured during different cultivated periods; this may be attributed to the different greenhouse environment conditions (temperature and light intensity). The concentrations of NO_3 and PO_4 in the leaves and in the shoots of the plants were found to correlate to the light intensity and the temperature sum during the cultivation period, when there is no limitation in nutrient supply. In contrast, there is no correlation of the SO_4 concentration in plant leaves and shoots with the above greenhouse climatic parameters.

Good correlations were found between the concentrations of Ca and Mg, Ca and K as well as between the concentration of Mg and K in the nutrient solution. As expected, the Ca concentration in the leaves was correlated with the transpiration of the plant (Adams, 1991) and the concentration of this element in the nutrient solution (Bell *et al.*, 1989; Gunes *et al.*, 1998).

The critical level (% DM) was determined for some of the nutrient elements in different plant organs (leaves, shoots and roots), during the hot period (spring and summer) and during the cold period (autumn and winter) of the year. In many cases it was not possible to determine the critical level as the increase of the concentration of a nutrient element in a plant organ (% DM) caused an increase of the plant's growth. For example, the increase in plant growth caused by a continuous increase in NO_3 concentration in the leaves, during the hot and cold period. The same was observed with the increase in PO_4, SO_4, Ca and Mg concentrations in the leaves but only during the hot period.

For the hot period (spring and summer), time constants were determined for PO_4, SO_4 and Ca. During this period, 7 days depletion did not decrease (lower than 50%) the concentrations of NO_3, Mg and K in the tissue of the treated plants compared to the control plants. For the cold period (autumn and winter), time constants during recovery period were determined for NO_3 and PO_4. During this period, 7 days depletion did not decrease (lower than 50%) the concentrations of SO_4, Ca, Mg and K in the tissue of the treated plants compared to the control plants. One day depletion was enough to decrease the SO_4 concentration (%DM) in the tissue of the treated plants more than 50% compared to the control plants during the hot period of the year (spring and summer). Rose plants did not recover when depletion of this nutrient element lasted for a longer period.

Validation experiments

The initial total LAI for plants irrigated with high (HIF) and low (LIF) irrigation frequency was about 0.27. However, after that point, the values of the total LAI observed in the case of the plants with HIF were always higher than those observed in the case of the plants with LIF. However, the statistical analysis performed in order to check the significance of the effect of irrigation frequency on LAI evolution showed that there were no significant differences ($p< 0.05$) between the two treatments for shoot LAI. However, based on the LAI trend observed in both treatments during the period of measurements, possible continuation of measurements over a longer period could have revealed a positive effect of HIF on LAI.

From the greenhouse and crop microclimate modification point of view, a high LAI should enhance the bulk (canopy) aerodynamic and stomatal conductance (Katsoulas *et al.*, 2002) and thus, maintaining a high value for LAI in the greenhouse significantly increases gas exchanges, which sequentially modify the internal greenhouse climate, mainly air temperature and vapour pressure deficit. In turn, these microclimatic changes act on the bulk stomatal conductance; leading to a 'feedback' control, or 'coupling' that has been detailed and formalized in several previous works (e.g. Nederhoff & Vegter, 1994).

Concerning the production of harvested flowers, both treatments followed almost the same trend during the period of measurement, with the values of total fresh weight of shoots harvested from the crop with HIF most of the period being higher than those observed for the crop with LIF. However, statistical analysis showed that there were no significant differences between both treatments. The ratio of dry to fresh weight of harvested shoots was almost constant during the period of measurement for both treatments.

The values of cumulative shoot dry weights were higher for HIF than for LIF. However, normalizing the dry weight values above for total crop LAI removed the differences observed and discussed above. Plants irrigated with high frequency produced slightly longer stems than those under low frequency irrigation. However, statistical analysis revealed once again that there were no significant differences between both treatments.

5.5 Water and nutrient demand sweet pepper

Short-term experiments

Figure 3.5.1 shows the concentration decrease of the depleted nutrient in leaves. Sweet pepper leaves show the most rapid response under K starvation, caused by the nature of its transportation within the plant (Marschner, 1989), whereas the leaf Ca concentration decrease appeared after 6 days of starvation. Root nutrient concentration decreases from the beginning of the starvation treatment in all cases. The cation ratios were also rapidly affected; nevertheless, the cation sum remained fairly constant along the 14 days of starvation.

The effect of 14 days P, K and Ca starvation on the vegetative phase of pepper growth was limited. Only in case of nitrogen starvation an effect is noticeable: after 8 days of N shortage a reduction of both leaf area and weight was observed. By contrast, nutrient (N, P, K, and Ca) concentrations in organs decreased along the corresponding starvation experiments. The reversibility of the effects of nutrient starvation in the recovery period could be considered complete (in terms of nutrient concentration in the plant) for N, P and K, whereas for Ca this was only partially achieved.

