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ON-LINE MONITORING OF PROTECTED CROPS AND THEIR ENVIRONMENT: TOWARDS THE SPEAKING PLANT

by

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ABSTRACT.

The horticultural industry is rapidly changing from a producer to a consumer orientated industry. Changes include the need for more planned and sustainable production, which requires less input of fertilisers, energy and crop protecting agents. Setpoints for greenhouse controllers are at best obtained from experience, trial and error, or experiments. On-line interpretation and use of signals from plants and their environment (the 'speaking plant' approach), could directly or indirectly give feedback to controllers as a warning system for stressful conditions. Examples of monitoring in relation to both unwanted and beneficial stress conditions are given. Sensor requirements, spatial variability, data interpretation and the possible uses of sensors in control systems are considered.

The practical questions a grower faces with plant-monitoring equipment are addressed. For improving plant quality and yield prediction, a combination of plant monitoring and empirical or mechanistic crop growth and development models is promising. Examples are the graphical tracking and visual quality of pot plants, and yield prediction of tomato.

CONTENTS

Keywords: transpiration, crop models, sensors, lysimeter.

1. TRENDS IN THE HORTICULTURAL INDUSTRY.

During the last decade in Western Europe glasshouse horticulture is shifting from being producer orientated to being consumer driven. The influence of retailers has increased by specifying the quality and quantity of products in contracts with growers. Tracing and tracking has been introduced, with specified delivery dates, which decreases the need for extensive storage facilities (just-in-time delivery). Moreover, both governmental regulations and consumers/retailers demand ecological and sustainable cultivation, which means that the inputs of energy, nutrients and crop protection agents should be minimised and monitored.

Besides the shift to a consumer market and governmental regulations, labour is the largest future concern for growers because it comprises a large part of the costs, and fewer people are willing to work in the horticultural industry.

These trends are having a significant impact on developments in the horticultural industry: cultivation area per grower increases to reduce costs, and there is an ongoing demand for further automation to save labour and increase production. More and more crops are cultivated in closed nutrient systems, and energy input is decreased by the use of thermal screens, heat buffers and climate controllers which use temperature integration with up to 1-week weather forecast to optimise heating strategies.

The horticultural industry has a large requirement for sunlight as a production factor. Despite the increasing intensities of artificial light used in glasshouse horticulture in the northern regions of Europe, the influence of sunlight on climatic factors and on biomass production remains largely dominant for most of the year. In consequence the variable light input and growth (and stages of development) demands variable inputs of water, fertilisers, CO_2 and energy. To match the supply of growth factors to their demand by the crop, different system approaches and techniques have already been developed in glasshouse horticulture.

- Nutrients/water: recirculation of drained nutrient solution. Laboratory nutrient analysis on a regular basis (week) in the nutrient solution or growing medium. Limiting or excess nutrient concentrations, excess salinity and extreme pH conditions determine boundary conditions.
- Light: regulation by artificial lighting and light reducing screens. Boundary conditions determined by excess light and temperature.
- Temperature: regulation by heating and ventilation. Boundary conditions determined by minimised energy input realised by the use of e.g. energy screens, temperature integration.
- Humidity: regulation by misting systems, heating and ventilation. Boundary condition determined by the risk of condensation in relation to fungal diseases such as *Botrytis cinerea.*
- CO_2: regulated by supply in a closed greenhouse according to a setpoint. Boundary condition determined by ventilation.

The regulation of the growth factors in such systems is mainly by setpoints in climate and irrigation controllers, which are highly automated in modern glasshouse horticulture. However the missing link is the feedback of the crop on these setpoints.

2. WHY PLANT MONITORING?

The variable outdoor climatic conditions require the constant attention of growers to adjust the setpoints in the climate and irrigation controllers. Particularly with regards to the numerous (>100) setpoints in modern controllers there is a need for measuring and understanding their impact on crop 'performance'. Plant monitoring – on-line measuring and interpreting plant-related and environmental parameters – may meet this demand.

Setpoints for climate and irrigation controllers may be obtained from experience ('green fingers') and trial and error. Setpoints obtained from experimental studies are 'only valid under the given conditions', which means that one cannot exclude that for example other cultivars or more extreme conditions require new or additional calibration procedures. In order to define a range for 'safe conditions' plant monitoring could be a valuable tool.

A related reason for the use of plant monitoring is the need for a 'warning system' in case of technical failure of climate and irrigation control or human mistakes. This is particularly useful because growers are increasingly involved in other aspects of their business than in crop cultivation itself and spend less time monitoring their crops. Moreover, cultivation itself has become increasingly vulnerable with the use of limited buffer volumes in hydroponics. As in other industries, a (semi-) automated 'stress warning system' based on crop performance is necessary. For instance, in the poultry industry, the weight or food consumption can be indicators of the 'well-being' of the animals.

