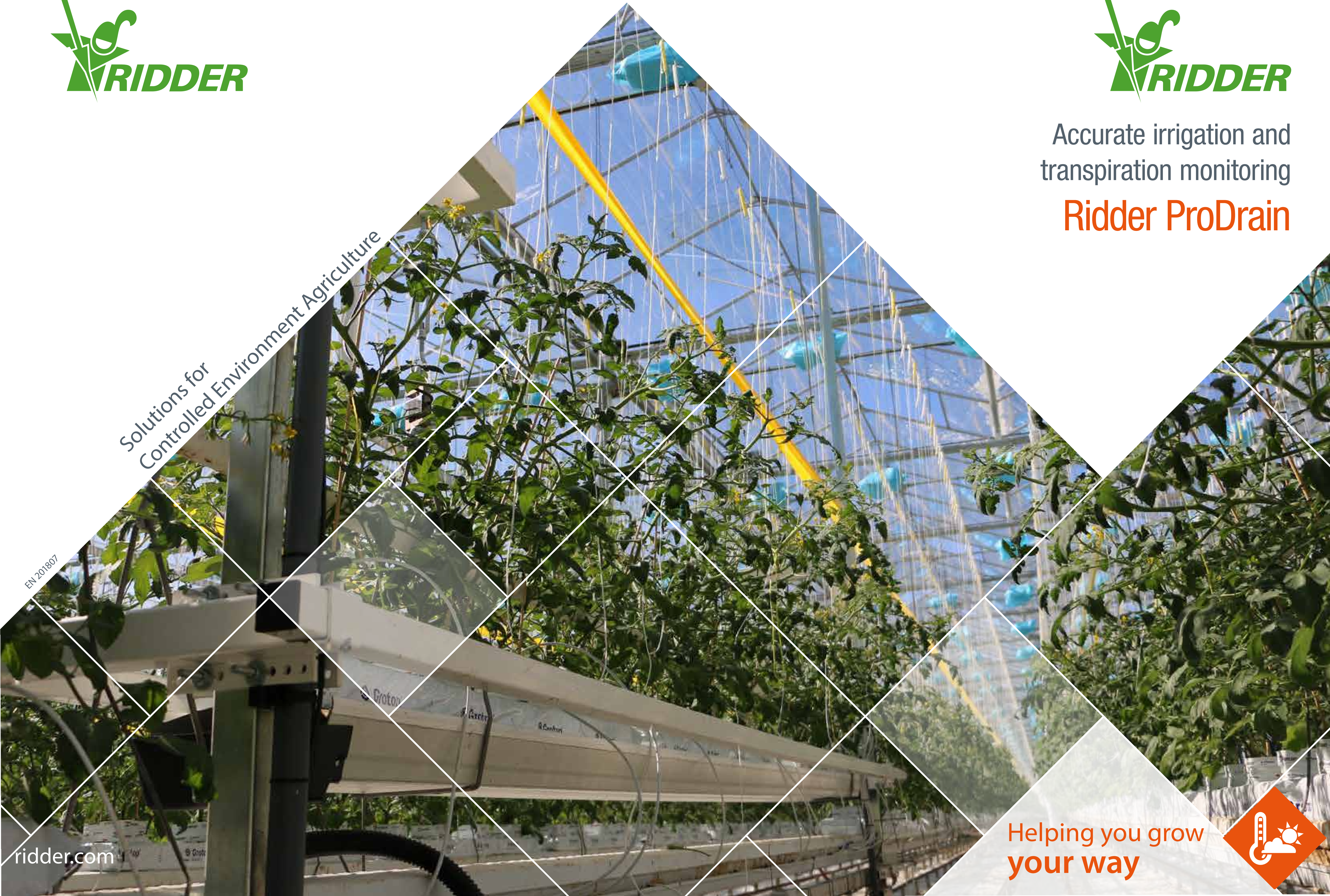
Accurate irrigation and transpiration monitoring

Ridder ProDrain



Solutions for Controlled Environment Agriculture

EN 201807

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Helping you grow **your way**

Make your crops thrive with precision irrigation

Ridder ProDrain allows you to monitor the water uptake, transpiration level and growth rate of your crop plants. ProDrain displays real-time information on irrigation, water uptake, transpiration, growth, the substrate's saturation level and the drain water volume 24 hours a day. It even displays this information when there is no solar irradiance (incoming sunlight) or drain water. With ProDrain, you can determine exactly when and how much irrigation to apply based on your plants' needs. ProDrain provides extremely accurate data on the substrate's saturation weight and plant transpiration. The system is also able to provide a long-term indication of your crop's health and growth.