Long-term experiments

Nutrient concentration values in leaves 3 - 6 weeks after the start of the spring experiment (the vegetative stage running from flowering to the beginning of fruiting) can be considered most relevant as these are usually used as reference for diagnosis prospect. N, P, K, Ca and Mg concentrations in the leaves corresponded with those referred to by Jones *et al.* (1991) and Zornoza *et al.* (1986) as sufficient in fully expanded leaves for sweet pepper bell type. Higher values, however, were obtained for K.
Plant nutrient demand in spring is approximately three times than in autumn, just nutrient concentrations and plant weight mentioned above. A linear relationship between each macronutrient (N, P, K Ca and Mg) content and time was found. Significant correlation coefficients were obtained. The linear slopes were marked as indexes for the nutrient uptake rate. As expected, the nutrient uptake rate was higher in the spring experiment than in the autumn experiment. For both experiments, the highest uptake rate was obtained for K and the lowest for Mg.
Yields for both experiments were very different also: 1381 g per plant in spring against 367 g per plant in autumn. Several authors (Stanhill & Cohen, 2001) have reported low harvestable yields when radiation was reduced to any degree, but this light load decrease not only affects harvestable material but also potential plant growth, which is also dependent on plant growth stage. A positive and highly significant relationship between cumulative radiation and dry matter production, irrespective of the growing season, was found. Several authors (De Pinheiro & Marcelis, 2000) have reported that dry matter productivity in crops is proportional to the amount of solar radiation absorbed during a growing season. High correlation was also found with nutrient content and radiation (Figure 3.5.2b).

Validation experiment

High plant density and high irrigation frequency resulted in the lowest fresh vegetative weights and in the highest fruit yield. Extensive data sets were gathered in order to validate the plant model.

5.6 Plant/substrate model

The goal was to develop a model that could predict crop growth and demand and uptake of water and individual nutrients of sweet pepper and rose. This goal was achieved, even though the simulation of interaction between the uptake of different nutrients requires further attention. A number of developmental and physiological processes remain difficult to describe. Node formation rate of sweet pepper towards the end of the season, the associated individual fruit weight and dry matter partitioning of mature plants, and shoot dynamics of rose are some examples.

Such shortcomings, however, do not hamper the application of a crop growth model in the management of water and nutrients. The self-learning capacity on the basis of historical and recent data sets enables the user to fine-tune the model to the actual status of the crop, and to use the model for adequate and useful forecasting purposes. This was especially proven in the final field trial in Carquefou, 2004. In that trial, the most important determinants for nutrient uptake, i.e. crop biomass and crop nutrient content, could be simulated with the aid of the model's self-learning properties using sensor information. Also the fact that a final field trial is continued in Carquefou in 2005 indicates that the combination of a restricted set of observations, modelling and self-learning is fruitful.

5.7 Substrate characterization and models

Characterization

The substrate FL has a tendency to develop a high humidity in its bottom part, especially under high-frequency irrigation, with a risk of inducing conditions of anoxia for the crop in this part (Riviére *et al.*, 1993; Gislerod *et al.*, 1997; Block, 1999; Bonasia *et al.*, 2001; Stepowska, 2002). EX, on the other hand, has so high a hydraulic conductivity that its top part is often too dry, especially under low-irrigation frequency. On the other hand the high hydraulic conductivity of EX allows more variation in water content, and a fast turnover of the nutrient solution may be expected, which may be useful to regulate the root environment. These results were used to suggest the design of an improved rockwool slab to obtain a better distribution of water and roots in the slab. To maximize the colonization of the slab space by the roots, the water content must be kept between excessive saturation, to avoid anoxia, and excessive dryness, to allow root absorption

Comparing the root distribution with the humidity values obtained in the same experiment, showed that the differences in root distribution according to treatment leads to roots located mainly in the slab parts where water content is high (RWC > 50%), but not saturating (RWC < 90%). In EX slabs, the roots grow quickly to the bottom of the slab, and are almost totally absent from the top part, especially under LF irrigation. In FL slabs, the roots remain more in the top part of the slab, especially under HF irrigation. So the roots are able to colonize only those parts of the substrate where both water and oxygen are available. It has similarly been shown that the distribution of tomato roots in various substrates is affected by the position of the drippers (Leonardi *et al.*, 2003). On the other hand, the availability of oxygen is an essential factor affecting root distribution (Vidal, 1988).

During the propagation of rose cuttings, applying a water tension of up to 6 cm can enhance root growth of rose cuttings (Baas *et al.*, 1997); this can be explained by the occurrence of oxygen stress when no tension is applied (Gislerod *et al.*, 1997).

In our experiments, the water tension in the substrate has a strong effect on water absorption by the plant. The optimal value is between 1 and 5 cm for rose, and between 0 and 10 for sweet pepper. Nevertheless, the values for sweet pepper should be considered with some caution: the plants used were still actively growing at the date of the experiment, so that during the treatment the growth of roots along the capillary mat, towards the solution tank, was as high as 15 cm in some cases, especially for the treatments at 5 and 10 cm water tension. This means that the tension actually supported by the most active absorbing roots could well have been quite lower than it was supposed to be.

These results pointed out two main points which deserve to be discussed: i) the lack of a model describing substrate colonization by plant roots and the difficulties to validate the numerical results due to the complexity of the characterization of the hydraulic and mineral results within the slab, and ii) the need for a simpler model which could easier be coupled with the plant model for operational uses.

Lack of a model describing substrate colonization by plant roots

A major limitation of our approach lies in the uncertainty of the characterization and modelling of position and activity of the root zone. Though the positioning of this sink term plays a crucial role in the dynamics of water and minerals within the slab, it could hardly been characterized because this requires destructive methods which are very time consuming. Currently, no methods allowing for a quick localization of the roots exist, either experimentally or by modelling and the uncertainty in the estimation of this parameter can generate a strong doubt about the results of the plant substrate model.

A simplified experimental model correcting optimal sweet pepper water and mineral absorption as a function of substrate water content θ and electro-conductivity EC

Due to the difficulties for on-line use of a mechanistic detailed model, a simplified plant-substrate model was developed, which meets the control and expert system needs.