Another aspect is that stress conditions sometimes are desirable for quality aspects such as hardening off or to reduce growth in bedding plants or potted plants. For instance, by applying water stress (Hendriks and Ueber, 1993) or by limiting phosphate (Baas *et al.*, 1995) the use of growth regulating agents such as Alar can be decreased. For other crops such as watermelon, sugar content may be increased by water stress conditions. But, to apply stress beneficially, a quantitative feedback signal from the crop, in addition to the growers 'green fingers' - is required.

Some two decades ago the need for feedback control of 'plant performance' was hypothesised as an option for greenhouse control, the so-called 'speaking plant' (Hashimoto *et al.*, 1985). The concept of sensors picking up (stress) signals from a plant and the environment, directly controlling climate and irrigation, was the horticultural equivalent of an 'intensive care unit' in hospitals. However, there are significant physiological differences between warm-blooded organisms like humans, and plants. For example, in humans - due to regulatory mechanisms - measured variables like heart rate, blood pressure, temperature and oxygen saturation are all within specified ranges. Stressful conditions therefore can be assessed rather easily. For plants, these ranges are often not so clear, and may differ with climatic conditions, crop, plant part, and plant age. However in the last decade developments in sensor and information technology have created improved opportunities for data acquisition and data processing. From the technology side therefore possibilities exist for an increasingly affordable use of feedback information derived from the crop.

3. WHICH QUESTIONS, GOALS, PROCESSES AND SENSORS?

Instead of taking the technical possibilities as a starting point, the growers concern is that the setpoints (1) should be relevant. Growers question the setpoints for irrigation and climate since they are input to their greenhouse controllers and since outdoor climate changes on a day-to-day basis.

The goals (2) for the setpoints can be diverse and should be recognised: for example irrigation is supplied in order to prevent water stress or blossom end-rot, to regulate the vegetative/generative status (fruit vegetable crops) or growth (bedding plants), or to regulate nutrition or pH in the growing medium. Multiple goals can also exist, e.g. to minimise water use and to maintain low salinity.

The next step would be to assess which physical/chemical or plant-related processes/parameters are relevant (3) with regards to (2).

From (3), sensors suited to determine the relevant data (4) could be chosen, and potential methods to use the sensors and their information (5).

In Table 1 some examples are given of stress diagnosis methods using this scheme. Plant water status is, in most cases, probably the most important factor that has to be controlled in order to maximise the yield and quality of agricultural products (Baille, 1991), and this requires the constant attention of the growers. Not surprisingly therefore, particularly processes, sensors and methods with regards to plant water relations are available in commercially available plant monitoring systems.

At Applied Plant Research, lysimeter systems are used to study aspects of water relations. For fruit vegetable crops grown in hanging metal gutters, a system based on weighing 4-6 meters rockwool on a minute-by-minute basis is used (Figure 1, overleaf). Drainage is weighed separately. The system allows following irrigation cycles, drain, water content in the rockwool and transpiration. Because the shoot is hanging alongside the gutter, it can be weighed separately to follow changes in fresh weight during the day, for example as a result of differences between water uptake and transpiration (van Ieperen, 1996).

Table 1. *Examples of questions, goals in relation to setpoints for irrigation/climate controllers. Identification of relevant processes, sensors and possible method(s) to elucidate the questions.*

Question 1.	**Frequency of irrigation, period.**
Goal(s).	Avoid water stress; regulate growth. Minimise irrigation to decrease run-off, decrease transpiration (decrease energy input for ventilation).
Physical/chemical or plant-related processes/parameters.	Water content of growing medium, transpiration, water uptake, stomatal conductivity, leaf temperature, stem/fruit diameter growth.
Sensors to determine the relevant data.	FD, TDR sensors, tensiometer, lysimeter, IR sensor, LVDT, radiation (solar), psychrometer.
Methods to use the sensors and their information.	Relate actual and potential transpiration (CWSI, Jackson *et al*., 1981), canopy temperature variability (Blad *et al*., 1981), difference leaf-air temperature, current and daily transpiration or stemflux rate and/or leaf temperature in relation to VPD. Relation between transpiration and radiation, time trends in stem/fruit diameter.
Question 2.	**Maximum level light-reduction screens.**
Goal(s).	Avoid photo-oxidation, stomatal closure.
Physical/chemical or plant-related processes/parameters.	Photo-oxidation, increased leaf temperature.
Sensors to determine the relevant data.	Light sensors in greenhouse (PAR, solari), porometer, chlorophyll fluorescence meter, leaf temperature.
Methods to use the sensors and their information.	Determine photochemical quantum yield and stomatal opening in relation to light, temperature (Lu *et al*., 2003).
Question 3.	**Lowest setpoint greenhouse temperature, ventilation.**
Goal(s).	Energy reduction, disease prevention.
Physical/chemical or plant-related processes/parameters.	Condensation on fruits, flowers, growth, nutrient disorders.
Sensors to determine the relevant data.	I.R. temperature, psychrometer, chlorophyll measurement.
Methods to use the sensors and their information.	Measure temperature of the thickest fruit/flower at the coldest place and relate to dewpoint temperature.