Your benefits at a glance:
- 24/7 Irrigation scheduling
- Water management tailored to your crop's needs
- Maximum CO_2 assimilation for the best yields
- Control based on the undersaturation level
- Unique transpiration measurement
- Growth monitoring for hanging crops
- Suitable for all substrate-grown crops
- Management information

24 / 7 Irrigation scheduling

Water is one of the key factors that affect plant growth. About 90% of plant transpiration and thus water uptake is determined by solar irradiance. Most irrigation controllers are designed to apply water at fixed time intervals. These intervals can often be adjusted automatically based on the radiation sum. Another factor that can affect automated irrigation is the drain water percentage. However, when there is little drain water flow or no solar irradiance at night, accurate irrigation scheduling becomes extremely difficult. Not so with ProDrain, which will provide you with the information you need. Based on data from ProDrain, you can apply night-time irrigation with great precision. If ProDrain is combined with our Ridder MultiMa control computer, night-time irrigation can even be controlled automatically.

Maximum CO_2 assimilation for the best yields

Plant activity is a key indicator of your crop's health and growth. When your plants' water uptake and transpiration rate are high, your plants are active. ProDrain measures exactly how much water your plants absorb and then transpire throughout the day. Based on this plant activity, you can see whether your crop is healthy and productive. The transpiration rate indicates whether your plants are able to cool themselves and whether the stomata are open. When the stomata are open, the plants can absorb and assimilate CO_2 for photosynthesis. This is the basis for high crop yields.

Water management tailored to your crop's needs

With ProDrain, you can avoid the following problems:
- Too much irrigation
- Too little irrigation
- Irrigation too early in the day, which can result in botrytis or root rot
- Irrigation too late in the day, which can result in generative crop plants (which is sometimes desirable) or stunted plant growth (which is never desirable)

Control based on undersaturation level

Every grower knows that you should avoid a wet root environment going into the night. That's why precise irrigation applications are especially important early in the evening. Although applying irrigation based on the radiation sum has always been considered a sound method of ensuring that your crop receives sufficient water during the day, the radiation sum provides only a rough indication of your crop's actual water needs. If the substrate still contains water, it's difficult to determine how much water to apply. Thanks to a patented method for determining the saturation weight, ProDrain allows you to apply irrigation based on the undersaturation level. Using the MultiMa's ProDrain software, you can control irrigation automatically so it matches your crop's exact requirements.

Unique transpiration measurement

By continuously monitoring the water flows to and from the crop, ProDrain is able to measure your crop's transpiration rate (in g/m²/hour) in real time. Knowing the transpiration rate is of great value in determining the best control strategy for your greenhouse climate. It tells you precisely when your crop has reached its maximum transpiration capacity and action is needed to slow down the moisture loss. This could prompt you to, for instance, close the shade screens or activate the roof sprinklers. ProDrain's transpiration measurement is so unique that researchers use it to test their transpiration models. This has already resulted in a more accurate model for calculating the transpiration rate in rose cultivation. If this calculation model is combined with the ProDrain measurements, it can even serve as an early warning system.

Do you want your irrigation scheduling to be more precise? Do you want to avoid your crops receiving too much or too little water? Would you like to monitor plant transpiration in real time? Then ProDrain is the solution for you!

Growth monitoring for hanging crops

If used for hanging crops (e.g. high-wire tomatoes or cucumbers), ProDrain includes the ability to measure crop growth. By suspending plants from the weighing setup, the system can provide you with a wealth of additional information. The gross weight of your crop plants is an indicator of their fruit load. By monitoring this measurement over a prolonged period of time, you can determine whether the fruit load is satisfactory or adjustments need to be made. Based on your crop's increase in weight, ProDrain is able to determine its exact growth to within a few grams. You can use this data to predict crop yields or check whether your crop is healthy and productive. Where the transpiration rate is a reliable indicator of your crop's maximum capacity to cool itself, the cumulative growth is a good measure of how your crop is developing. This is because plant growth is less dependent on the amount of solar irradiance.

Suitable for all substrate-grown crops

The ProDrain weighing setup can be used for virtually any crop that is grown in substrate. Whether you grow roses, strawberries, sweet peppers, cucumbers or tomatoes, the system is able to calculate the substrate's saturation level and measure plant transpiration. The irrigation and drain water sensors provided with the system accurately measure the amount of water entering and leaving the substrate.