Its major assumptions can be recapitulated as follows:

- WC and EC measurements given by Grodan sensors (WMC) in the substrate are assumed to give an average value of the part of the substrate colonized by roots.
- Substrate suction is deduced from substrate water content.

- Root relative absorption rate is deduced knowing the measured water content and EC.
- Actual absorption is equal to optimal absorption multiplied by relative absorption.

This simplified coupled plant-substrate model allows calculating plant solution uptake and its ions concentration. Using this model and the weather forecasts for the next few days, the Expert System is then used to automatically generate a fertigation strategy to satisfy plant needs and the Real Time Controller applies this strategy via the fertigation computer.

5.8 Improved substrate

A problem in developing an improved substrate was the fact that the properties of the substrate were not constant during the length of a growing season over which a substrate is normally used. Since the growing season is at least one year, it took some time to find out that the properties were not constant during the growing season. These irregularities can probably be solved, but could not be solved within the time scale of the CLOSYS project.
With the results of substrate characterization and modelling (paragraph 4.7), an internal study was performed within the R&D department of Grodan to look for these desired substrate properties. This was mainly dealing with standard properties for our substrates such as water retention, water holding capacity, hysteresis in the pF curve and hydraulic conductivity. Several production trials were done to realize the required properties. Although not all of the trials were successful, the correlation between product properties and the production process improved. Although we learned which factors in the production process had the main impact, changes did not lead to the desired goal. Specific variations were not reduced enough in the time span available.
To be able to use an improved substrate in the CLOSYS system (paragraph 4.13), a new substrate from an alternative development line was used. This experimental substrate slab with properties close to the demands of the CLOSYS project was delivered and used in the final field test of the CLOSYS system.

5.9 Substrate sensor

The results described in paragraph 4.9 show that the tested on-line multi sensor probe which includes sensors for Na^+ was developed successfully. However, the development of a Mg sensor that could be implemented in the multi-ion sensor unit and could be used for measurements in greenhouses proved not to be successful. A ‘Soft sensor’ for an indicative measurement of Mg^{++} was found to be possible but for practical use further examination is needed.

5.10 Expert system

Crop transpiration and hence crop nutrient uptake depends on the environmental conditions around the crop and on the interactions between the crop roots and the slabs. Transpiration is driven by the net radiation balance of the crop and by the water vapour deficit in the greenhouse, but may be limited by the root uptake rates. During the day, the net radiation evolves from low values (night) to possibly high values (bright day), and so does the crop transpiration if water absorption is not limited. Hence it is expected that the concentration of the solution absorbed by the roots evolves during the day and should be less concentrated at times of high transpiration. However, it is not possible for the expert system to define decision steps within the day because water and nutrient absorption determined by the model are only available once per day when daily growth is computed.

Defining daily decision steps implies that the expert system provides the user with daily average target values for the slab states. All possibilities offered by closed recirculating systems are therefore not exploited and the solution proposed is only suboptimal with respect to the knowledge available and the physical capacities of the system. On the other hand this feature limits the number of decision steps to the number of days over which weather forecasts are available, a very low number. It is therefore possible to apply a forward dynamic programming algorithm instead of a Q- or R-learning algorithm of the reinforcement learning class. Computations are limited and an exhaustive search over all possible fertigation strategies can be adopted.

The model also gives the daily values for the individual uptake of the mineral elements. This information is not directly used in the expert system, but it is given to the user along with the solution (a solution is a set of slab relative humidity and electrical conductivity). The user can use this information to determine the ionic composition of the solution that will be used in fertigation to maintain the set-points provided by the expert system.

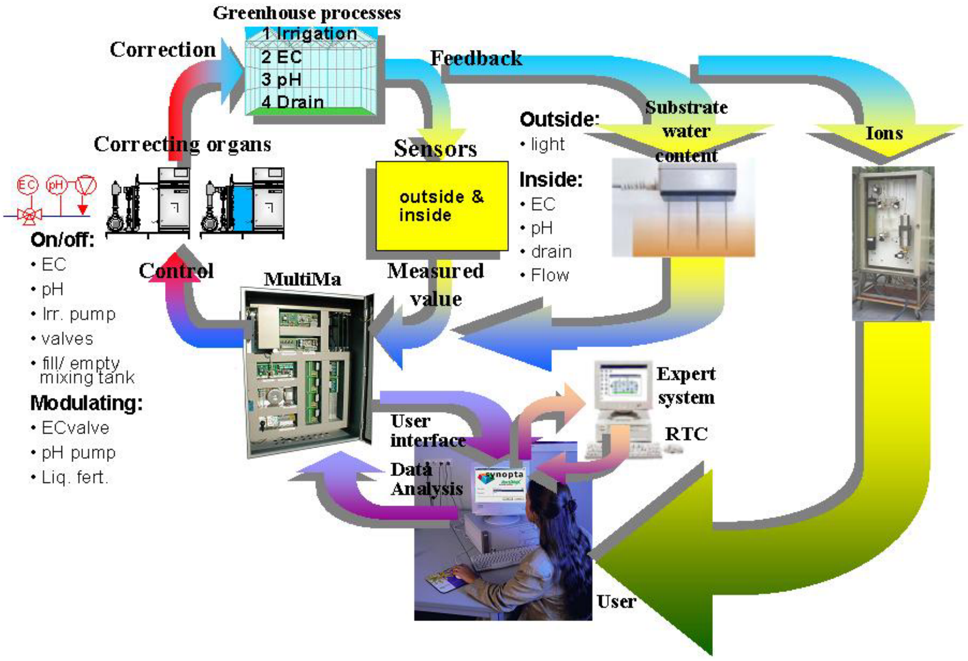
5.11 Real Time Controller

The final result is always a compromise between all the parameters. The most important values to determine are weighting parameters: Uthreshold (depends on the process) and kthreshold.
General rules could be:

- do not weigh drainage ratio too much,
- HRs and drainage ratio set-point functions have to be adjusted as precisely as possible, in order to take into account system inertia for drainage and to avoid over- or under-irrigation,
- if the wanted value is under (over) the corresponding set-point, kthreshold parameter could be decreased (increased).