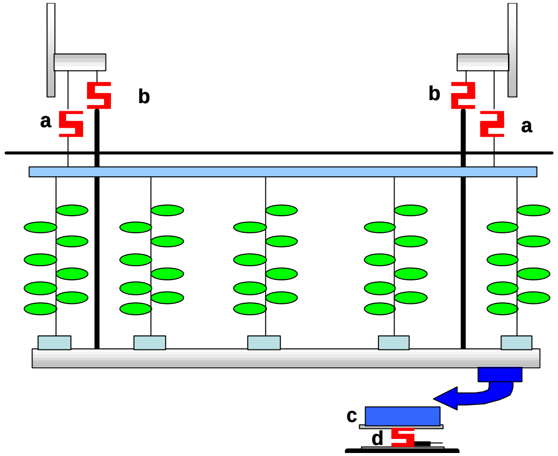

Figure 1: *Lysimeter system used for fruit vegetable crops.* a *= loadcell used for determining shoot weight,* b *= loadcell used for determining weight of the gutter including rockwool,* c *= drain tank,* d *= loadcell used for determining weight drain tank. For other crops such as flowers, loadcells* a *are not present, and FD sensors are used to determine water content in rockwool.*

Most crops, however, cannot be weighed apart from the lysimeter system. By combining a lysimeter system with FD sensors in the rockwool (Hilhorst, 1998, Baas and Straver, 2001), differences in the weight of the plants can be calculated by comparing water content of the rockwool with total water content (weight) of the system. By using two systems, the effects of for example heating pipes underneath the canopy on transpiration could be studied (Figure 2). The results of those kinds of studies may contribute to a more effective use of heating pipes, thus saving energy.

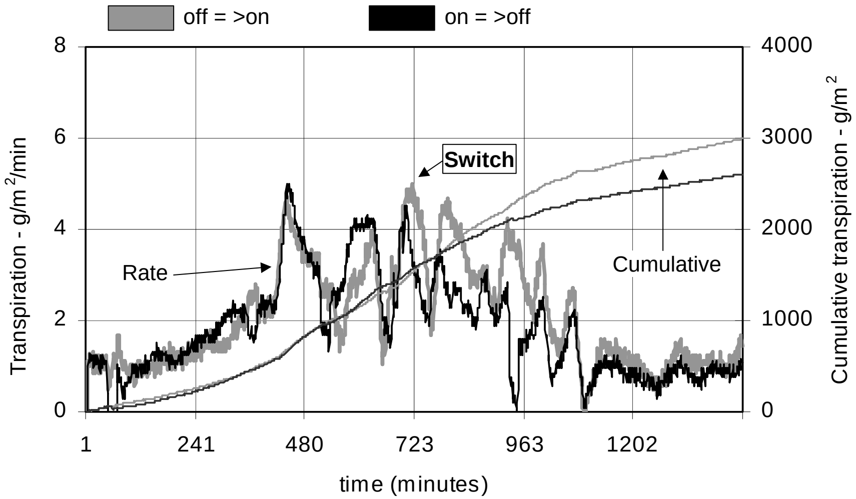

Figure 2: *Effect on transpiration of switching on or off the heating pipes under the canopy of a Gerbera crop. Two lysimeter systems were used.*

3.1. Considerations in using plant monitoring.

Users of plant monitoring equipment who manage according to the scheme as described above (Table 1) are still confronted with different issues. These are related to sensor characteristics and requirements, the measured variability, and the interpretation of signals.

3.1.1. Sensor requirements and crop variability.

The conditions in glasshouses such as high humidity, rapidly changing temperatures, corrosive nutrient solutions, and pesticides are far from ideal for the operation of many sensors. Ideally, sensors are accurate, show good repeatability and no drift or interactions with environmental parameters (e.g. temperature, humidity), require no calibration and maintenance, are robust and inexpensive. There are considerable differences between sensors with respect to, for example, the need for calibration. Additionally, the use of the sensor should preferably require little labour for adjustments, be non-invasive and should be on-line, which until now has excluded the use of a number of methods with 'attached sensors' such as gas-exchange measurements for photosynthesis and stomatal conductivity.