Management information

In addition to providing real-time measurements, ProDrain monitors your crop's long-term development. ProDrain is able to do this by measuring the cumulative growth and comparing the transpiration sum to the radiation sum. This shows you whether your crop's water uptake and development are normal, or whether there are abnormalities that require your attention. The software filters the measurements for disturbances, such as crop handling.

ProDrain will provide you with invaluable crop information that can be used for:
- Plant stress detection
- Growth monitoring
- Production planning

Maximize production by placing your crop in control

Commercial growers have always been taught that maximum crop production depends on maintaining the ideal greenhouse climate. This makes sense, of course, and up to now, most growers have been steering their crop from such a 'climate perspective'. But did you know that this approach is no longer the most effective? Current technology allows growers to obtain direct feedback from their crops and include more factors in determining the best growing strategy. Using this 'crop control' approach, growers can raise crops even more effectively and further increase yields.

To achieve the best production results, commercial growers aim to keep the greenhouse climate as favourable as possible for the plants. But maintaining an optimum climate and applying sufficient water won't necessarily make the plants thrive. Two factors are essential in maximizing production: plant transpiration and photosynthesis (CO_2 fixation). Many growers call this the 'plant activity'.

To optimize photosynthesis, growers aim to maintain the ideal temperature, light and CO2 levels in the greenhouse at all times. This requires these factors to be monitored constantly. The only problem is that it can be difficult to determine how the crop is responding. An essential piece of information is the water transport through the plant. Water carries nutrients throughout the plant and allows the plant to cool itself by evaporating moisture from its leaves (transpiration). If the plant transpires more water than it can absorb through the roots, the plant will close its stomata and growth will come to standstill.

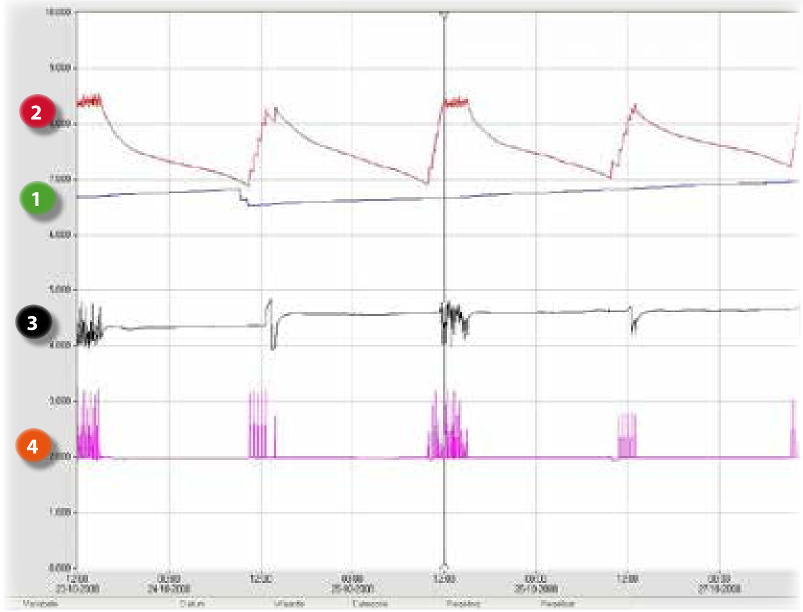
That's why growers are extremely interested in the actual water uptake and transpiration rate of their crop plants. What not many growers know, however, is that it has been possible to monitor these key values for some time now. ProDrain is able to measure the exact quantities of water flowing to and from the plants in real time. The first ProDrain systems were installed in 2006, and now the system is being used all over the world for a wide variety of crops, such as tomatoes, cucumbers, sweet peppers, strawberries and roses. ProDrain has become a highly useful product for growers, and is no longer just a tool for developers and researchers.