5.12 Technical infrastructure

The implementation of the technical infrastructure in the way as was done has caused the greenhouse control process to be built up in several layers, as shown in the figure below. The elementary control processes are controlled by the Multima.



Feedback control is achieved with outside and inside sensors. Control is also achieved of substrate water content and substrate EC. The measured values are transported via the Multima to the historical database of Synopta and can then be used via the IO client by the real time controller, in order to change the set-points of the irrigation. This real time controller and also the expert system are analyzing the historical and actual data and, on the basis of that, change the control set-points for the Multima. The RTC and the expert system are advanced control blocks, which base themselves on large amounts of data. In case there are problems with these data or with these controls, the simpler process control via the Multima will still be able to control the process in a simpler way. In this way it is ensured that there are different layers of safety, if some of the more advanced modules are for some reason inactive, there are always more simple layers which can take over process control.

5.13 Closed system

The complete CLOSYS system has been running for a number of months, supplying in a first approach the sweet pepper crop with an appropriate amount of water and nutrient. As a consequence, no significant differences in quality or yield were noticed between the CLOSYS and the standard treatment from July to October 2004, in spite of the differences in plant water consumption, substrate humidity, K/Ca+Mg ratio and [Na^+], [Cl^-] in drainage between both treatments. However, there was no difference in plant nutrient consumption between the CLOSYS and the standard treatment.

The CLOSYS systems consisted of different modules. The multi-ion sensor showed a good measurement reliability and repeatability. This sensor system can be considered as an interesting tool for growers, but needs to be improved with regard to maintenance needs.
LAI measurements by reflectance were found to be necessary to calibrate the plant model, of which the simulations were improved due to this calibration between 2003 and 2004.
Functioning time of the expert system was too short for us to be able to evaluate its long-term performances.
The RTC, on the other hand, showed a good reliability and could be considered as an alternative to the PID systems.

6. Conclusions

6.1 Fluorescence imaging sensor

Using fluorescence/reflectance sensor equipment to detect low levels of stress in an early stage is difficult and requires more investigation than performed within the scope of the CLOSYS project before it can be applied successfully in greenhouse management. This development is seriously hampered by the fact that mild stress was found to be not detectable by the sensors. Only severe plant stress could be detected, at a moment at which this stress was already visible by photosynthesis measurement or by visible inspection. The CFM meter developed by the Technical University of Budapest appears to have shown the most promising results. Furthermore, this meter is small and portable and can therefore be used under greenhouse conditions.

6.2 UV-LED array

Comparing the fluorescence images generated by the two light sources (Figure 4.2.2), it can be concluded that the new UV LED-array based light source has the same efficiency in generating fluorescence as the Xe-arc lamp based source. The advantage of the LED array is that it requires a low driving power.

6.3 Portable fluorometer

Evaluation and calibration of the fluorescence signatures yielded the following conclusions:

- Fluorescence monitoring supplied reliable data as no significant deviation was measured between the blocks within a single fertigation scheme.
- No significant difference is found between the CLOSYS system and the classic fertigation schemes suggesting that the CLOSYS scheme did not introduce any significant stress factors to the plants.
- If no stress effects are recognized by any other monitoring systems utilized during the final tests and yet the water/nutrient demand of the plants managed with the CLOSYS system is less than that of the classic scheme, the CLOSYS system can perform more effectively.
- The temporal change of rational fluorescence signatures are reliably correlated with the recorded climatic and fertigation data, suggesting that temporal water deficiency might occur in the plants in case of elevated outside global radiation.

6.4 Water and nutrient demand rose

During a cultivation period, nutrient solutions with different composition must be applied to the culture due to different nutrient demands by the plant's organs.

The critical level for NO_3 in leaves, shoots and roots seems to be much higher than for the other nutrient elements.

The time constant differs for each nutrient element depending on the cultivation period. During spring and summer 7 days depletion did not decrease lower than 50% the concentrations of NO_3, Mg and K in the tissue of the treated plants. In the same way, during autumn and winter 7 days depletion did not decrease lower than 50% the concentration of SO_4, Ca, Mg and K. In contrast, one day depletion was enough to decrease the SO_4 concentration (%DM) in the tissue of the treated plants during spring and summer.

The irrigation frequency affected cut flower fresh and dry weights as well as flower production. Production increased with higher irrigation frequency. lThe quality of rose flowering shoots, however, was not affected by irrigation frequency. In conclusion, it seems that the higher irrigation frequency improved the biomass production but did not affect the quality of harvested flowers.

6.5 Water and nutrient demand sweet pepper

Short-term experiments

Starvation period
The concentration of the depleted nutrients in roots drops rapidly in all cases, whereas in leaves this drop was slower, clearly reflecting nutrient mobility. Only N starvation affects growth parameters. Effects on growth were found only in the –N treatment. The cation sum remained constant, even in the Ca and K starvation treatments.