Variability within and between plants can play a significant role in signal response. Biological systems typically show large variation, and individual plants can differ up to 100% in size. Moreover, varying light conditions during the day, the position of the heating pipes or drippers and methods of greenhouse construction can all induce variation.

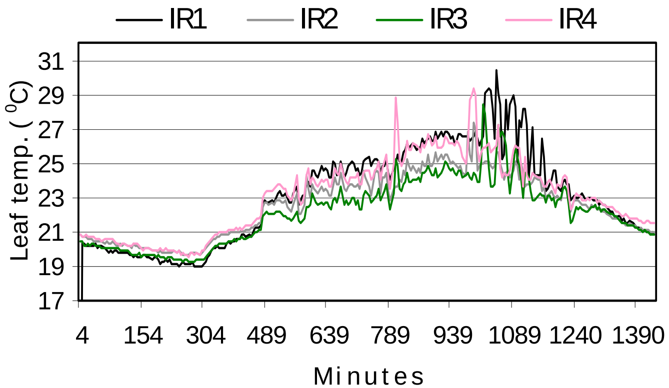

Figure 3: *Differences in leaf temperature of Gerbera within a day as measured from midnight with 4 infrared sensors, each measuring ca. 10 cm^2.*

As an example, differences in leaf temperature within 2 m^2 may vary several degrees under sunlit conditions, whereas in the night-time the differences are negligible (Figure 3). With regards to plant temperature, increasing the measured area - thereby using the average temperature of a few m^2 - has been suggested as a way of overcoming this variability. Increasing the sampling area or volume requires more sensors. In a regular ventilated climate box used for assessing greenhouse air temperature and humidity, the displacement of air also assures the sampling of a larger volume. To obtain a more reliable average on water relations, the lysimeter systems (Figure 1) also monitor a few m^2 in the greenhouse.

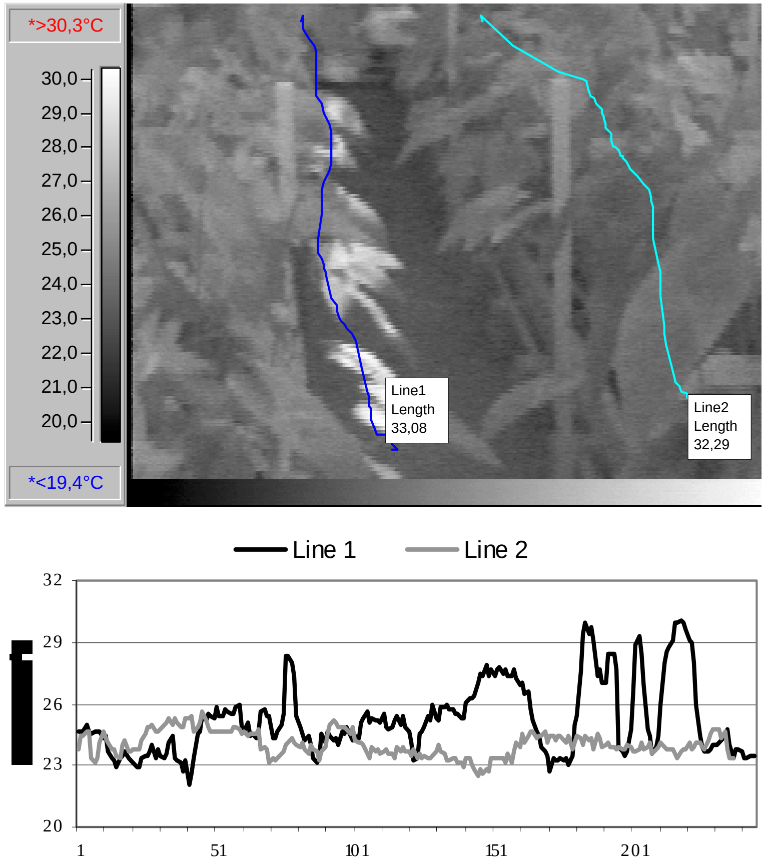

Figure 4: *Thermographic image of Anthurium crop (upper), with the temperature variation of the drawn lines in the image (lower).*

However, it should be noted that relevant information is sometimes ignored when average conditions are monitored. When infrared sensors are used to determine the risk of condensation, a small field of view is necessary, since the plant parts with the lowest thermal time constants (i.e. fruits) are of interest. The canopy temperature variability increases under water stressed conditions and therefore has been used as an estimator for water stress (Blad *et al.*, 1981; Clawson and Blad, 1982). Although spatial variability can be determined by using thermography (Figure 4), the high cost of thermographic imaging equipment does not justify its use by growers at present.