Monitor plant transpiration with ProDrain

Measures plant transpiration

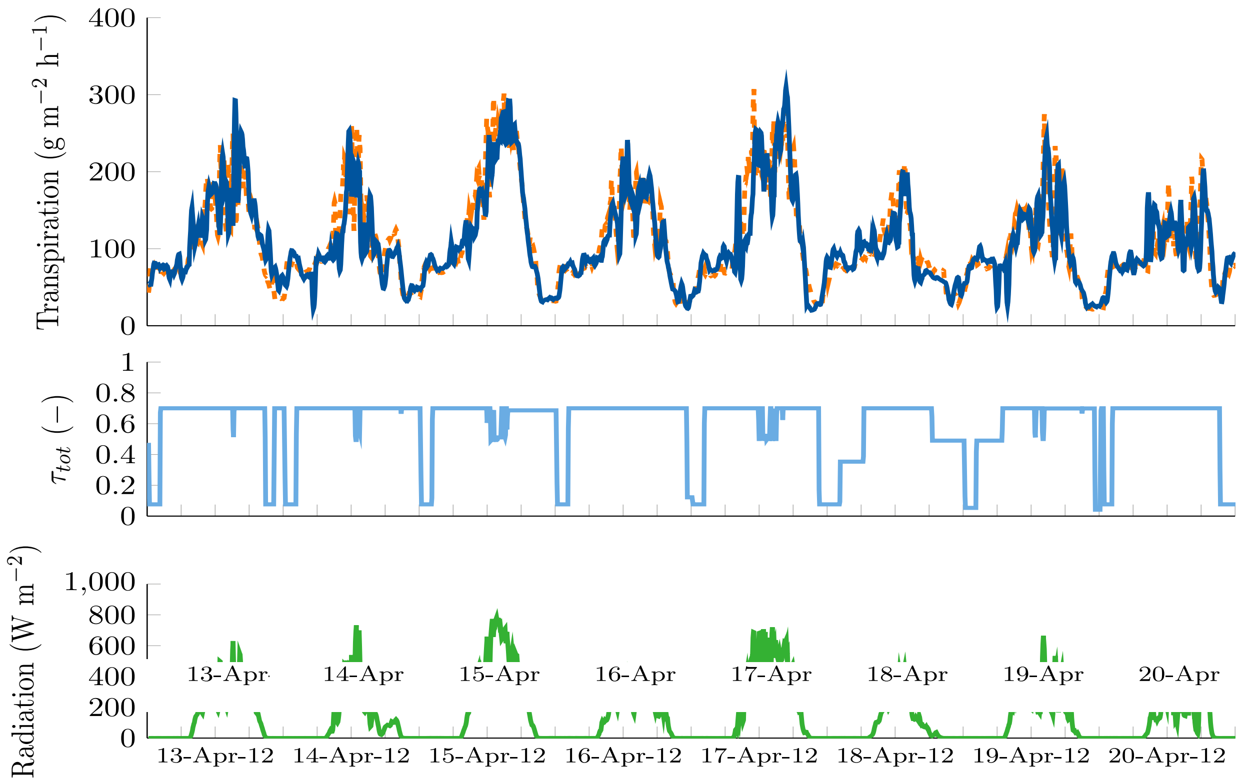
ProDrain accurately measures plant transpiration:

- Weight measurement of irrigation water, gutter weight and drain water
- Measured crop area: 5-10 m^2
- Real-time measurements of transpiration rate ($g/m^2/h$) and cumulative transpiration (kg/m^2)
- Accuracy within 5 grams

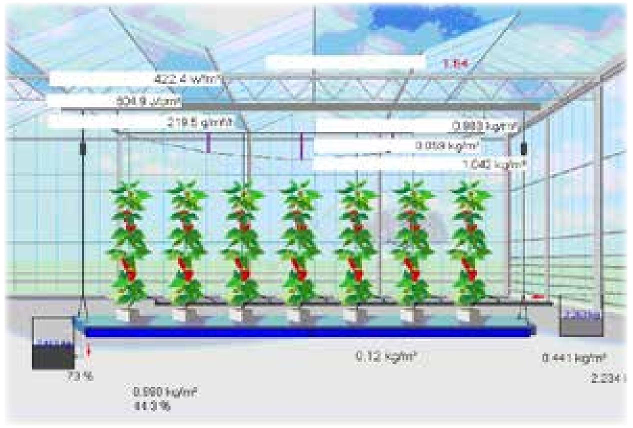


1 Plant weight
2 Slab weight
3 Drain water
4 Irrigation water

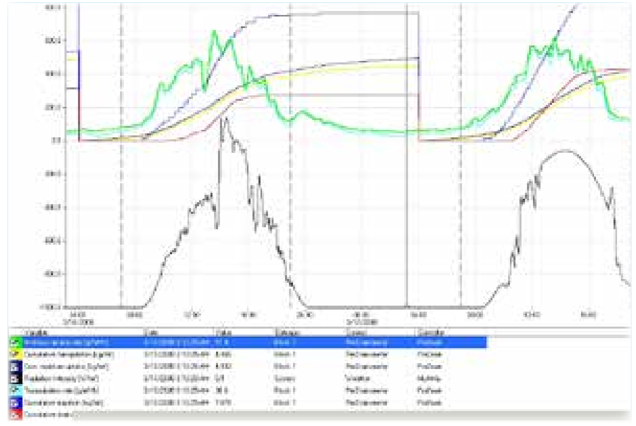
Wageningen University and Research Centre (WUR) findings