Recovery period
Nutrient uptake rates were higher for recovered plants in -N, -P and -K treatments. In general, the control values were reached after 6 days of recovery with full nutrient solution. Recovery is not fully achieved in Ca-depleted plants after 6 days of recovery. Ca content in zero–Ca was 80% of the control.

Long-term experiments

Different light loads in the sweet pepper growth cycle promoted strong differences in plant growth, productivity and also in BER appearance. BER disorder seemed to occur when Ca concentration in the fruit was reduced and K/Ca ratios increased promoted by a high light regime. The different pattern of plant growth was probably due to a different behaviour in cation transport and distribution within the plant organs.

Validation experiment
High plant density and irrigation frequency provided the maximum yield per m^2 and the lowest incidence of BER. This treatment also produced fruits with a higher commercial quality. From the two variables studied, plant density appears to be the key in obtaining the highest sweet pepper fruit yield. It must also be concluded that an adequate control and management in greenhouse sweet pepper cultivation is essential to minimize water and nutrient waste, as well as to obtain the highest yield as possible.

Following the initial assumption that cation uptake and regulation is determined by plant anion and water uptake, which is directly related with the amount of radiation they receive at their different phenological stages, some conclusions can be drawn after analysis of the data obtained for the four hydroponic experiments that have been carried out.
Although the main focus of these experiments was on the critical nutrient concentrations and time constants, the study and interpretation of the results also allows making some remarks about the regulation of cation uptake. These remarks are similar as the initial assumption that cation uptake is a water absorption subsidiary since it is transported passively.
In the two long-term experiments carried out over both growing seasons, the evolution of the cation sum is closely related to the evolution of fresh weight of the plant and the different organs and, consequently, proportional to water consumption. This might be the cause of the different total cation amount found in spring and autumn experiments. On the other hand, cation relationship in leaves kept fairly constant.
About the short-term experiments, focused on nutrient starvation and recovery, it can be noted that the cation sum was maintained over the experiment (21 days), but oscillations in cation relationship were found when the plant was cation-starved. Difficulty was found in Ca recovery; in contrast, the recovery of K was fairly complete at the end of the recovery period for all K-depletion treatments.

6.6 Plant/substrate model

A model for the prediction of crop growth and demand and uptake of water and the individual nutrients by sweet pepper and rose has been developed successfully. Self-learning capacity that makes use of historical and recent observations is essential for practical application. Self-learning plant models are powerful tools for prediction of crop behaviour.

6.7 Substrate characterization and models

The effect of water content in the slab on water absorption by the plant can be significant, though not drastic. So it is important to optimize water distribution on the one hand, and substrate colonization by the roots on the other hand. For this it is important to maintain a sufficient relative water content in the top part of the slab and sufficient air content in the bottom part. One possible way of realizing this is to design a ‘hybrid’ substrate, the top part of which has a high density and a low conductivity (FL-type) to avoid too fast drainage and allow horizontal growth of the roots, while the bottom part has a higher conductivity to allow faster drainage and thus avoid the occurrence of anoxia. A sweet pepper crop grew well on a substrate close to these characteristics in order to verify the validity of these assumptions.

By combining the root response to water tension and the mapped measurements of relative water content (RWC) and root density in the slab, we were able to compute an overall reduction factor for whole plant water absorption in response to non-optimal RWC of the slab. By establishing a correlation between this reduction factor and the routine measurements of RWC realized with a GRODAN® water content meter, we could compute a daily reduction factor for water absorption. The results of this simulation show that since the shoots are mainly located in slab parts with near-optimal RWC, the reduction of water absorption by non-optimal RWC is generally low, though it can be significant at times of strong plant growth.

Solution transfers in a rockwool slab partially occupied by plant roots can be accurately simulated using numerical schemes of CFD software. Experimental and simulation studies show that both physical substrate characteristics (particularly hydraulic conductivity) and watering frequency are crucial parameters. Both experimental and modelling studies show that saturated areas are located below the drippers and along the base of the rockwool slab and that the dry zones extend along the surface of both substrates, particularly near the two extremities. Both experimental and numerical results also highlight that saturated areas are more extended in the high density slabs (Floriculture®) than in the lower density ones (Expert®).

Watering policy and particularly frequency have important effects on slab humidity: the Floriculture® substrate can retain a high percentage of water, which in turn can induce anoxia conditions in the lower parts of the medium when irrigation frequency is high. With the lower density slabs (Expert ®) and under low irrigation frequency, on the other hand, the top of the slab shows larger dry zones where roots cannot develop easily.

Once qualitatively validated, the numerical model has allowed performing sensitivity studies and testing an optimized substrate adapted for recycling conditions. Thus, a composite slab was designed, which can keep a higher water content in its upper part and higher hydraulic conductivity in the lower part for maintaining a more even repartition of humidity along the slab height, while decreasing the drainage inertia of the whole substrate.

If we now consider such a mechanistic model for operational purposes, such as on line management or control, it is clear that due to the uncertainty in the root repartition determination and the slowness of process solving, simpler models better adapted for such purposes need to be considered. However, this study has also clearly shown that root repartition was a key factor, about which rather little was known and which needed further study. Consequently, a simplified model was developed, which meets the control and expert system needs. It was integrated into the global management of the closed system and was successfully tested in the CTIFL experimental centre of Carquefou in 2004.

6.8 Improved substrate

An improved substrate was developed which meets the demands defined in the simulation studies of CLOSYS. The properties were significantly different from the earlier tested standard substrates. The experimental slab was considered to fulfill the needs with respect to the technical possibilities available for new substrates at this moment within Grodan.