In general, the number of data points (n) needed to obtain a mean average with a specified confidence interval (ci) can be calculated as

$$n = (2*t*sd/ci)^2 \qquad (1)$$

Where t is Student's t, usually taken in a First approximation to equal 1.96, and sd is the estimated standard deviation (Miller, 1971). As an example, average and standard deviation are given from plant parameters as measured in chrysanthemum in relation to irrigation frequency (Table 2). When the confidence interval is taken as equal to the (average) standard deviation for all parameters, the number of samples required to obtain an accurate average is between 8 and 25. The use of this number of sensors is hardly feasible for most on-line sensors under commercial growing conditions. Therefore, other methods such as increasing the sampling area should be applied to overcome the problem of spatial variation.

Table 2. *Average water content, EC, stomatal conductivity, shoot weight and leaf temperature of individual pot chrysanthemums (n=18). Standard deviation sd in brackets. The number of observations n needed to obtain an average with a confidence interval ci is given in the two last columns as calculated according to equation (1).*

	Irrigations/week			Irrigations/week	
	2	7		2	7
	Average (sd)		ci	Observations needed	
Water content (v/v %)	42 (5)	62 (3)	3	24	8
EC medium solution (mS/cm)	2.5 (0.4)	2.6 (0.2)	0.3	22	10
Stomatal conductivity (cm/s)	1.9 (0.5)	3.1 (0.9)	0.6	8	26
Shoot weight (g FW)	21.8 (2.3)	24.5 (4.1)	3.1	8	25
Leaf temperature (^{0}C)	23.7 (1.0)	22.8 (1.1)	0.9	17	20

Growers frequently know areas within the greenhouse, which show the earliest wilting in case of sudden climatic changes. These could be places which receive more radiation such as the south or west side of a row, or places with a different (lighter) soil texture in case of soil-grown crops. When stress detection is the grower's goal, the sensors should obviously be positioned in these places. In this way, the risk that stressful conditions are overlooked in these vulnerable areas is minimised. Similarly, for determining the risk of condensation, the temperature of the coldest fruit in the greenhouse should preferably be measured.

For each type of sensor/parameter, information on the expected variability should be known; the spatial variability can be determined by taking for example 10 - 20 readings. Subsequently the sensor could be positioned on a location that -depending on its use - either gives an average reading, or which is at the high or low end of the readings.

3.2.2. Signal interpretation.

In using plant monitoring for stress detection, questions arise when a signal deviates from natural or diurnal variation and when stress is actually occurring. In other words, how should signals be interpreted, both for long-term (yield) and short-term (transpiration, photosynthesis) processes.

One way of interpreting data is by studying time trends. The data on water content of four sensors in different slabs of rockwool growing *Gerbera* show that although the absolute values differ, the trend is similar (Figure 5). Differences in water content during the day therefore may be used as an indicator or setpoint for irrigation rather than absolute values. Due to the large variation, this approach may be more appropriate than irrigating on a fixed setpoint (e.g. minimum water content), and is also an approach to overcome the variation. Another example using time trend analysis is the decrease in stem or fruit diameter, which deviates from the normally observed diurnal variation under water stress.

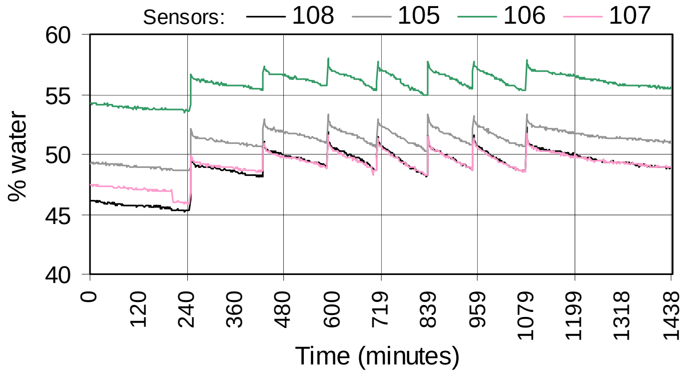

Figure 5: *Daily variation in water content in rockwool as measured with 4 FD sensors.*

Combining data from different sensors allows more complex interpretations. Transpiration or stem flux rate can be related to vapour pressure deficit; if the diurnal dependence is curvilinear and loop-like, the plants may be under water stressed conditions (Anon., 1998). The same applies for leaf temperature: the crop water status index relates the actual with the potential difference between leaf and air temperature in relation to vapour pressure deficit (Idso *et al.,* 1981). This method is applied for outdoors-agricultural crops in semi-arid regions (Jackson *et al.*, 1977, 1981; Wolff, 1998).