Real-time symbolic view

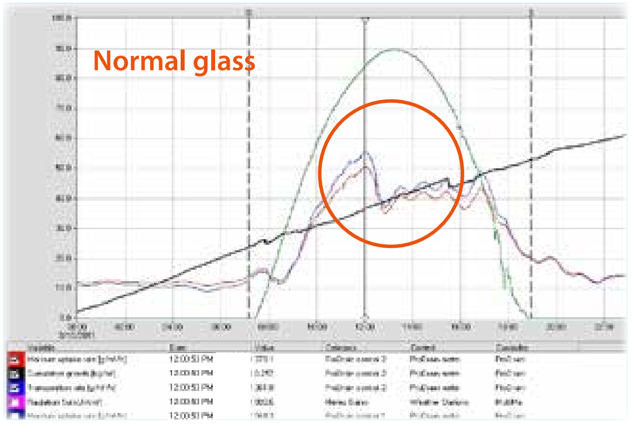


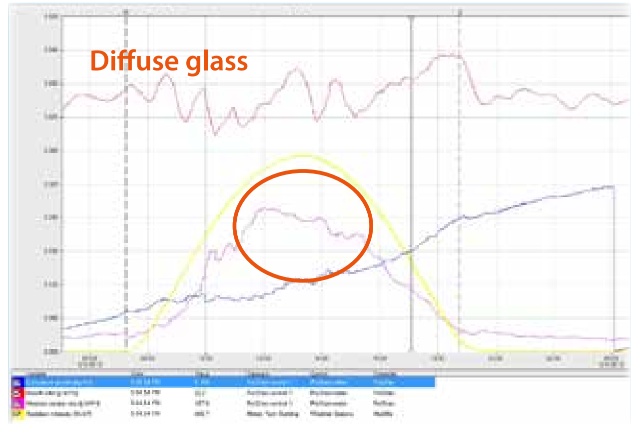
Real-time transpiration measurement



Plant transpiration under normal and diffuse glass

Plant transpiration under normal glass is much more irregular than under diffuse glass. This is shown clearly in the graphs below.





Measured values

Comprehensive data on each of the water flows

- Irrigation water volume (kg/m², cc/dripper, cumulative/per irrigation cycle)
- Drain water volume & percentage (kg/m², %, cumulative/ per irrigation cycle)
- Current saturation & under saturation levels (kg/m²)

Plant activity

- Wateropname en verdamping (momentaan gr/m²/u, cumulatief kg/m²)
- Groei (momentaan gr/m²/u, cumulatief kg/m²)

- Water uptake and plant transpiration (current g/m²/h, cumulative kg/m²)
- Plant growth (current g/m²/h, cumulative kg/m²)

Source: Van Beveren, P. J. M., Bontsema, J., Van Straten, G., & Van Henten, E. J. Minimal Heating and Cooling in a Modern Rose Greenhouse. Manuscript submitted for publication.
Bovenste grafiek blauwe lijn gemeten verdamping oranje gestreepte lijn berekende verdamping.

WUR conclusions about measuring plant transpiration

- Measuring plant transpiration in real-time provides unique insight based on which informed growing decisions can be made.
- ProDrain is a valuable research and model validation tool thanks to its extremely accurate filters.

How does ProDrain work?

ProDrain constantly measures the weight of the irrigation water, the drain water, the substrate slab and the plants (the last-named in the case of hanging crops). The system keeps track of all fluctuations in weight. Since measurements are performed every second, the system can detect even the slightest change in weight and determine where the irrigation water has gone. Is the water still in the substrate slab? Has it been absorbed by the plants? Or has it run off as drain water? If the water is no longer in the substrate or hasn't run off as drain water, and the plants have not increased in weight, then the water must have evaporated into the air through transpiration.

ProDrain is also capable of identifying and filtering out large weight variations caused by harvesting or crop maintenance. This creates a continuous closed loop of information, allowing the system to determine the plant transpiration rate in real time. In addition to measuring transpiration and water uptake, ProDrain can even monitor the growth rate of hanging crops. ProDrain can display the growth rate both as a real-time value in g/m^2/hour or a cumulative value over the entire day in kg/m^2. Unlike comparable systems that measure only a single plant, ProDrain monitors a plant area of up to 8 m^2. This provides representative data for the entire crop.