6.9 Substrate sensor

In the CLOSYS project, a working ion-selective pH non-sensitive sensor for Na^+ was developed. Apart from the developed PVC membranes the efforts for development of a membrane with a matrix based on ceramics needs

further investigation. With those ceramic membranes life span of the sodium sensor could possibly be extended; this requires additional research.
The development of a Mg sensor that could be implemented in the multi-ion sensor unit and could be used for measurements in greenhouses was not successful. A 'Soft sensor' for an indicative measurement of Mg^{++} proved to be possible, but for practical use further examination is needed. In the Mg 'soft sensor' a calculation is made of the expected amount of Mg by means off a calculation in the Hydrion multi-sensor probe. Compared to the laboratory analyses a good estimation can be made.

6.10 Expert system

An expert system has been designed based on a coupled crop–substrate model that provides the user with the best slab states for the coming days and the composition of the fertigation solution. The crop model is used to assess the crop response to the fertigation strategy under forecasted weather and current greenhouse climate set-points (temperature and water vapour pressure deficit). Crop performance is measured by its harvest, a quality indicator of the harvest (fraction of BER) and crop transpiration. The user can decide upon the relative importance of each of these three elements. The solution proposed by the expert system corresponds to the set-points necessary to the real-time controller which is in charge of actually maintaining the system along these values.

The expert system and the application of its solutions by the real-time controller have been tested on a real pepper crop.

6.11 Real Time Controller

Multivariable greenhouse control is an interesting tool for fertigation management, to achieve a better control of substrate relative humidity, electro conductivity within the substrate and drainage rate.
However, precise adjustment of the most important parameters is important in order to avoid over- or under-irrigation and thus losing all advantages of such a precise system.
Multivariable greenhouse control will be further tested in the coming year in order to evaluate its feasibility to be used by growers and to be incorporated in a commercial greenhouse fertigation management system.

6.12 Technical infrastructure

The technical infrastructure written by HortimaX enables the Closys modules to:
- mutually exchange both historical and actual process data, and
- exchange process commands from the subsystems to the HortiMaX process computer.

The technical infrastructure is set up in such a way that if one subsystem malfunctions, process control will revert to a simpler subsystem.

The technical infrastructure has been efficiently used in the final field test at CTIFL without big problems. It has therefore been proven to be reliable.

6.13 Closed system

Results of the comparison between the CLOSYS system and the traditional sweet pepper growing system are promising. With a lower water use, the CLOSYS system has the same plant growth and fruit production as the standard system.

The CLOSYS system will be tested in another production season at the same site as the final field test was held. This will allow solid conclusions to be drawn from the comparison of the CLOSYS and the standard system.

7. Exploitation and dissemination of results

In 2004 and 2005, in five different European countries (i.e. The Netherlands, France, Spain, Greece and Hungary) one-day national workshops were held to disseminate the results of the CLOSYS project. The programme and findings of these workshops are presented in the following paragraphs.

Workshop in The Netherlands

On 31 January 2005, a national workshop was organized on water and nutrient management in glasshouse horticulture. This workshop was organized on the occasion of the finalization of the EU project CLOSYS. Results of the CLOSYS project as well as of some other research projects on water and nutrients were presented by researchers of Wageningen UR and a consultant. The programme was the following:

- Peter Stradiot (Substratus): Experience from practice about fertilization in hydroculture in intensive and semi-intensive horticultural regions.
- Cecilia Stanghellini (Agrotechnology and Food Innovations, WUR): Water and bulk nutrient uptake under different fertigation strategies.
- Theo Gieling (Agrotechnology and Food Innovations, WUR): Control system for flow and nutrient concentration of drainage water.
- Anne Elings (Plant Research International, WUR): Predicting water and nutrient uptake of plants (CLOSYS results).
- Leo Marcelis (Plant Research International, WUR): A control system for water and nutrient management (CLOSYS results).
- General discussion.

This workshop was attended by approximately 40 persons. They originated from the university (staff and students), research institutions, applied research station, advisory companies (Phytocare, Substratus) and other commercial companies like Hortimax, Grodan, Hydrion and others.

On this workshop the end of the CLOSYS project was celebrated by the official handing over of the Hydrion sensor to a representative of the Hortimax company. As a spin-off of the CLOSYS project, Hydrion and Hortimax have drawn up an agreement that Hortimax will serve as the official distributor of the Hydrion sensor.

Workshop in France

Dissemination to growers, technicians, advisers, students and other researchers was performed in collaboration between INRA and the CTIFL team in the experimental unit of Carquefou where the whole CLOSYS system was tested for integration. On September 23rd 2004, a meeting especially devoted to management of fertigation of glasshouses was organised, with special attention for closed systems.

The 120 participants to this meeting could visit the experimental CLOSYS system used for integration together with lectures and posters made in relationship between INRA and CTIFL teams.
The following main CLOSYS topics were concerned:

- Hydraulic properties of rockwool substrates and their optimization for closed systems.
- Optimizing the fertigation policy of closed systems with Expert System and Real Time Controller.
- Integration of a whole fertigation closed system.

Global results were exposed and presentations and demonstrations of each module (ES, RTC, Hydrion line) were also provided.
Altogether, about 120 participants attended this meeting. They appreciated this new concept of fertigation management, both for their water / nutrient knowledge improvement and for the opportunity to get a new tool to manage fertigation in the future. However, they also underlined the limits of the trials due to a lack of results on the

whole system over an entire year. As CTIFL plan to repeat the experiment in 2005 with the whole system during a full growing season for sweet pepper, a future meeting on the same subject is planned for September 2005 in both the North of France (CTIFL Carquefou) and the South of France (CTIFL Balandran).