Under greenhouse conditions using rockwool for *Gerbera* or cut roses, transpiration and leaf temperature were shown to remain unaffected until very low water contents. The reason is the high hydraulic conductivity of growing media such as rockwool. Slight water stress, which may occur in e.g. soils with fine texture (lower hydraulic conductivity) therefore, does not occur, and plants can change from fully turgid conditions to severe water stress within a day. Monitoring only leaf temperature or transpiration therefore was found to be a very late stress signal in commercial glasshouse horticulture. The combination of a setpoint for minimum water content using FD sensors in combination with leaf temperature with IR sensors appears to have the best prospect for on-line irrigation control. For instance, for *Impatiens* cv. New Guinea, a crop requiring growth regulators, an automated irrigation based on FD sensors was used (Baas, 2000). A minimum setpoint at which visible turgor loss occurred (wilting point) was taken as setpoint for a fertigation cycle in an ebb/flow system. During cultivation, the setpoint had to be increased a number of times, probably because the available water at wilting point decreased as a result of the rapidly increasing root volume - which is measured as water by the FD sensor - during rapid growth. A feedback signal of leaf temperature (in relation to air or imitation leaf temperature) as a warning system could, in such cases, give additional information to detect water stress conditions and to increase the setpoint for irrigation.

The reference values for interpretation of plant-determined parameters therefore can be different. They may be target values (e.g. in nutrient analysis) obtained from historical data or experiments (e.g. determined wilting point), measurements of equal sensors at other locations (e.g. transpiration in two lysimeters, Figure 2), or calculated values from models (e.g. measured transpiration compared with estimated transpiration).

Another aspect in signal interpretation is that due to adaptation, the response to stress may change. An example of adaptation occurs in the case of plants 'adapting' to water stress by osmo-regulation: the concentration of osmotically active constituents increases, thereby increasing the future tolerance to the water stress. If the tolerance level is exceeded, more extreme reactions may take place such as loss of leaves and death of young shoots. In using plant monitoring as a stress warning system, these critical tolerance levels are most relevant. However, since these tolerance levels are sometimes not clear, or may depend on the circumstances, the grower may overreact to plant responses at far from critical levels. Moreover, what should the reaction be?

4. HOW TO USE SENSOR INFORMATION.

Sensor information can be used in different ways, from decision support and direct controlling, to complex multi-sensor calculations in combination with data processing.

In decision support the information from sensor(s) is not directly linked to the controllers, but supports the grower in decision making for setpoints. Both on-line and off-line sensors are used for this purpose, e.g. pH, EC or specific nutrients measured in the drain solution, or the water content of rockwool. As mentioned before, another important application is for their use as a warning system in case of technical failure or human mistakes. Examples are: checking the photoperiod of assimilation light by light sensors, and irrigation by lysimeter or water content.

Signals may also directly switch on or off a controller. Examples are the greenhouse air temperature, which above a certain setpoint regulates the ventilation, or irrigation based upon a setpoint for water content.

Using an irrigation system based on the average of three FD sensors, which measured water content and controlled irrigation, the growth of *Nephrolepis* was improved compared to that using a standard time-based irrigation regime (Figure 6). Apparently, water and/or nutrient availability was improved compared to the time-based control treatment, despite the absence of visual water stress. This shows the potential of sensor driven irrigation for yield improvement.

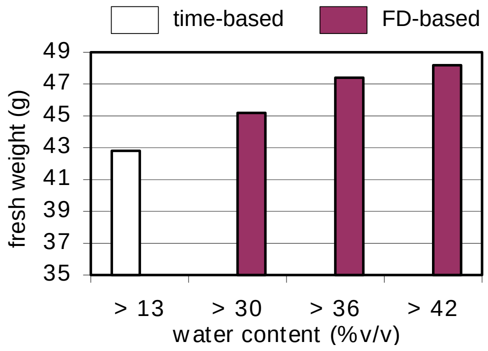

Figure 6:
Fresh weight of Nephrolepis in response to different water contents. Setpoint for FD-based irrigation differed in each treatment. Time-based treatment 2 irrigations/week.

Besides production improvement, this kind of irrigation control may also decrease the amount of water and fertilisers in open systems. For chrysanthemums, irrigation controlled by soil moisture tension decreased the amount of water applied compared to time-based treatments (Lieth and Burger, 1989). In the Netherlands, a so-called fertigation model was developed in order to decrease the fertiliser application which uses tensiometers as feed-back. It is increasingly being used for soil-grown crops such as chrysanthemum and *Alstroemeria* (Voogt, 2000).

A large number of sensor feedback signals in greenhouses work on this principle. This kind of simple on-off regulation may be influenced by a large number of additional factors which may make management for the grower more complex when several devices have to be controlled simultaneously. For example ventilation may occur because of humidity control, which conflicts with energy saving.