Increased interest in crop transpiration

Recent research has revealed that reducing crop transpiration can lower greenhouse energy consumption significantly. However, to reduce crop transpiration safely and effectively, it's essential to measure the transpiration rate in real time.

Fully automated irrigation based on water uptake

The desired water quantity in the substrate slabs can be represented as the moisture content from 0-100%. The problem is that irrigation is applied in volume (e.g. litres) rather than as a percentage. By determining the saturation level in kg/m^2, it is possible to set the desired degree of saturation (or undersaturation) and control irrigation based on this value. In this way, the irrigation controller can automatically match irrigation application to the exact water uptake of the plants. This ensures that the moisture content of the substrate slabs will never drop below the pre-set minimum level. Most ProDrain users now utilize the ProDrain measurements as their preferred irrigation trigger, since it's the only method that actually takes the plants' water uptake into account and can be used throughout the day (so even at night).

Paul Selina

Village Farms, Texas USA

We've been using Ridder ProDrain since 2007. First at our GATES™ greenhouse and now all our Texas facilities will be equipped with at least one ProDrain system. The information that ProDrain provides us is priceless: we can use it for irrigation management, stress detection, growth monitoring, and production planning. It is key to our GATES concept, and without it we wouldn't have been able to go to the edge of what is possible with the plants and learn about their capabilities in high radiation climate.

After Ridder introduced the 'ProDrain irrigation start' for the Ridder MultiMa in 2009, we used it to trigger irrigation at our Gates™ facility, consistently maintaining moisture content and undersaturation in the desired ranges at different times of the day.

Over the years, we've learned a tremendous amount from the ProDrain readings. The system shows us the transpiration rate in relation to radiation, humity, and temperature. At our facilities in Texas, radiation levels can exceed 1,000W/m^2 for long periods, resulting in high plant transpiration. If conditions become too extreme and the plants' stomata close, we see the impact as a reduced (or even negative) growth rate. ProDrain allows us to anticipate and prevent these 'stress situations'.

We will adjust the pad and fan or fogging system setpoints, or close the shade screens based on our observations of previous days. Since we know how far we can go, we can plan ahead and minimize any potential problems. But that is not all. ProDrain's plant measurements also enable us monitor both the absolute plant weight, and the cumulative fresh weight increase, from day to day. We can compare these measurements with previous seasons and age of plant. Based on this information, we can anticipate production, without having to count or measure the fruit manually.

Measure to manage

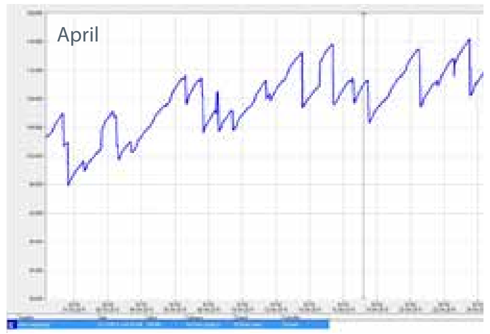
All growers aim to produce the best-quality product, in maximum quantities, at the right times and with as few resources as possible. Tracking daily crop performance is the key to producing maximum yields. To monitor crop performance, ProDrain determines the actual crop growth rate by measuring the increase in fresh weight.

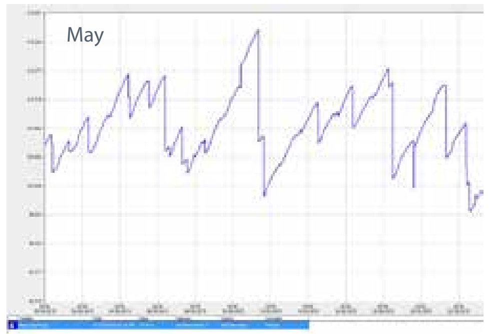
Continuous process

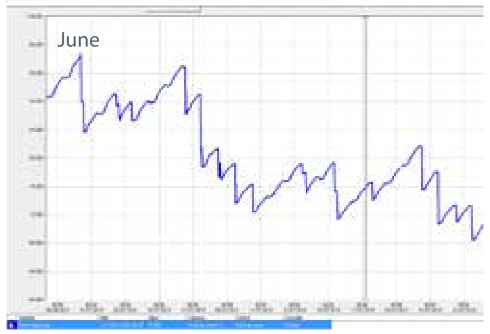
The system continuously weighs eight square metres of crop plants (86 square feet). A sophisticated computer algorithm identifies any irregularities in the plant weight and filters out even the smallest variations caused by harvesting, de-leafing or other crop work. What remains is a direct measurement of the crop's growth rate (g/m^2/h), the cumulative fresh weight increase (kg/m^2) and the total weight increase per day (kg/m2/day). The fresh weight increase per week provides essential input for yield forecasting. For example, tomato crops require about four weeks of growth before they will produce harvestable yields.