Workshop in Greece

During the last year of the project, a national workshop entitled 'New technologies for environmental friendly greenhouses with emphasis to hydroponic cultures' was held in the Technological Education Institute of Larissa. In this workshop, attended by more than 300 growers, students, agronomists and advisors, the results of the project were presented.

Workshop in Spain

On 23 November 2004 a national workshop was organized in Almería, Spain, entitled 'Advanced systems in horticultural crop production: Sweet pepper production'. This workshop was organized by Departamento de Química Agrícola, Facultad de Ciencias, Universidad Autónoma de Madrid (UAM) and Centro de Formación e Investigación Agraria (C.I.F.A.), Junta de Andalucía, Almería. The objectives were to present the current situation on sweet pepper production in greenhouses and commercialization and presentation and dissemination of the results of the CLOSYS project.

The workshop was attended by approximately 100 people from research centres, associations of growers, technical workers and students. The programme was the following:

- Opening.
- Pedro Pleguezuelo (Syngenta Seeds S.A.): Innovación en variedades de híbridos de pimiento: Tendencias del mercado y criterios de selección. (New varieties on sweet pepper hybrids: market tendencies and selection criteria).
- Miguel Angel Zorrilla Lozano (Acrena SAT): Producción de plántulas de pimiento en semillero comercial. (Production of sweet pepper plants in commercial greenhouses).
- José Mº García (Grodan-España): Sustratos para el cultivo de pimiento en invernadero. (Substrates for sweet pepper production).
- Matías García Lozano (E.E. La Nacla): Manejo del agua y fertilizantes en cultivo sin suelo. (Water and nutrient management in soilless culture).
- Agustín Gárate Ormaechea (U.A.M.): Pautas de crecimiento de pimiento en función de factores ambientales y nutricionales. (Sweet pepper growth as a function of climatic and nutritional factors).
- Juan Carlos López Hernández (E.E. Cajamar 'Las Palmerillas'): Sistemas de modelización del cultivo bajo cubierta (Modelling systems in protected crops).
- Francisco Petit Espert (SAT Agromurgi): Comercialización y criterios de calidad (Horticulture commercialization and quality criteria).
- Jan van der Bloom (Coexphal): Perspectivas en el control fitosanitario: Problemática y posibilidades de control biológico (Main issues in pesticide management: problems and perspectives of biological control).
- Ana Roldán Serrano (CIFA La Mojonera, I.F.A.P.A.): Actividad de los abejorros en la polinización y fructificación de flores de pimiento dulce (Bumble bee activities on the pollination and fruiting of sweet pepper flowers).
- Conclusions and Closure.

Workshop in Hungary

As part of the dissemination of results in Hungary a workshop, titled 'Water and Nutrient management in Horticulture' was announced and held at TUBUD on 27 October 2004. TUBUD (Partner 10) made an overview of the CLOSYS project and presented the activities and results of the work packages related to TUBUD (e.g. portable fluorometer, fluorescence imaging systems – Xe-arc lamp system, UV-LED array). We invited Privatdozent Dr. Claus Buschmann to make a presentation about stress detection by fluorescence imaging, and Professor Dr. Dinesh K. Saxena from India to summarize the application of chlorophyll fluorescence in bryology.

The workshop for dissemination was also announced via the Hungarian Fruit and Vegetable Board (www.fruitveb.hu) mailing list. A wide spectrum of participants was interested in the dissemination: national and foreign professors and

students as well as visitors from the Eötvös Loránd University of Budapest; Szent István University of Gödöllő; Budapest University of Technology and Economics; FVM Research Institute for Viticulture and Oenology, Pécs and a plant grower from Agro-Ferr Ltd. (Dombegyháza). The total number of participants was 20-25. During the break and after the presentations, intensive discussions were held. The workshop closed with a laboratory visit at TUBUD.
Furthermore, CLOSYS results were disseminated in the following ways:

- at the Greensys congress in Leuven (2004), HortiMaX held a presentation about the technical infrastructure, and
- in a special edition of the Dutch greenhouse magazine 'Onder Glas' (March 2005), results from the Closys project, especially the final field test were mentioned by HortiMaX.

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8. Policy related benefits

The CLOSYS project used an innovative multidisciplinary holistic approach combining modelling and experimental research in plant physiology, substrate physics and chemistry, sensor technology, machine learning, control and optimization techniques and economics. In addition, the end users already had a considerable role in the project and the last year of the project was used to test the integrated closed system at an applied research station which ensures dissemination of the results. Furthermore, national workshops for dissemination of results were organized in five participating countries.

CLOSYS directly contributed to sustainability of agriculture which is an issue of international commitments. CLOSYS addressed several issues of The Common Agricultural Policy (CAP). In particular, it referred to objectives of production methods which are sound and environmentally friendly and which are able to supply quality products of the kind the public wants. CLOSYS also referred to community legislation on water protection (e.g. codes of Good Agricultural Practice through the Nitrate Directive).

CLOSYS has yielded a closed system for water and nutrient management in horticulture. With this system, water and each macro-element separately can be supplied in proportion to the dynamically varying demand of the plant. This results in zero waste of water and nutrients. Prevention of wasting of water and nutrients will increase the competitiveness of European horticulture indirectly, as it appeals to consumer’s wishes with respect to sustainability and soundness of production systems. Directly, the reduction in use of water and nutrients saves yearly € 2500-4000 per hectare. Moreover, a better control of crop growth and quality also leads to a better competitiveness. Furthermore, technologies developed in this project will have application outside horticulture and agriculture as well (e.g. ion-selective measurements, machine learning, control and optimization techniques). The CLOSYS project resulted in knowledge-intensive systems which improve competitiveness.