Finally, signals from sensors can be processed, before they are used to activate a process. These indirect signal to the controller, via data processing, may vary from simple linear models to complex dynamic models. Examples are the direct relation between radiation and transpiration (e.g. Kittas *et al.*, 1999), which makes radiation a good predictor for transpiration, on which irrigation can be based. Other examples of this group are related to predictions for the longer term (weeks). This involves the combination of sensors and crop growth or crop development models.

5. PLANT MONITORING AND CROP GROWTH/DEVELOPMENT MODELS.

To assist a grower in the trend of planned production, it is essential to control crop quality and to predict yield. For these goals, besides sensor information, information on crop growth and development is necessary. One way to handle this is to use empirically determined relationships between, for example, temperature and development. Three examples are given: graphical tracking of pot plants (Box 1), the crop quality control system of *Ficus benjamina* by means of visual grading (Box 2), and the yield-prediction of tomato (Box 3, overleaf). These kinds of mostly empirically based methods have the advantage that only a small number of variables have to be measured. On the other hand, these models are not explanatory, and interactions are not considered which may produce unreliable predictions under extreme conditions.

Box 1. *Graphical tracking of pot plants.*

To increase the visual quality of a large number of bedding plants and pot plants, growth-regulating agents are used to reduce stem elongation and influence flowering. Graphical tracking is a technique in which measured and extrapolated plant height is compared over time with a target height. This target height curve is a logistic function based on previously obtained experimental data.

A decision-support system has been made which helps growers to achieve height and flowering date targets for flowering pot plants, Easter lily and chrysanthemum (Fischer and Heins, 1996). In this greenhouse CARE System graphical tracking is combined with simulation models and knowledge-based systems to predict development rate and stem elongation five days ahead. Moreover, temperatures and growth retardant applications are advised in order to 'keep on track '.

For *Poinsettia*, *Kalanchoë* and pot chrysanthemum the Internet company LETSGROW.COM has an on-line service for growers based on this principle of graphical tracking. Feedback from the crop is realised by measuring plan height once or twice a week and from observations of the developmental stage. The grower delivers the data through the Internet and an optimal growing curve and advice are presented online.

Box 2. *The Crop Quality Control System of Ficus benjamina (Figure 7, overleaf).*

This system is based upon an integration of a model for visual quality, image processing and a neural network to grade plants and a crop growth control model. It aims to control the development of *Ficus benjamina* to uniform batches with a predetermined quality on a specified delivery date. The crop growth control model is based on experiments in which the variables spacing and temperature on plant quality (measured as height, width and density of leaf mass at certain heights by image processing) were obtained. A neural network is used for grading plants with image processing into uniform groups, which then receive different spacing and temperature schedules to increase uniformity. Although the system is not yet used in practice, a prototype of the system was able to increase uniformity, which decreased delivery time compared to a control group (Dijkshoorn-Dekker, 2002).

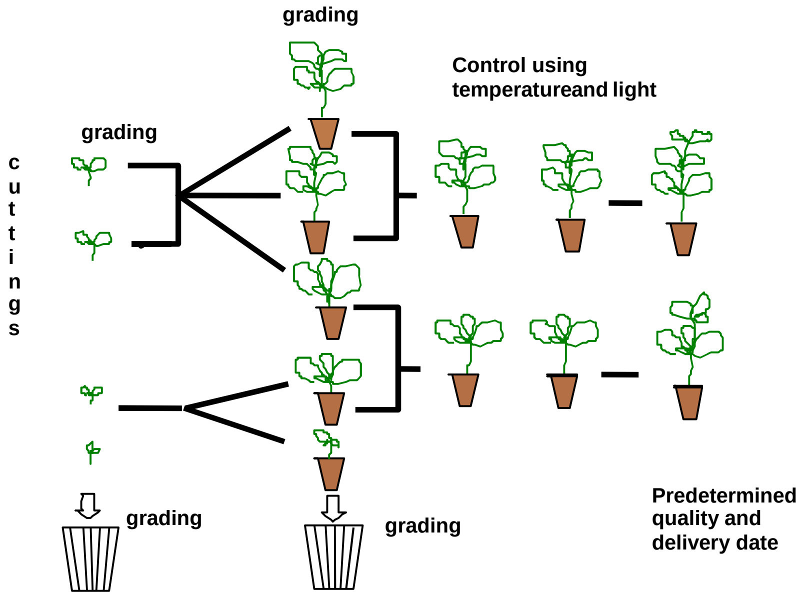

Figure 7: *In the Crop Quality Control System grading is performed by means of image processing of a quality characteristic such as height, width and density of leaf mass.*

Box 3. *Yield-prediction of tomato.*

The basis for the yield prediction program from LETSGROW.COM is a cultivation plan, which describes the weekly desired yield, fruit weight and fruit growth period during the growing season. From the cultivation plan and the monitored data on fruit set (by labelling) and greenhouse climate, a prediction is made for the coming weeks.