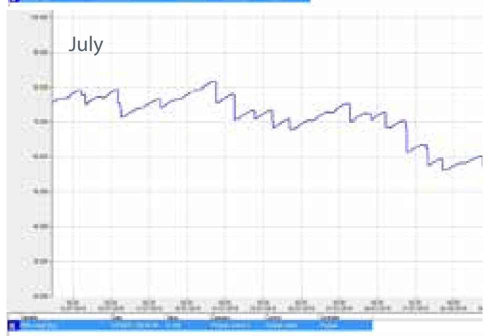
Plant weight

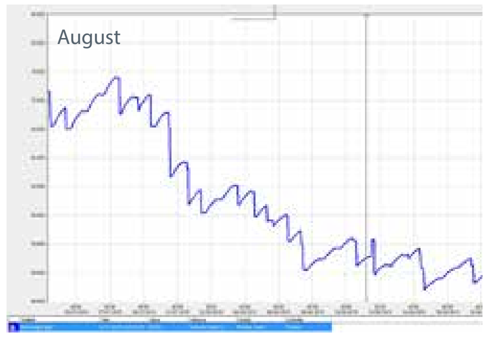
The trend in plant weight throughout the season provides invaluable insight into your crop's development. Just by examining the plant weight over longer periods and comparing it with previous months or the previous year, we can see clearly how the crop plants are developing (i.e. if the plants are growing or not). The graphs below show the increase and drop in the plants' fruit load and its effect on the total plant weight over 6 months. It is clear to see that the young plants gain weight in April and October, that harvesting and growth are in balance in May, and that the plants lose weight in June, July and August.











Experiences from the field

Paul Selina Village Farms has been working with ProDrain for over seven years. He uses the plant weight and growth data almost every day. Paul explains: "The weight measurements of the plants tell me a great deal. Firstly, disturbances in the daily growth curve can indicate periods of stress and then recovery during the day. We have adjusted our watering, ventilation and screening strategies from what we have learned from the shape of the daily cumulative growth.

Secondly, the total growth for the day, kg/m2/day, tells us a lot about how well the crop is growing. We look at these daily totals and compare them to the data of previous crops at the same stage of growth as an indicator whether the production in a month's time will be higher or lower than normal. We see that the daily growth does not depend on the Joules for that day, but that growth and development seems to be a function of the amount of 'reserve' in the plant and the average 24hr temperature.

Thirdly, we look at the total crop weight, kg/m2, when it is higher than normal it obviously tells us that we will harvest more fruit in the coming weeks, and we may be able use to higher temperatures to influence exactly when we pick them. Conversely, a lower crop weight is an indicator that we need to cool down, rebuild the fruit load, and prepare for a lower forecast in the coming weeks.

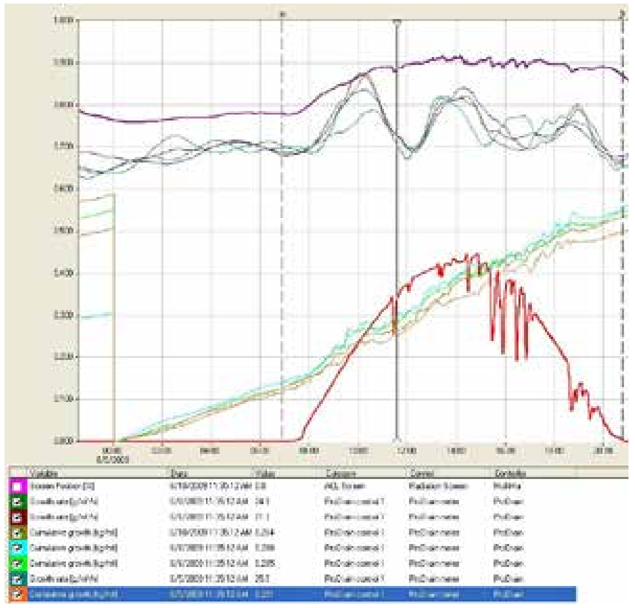
How quickly the crop is 'loading' (increasing in weight) has implications for short-term forecasting. Sometimes you will have a week with lower than expected production, but if the crop weight has increased more than expected, then that will indicate that next week's production will be higher. If this week's pick was higher than expected, but total crop weight did not increase, then next week's pick will be lower. A similar dynamic applies at times of 'unloading'.