The added value at European level for the consortium that worked on CLOSYS was in the interdisciplinary nature of the participants – targeted to provide a blend and greater depth of expertise. Models were thoroughly validated at different sites in Europe which was the only way to ensure the general applicability of the newly developed methodology and technology.

In the CLOSYS project several Community social objectives were addressed. These mainly refer to (1) Quality of life and health, (2) Preservation or enhancement of the environment and natural resources, (3) Employment, (4) Cohesion in the Union, and (5) Opportunities for education and training.

Quality of life and health

Shortage of high quality water is a major issue world-wide and especially contamination of water with nutrients such as nitrate is a hazard to human health. The CLOSYS project aimed at and resulted in a system to minimize water use in horticulture, which diminishes problems with water availability. Moreover, the CLOSYS project aimed at and resulted in prevention of pollution of nutrients below-ground. Hence it prevents pollution of ground or surface water with nutrients.

Preservation or enhancement of the environment and natural resources

The CLOSYS project directly contributed to the preservation and enhancement of the environment and natural resources by developing a closed system for water and nutrient management in horticulture. The use of water – a scarce natural resource – is minimized, while pollution by nutrients from horticultural production is prevented. Like in many other countries all over the world, salination is a big problem in Mediterranean countries. Optimizing water use and preventing nutrient losses, the results of the CLOSYS project, are important steps to control salination.

Employment

CLOSYS contributes to the competitiveness of European horticulture as it reduces costs of water and nutrients (€ 2500-4000 per ha per year) while it allows a better control of crop growth. Moreover, prevention of wasting of water and nutrients will increase the competitiveness of European horticulture indirectly as it appeals to consumers' wishes with respect to production systems. This increase in competitiveness will stimulate employment in not only primary production farms but in all organizations of the whole production chain from breeder to retailer.

Cohesion in the Union (such as opportunities for technology transfer to less developed regions)

Participants from six different countries participated in the CLOSYS project. Co-operation between these experts from different countries has stimulated technology and knowledge transfer between countries. Especially in countries from North-Western Europe there is more experience with re-use of nutrient solutions and modern technologies than in Mediterranean countries, while Mediterranean countries have a longer tradition in coping with short water supply and salinity problems. All countries will mutually benefit from the co-operation in the CLOSYS project.

Opportunities for education and training

In the CLOSYS project, young researchers were trained, either as students, PhD students or Postdocs. To them, it was a valuable experience to co-operate in a large research project and a pan-European consortium of universities and research institutions.

In (agricultural) schools and universities, models are used as educational tools, because this is one of the best ways to demonstrate (virtually) the whole functioning of agricultural systems, integrating fundamental knowledge from several disciplines. The model development in this project will increase the possibilities for computer-based learning methods.

Exploitation of results

Three industrial companies, who are users of the project results, have participated actively in CLOSYS. One of the companies, Hortimax is an international process automation company for greenhouse systems. They will commercialize the overall output of the project, i.e. the integrated closed system. For this purpose, they have an exclusive license for the integrated control and expert system for use in closed systems for water and nutrient management in protected cultivation; this system is based on the integration of crop and substrate models as well as sensors developed in this project. As Hortimax sells its products world-wide via a dealer/installer network to growers, this company ensures a widespread use of the closed system developed by CLOSYS.

The Hydrion company is specialised in the production and development of water quality monitoring equipment. They have developed a new sodium-selective sensor in order to have a complete on-line ion-selective sensor for all macro-nutrients. Ion-selective measurements are an important tool in controlling the nutrient use in closed systems in horticulture as well as in fish culture and all kinds of water control and purification systems. Hortimax obtained an exclusive license and commercializes these sensors in protected cultivation, while Hydrion themselves will commercialize these sensors in other areas such as fish culture and industrial waste water treatment.

The Grodan company sells substrates for growth of horticultural crops world-wide. Guided by the model calculations performed, Grodan has developed an improved substrate which allows better control of water and nutrient flows in the substrate. This new substrate will be marketed world-wide.

Strategic impact of CLOSYS in terms of competitiveness and market opportunities for the participants

The ability to offer complete integrated systems instead of different 'stand alone' subsystems increases the added value of Hortimax and therefore their competitiveness. For the grower, a complete, integrated system will increase the payback and optimizes performance because of the lack of compatibility problems which exist with stand-alone sub-systems. This will increase the sale of the integrated systems.

The on-line multi-ion sensor which includes measurements of Na^+, Ca^{++}, HCO_2^-, Cl^- and pH has already found interesting industrial applications wherever process water has to be treated for water hardness or demineralisation, thereby increasing the market potential for Hydrion.
Improvement of substrate and management of substrate has enhanced the competitiveness of Grodan.
The research organizations have increased their knowledge in the center of their own research fields, which helps to maintain and expand their expertise. This will increase their possibilities to attract external research funds.

Exploitation at policy level

The results of the CLOSYS project can be used by policy makers to develop directives for nutrient pollution of the environment and water use and to assign in which regions horticultural production should be stimulated and in which regions this should not be done. Some scientists participating in the project are members of national consultative committees on agricultural policy and will use the results and the tools of this research for the submission of concrete action plans for water and nutrient economy.

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