Every week the grower sends his data and the prediction is presented online. Since also a prediction is given in case greenhouse temperature is increased or decreased during the next week, the grower is able to control the production level. The empirically derived relation between temperature and fruit development rate (Koning, 1994) is an important algorithm in the program.

More elaborate crop growth models are based on algorithms, which describe plant physiological processes (Marcelis *et al.*, 1998).

Figure 8 is a diagram in which relations between environmental factors (climate and belowground) and several plant parameters (rates and state variables) are outlined. Although dynamic mechanistic models which describe these kinds of relationships have the potential to predict all kinds of different climatic conditions and interactions, generally more parameters are needed compared to the more empirical models. Moreover, the models are rather limited if not calibrated for the specific situation or grower. Plant monitoring may help to tune and reset these models by input of the parameters during crop growth. For instance, leaf area and light interception are very important variables for calculations of crop photosynthesis, which can be determined using infrared reflection techniques. Successful calibration of the model with these parameters may increase the reliability of prediction considerably.

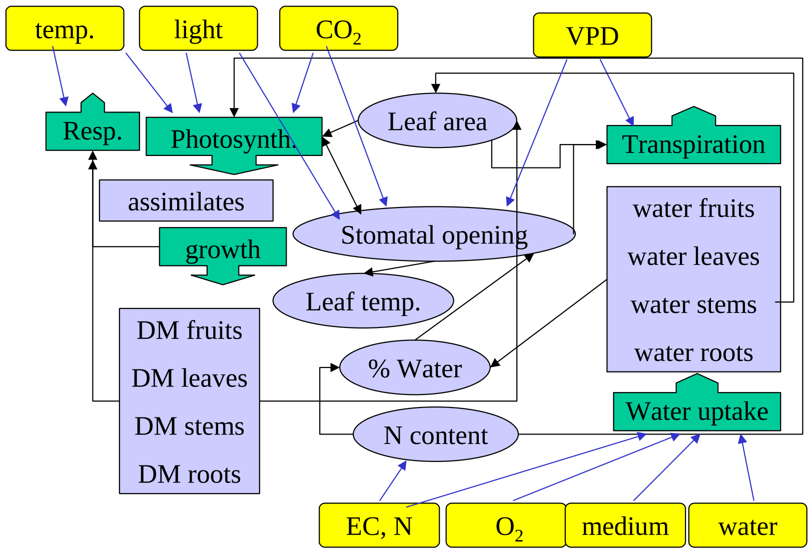

Figure 8: *Relational diagrams, for example for crop production and water relations, can be the basis for mechanistic models.*

6. CONCLUDING REMARKS.

Plant monitoring as defined here is the 'on-line interpretation and use of signals from plants and their environment'. Growers, which have obtained commercial plant monitoring equipment, until now face the questions and problems which have been described in this paper. Where do I place the sensors (for e.g. for soil moisture, leaf temperature, stem or fruit diameter, sap flow), what is the variation, how do I interpret the signals, when does stress occur?

Although these problems have been addressed here and some technical solutions are available, the risk of erroneous readings, failure, mis-interpretation or artefact is present. Moreover, the time needed for data processing and filtering 'odd data' should not be ignored. The conclusion is that until now, the present multi-sensor plant-monitoring equipment is not yet a grower's tool. Nevertheless, the information obtained by studying signals in stressed and non-stressed conditions or in step-response cycles can give very valuable information which can subsequently be used by growers to set their controllers (c.f. Figure 2).

Taking a broad view of plant monitoring, in which all feedback from plants is considered, sensor systems with or without a combination of models are already used in practice or will be used in the near future (c.f. Boxes 1-3). Particularly in the propagation of potted plants, video image processing or plant weight are extensively used for grading or spacing. There are developments in transport systems in modern greenhouses, where plants are not fixed at a certain position in the greenhouse, but move around (e.g. transport tables, Moving Flower System, Walking Plant System). These cultivation systems offer a number of advantages with respect to optimal use of space, reduced need for labour, more uniform growingconditions and the possibility of separate climatic treatments. In these systems, monitoring with a limited number of sensors (e.g. weight, water content, EC) is easily possible. Although it may seem very far-fetched for most current horticulture, the use of sensors positioned on, for example, commercial robots then becomes feasible. The Multiple Imaging Plant Stress (MIPS) facility (a joint venture between Wageningen UR and Plant Dynamics) has shown that early stress detection, for example by imaging using chlorophyll fluorescence in such a setting, is indeed feasible.

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