We know that there is much more to learn from our ProDrain crop weighing system, especially when we can compare measurements from two ProDrains and can quickly see the impact of different trials and strategies."

Waves of growth

The increase in plant weight is far from stable throughout the day. At night, water uptake and plant transpiration are in balance. As the sun is coming up, plant activity increases and growth speeds up. At midday, the plants tend to lose more water than their roots can absorb. Once noon has passed, the plants recover and growth rates go up again. Later, as solar irradiance drops, plant activity goes down again. If we put this data in a graph, it shows up as a set of waves.

In the graph below, you can see the data of five consecutive days combined. It shows the growth rates (wave pattern) and the cumulative growth (rising lines). This data was measured in an elevated area with virtually cloudless skies. Whether this wave pattern is less than optimal is unclear; we see the same pattern recurring with crops around the world. Most growers prefer to see some more variety, since variations in growth rate are also a generative strategy. The amplitude of the 'waves' is an important indicator. The general opinion is that if the waves are too large, the plants are experiencing stress and not producing the best possible yields.



Real-time comparison of measured and simulated crop transpiration in greenhouse process control

A.N.M. de Koning and I. Tsafaras

Abstract

Applying more intelligent algorithms in the process computers that control the greenhouse climate and irrigation may help growers to optimize crop growth and yields as well as save energy. A greenhouse process computer has been developed with an architecture that allows for easy implementation of custom algorithms without risk to control continuity. The system in question was demonstrated by implementing a transpiration model that predicts actual crop transpiration from greenhouse climate measurements. In addition, the process computer was connected to a system that calculates the transpiration rate from the rooting substrate weight, irrigation supply, drainage water and crop weight. Disturbances caused by harvesting and other crop-related activities were filtered out in real time. All the measured and calculated variables derived from the greenhouse climate sensors, weighing system and transpiration model were stored as averages per minute.

The transpiration model was calibrated and validated with historical data from the weighing system collected at a Dutch commercial greenhouse from April to May 2014. Then, the model was implemented in the process control computer at commercial nurseries in The Netherlands and Texas USA, respectively. Model predictions were compared with actual transpiration data from the weighing system in real time. This was done for two compartments at each nursery, resulting in four test sites in total. Generally, the predicted and measured data were in close agreement ($r2>0.90$) for all sites.

It can be assumed that the model predicts the transpiration rate of a healthy and productive crop. Therefore, suboptimal crop-performance is indicated when the measured transpiration rate is less than predicted. In the time period when the tests were conducted, the crops exhibited both low transpiration rates at midday and reduced transpiration rates due to insufficient irrigation. On those occasions, the process computer generated an alarm in order to warn the grower that a problem had occurred.

This study demonstrates that additional intelligence, such as simulation models, when implemented in a greenhouse process computer and combined with the appropriate measurements, can automatically alert the grower of potentially damaging conditions, e.g. reduced crop performance or a system malfunction in the greenhouse. The developed architecture will facilitate the design of new generation computer controls that take advantage of increasing knowledge of crop-functioning and other greenhouse processes.

Keywords: model, application, climate control, irrigation, automation

Introduction

In modern greenhouses a process control computer takes care of the integrated control of installations for irrigation as well as for conditioning the greenhouse climate. With numerous rules (if …then) and mutual influences and associated settings, the grower tries to achieve the desired strategy for irrigation and greenhouse climate. Operating of this system mainly relies on experience of the grower and heuristic rules. In addition, the computer reads the connected sensors, steers the actuators, provides alarms at undesired conditions or malfunctioning equipment and stores process data for analysis afterwards.

During the last decades, knowledge about the processes in the greenhouse has increased tremendously and it is described in mathematical algorithms (models) that can simulate and predict the behavior of the greenhouse climate as well as some specific crop functions. Models have been developed describing processes such as photosynthesis (Farquhar et al. 1980), transpiration (Stanghellini 1987), assimilates partitioning (Heuvelink 1996) and yield (Marcelis et al. 1998; Vanthoor et al. 2011). Although in research institutes and at universities these models are widely used e.g. for simulation studies, as far as known they have hardly left the research environment. However, model based knowledge implemented in greenhouse process computer may provide the grower with extra information about his growing process. It also may support the grower in making the right settings for achieving his goals. Why is model-based knowledge not yet implemented in process computers at commercial nurseries? First, models and/or their parameterization are specific for the crop, greenhouse structure and equipment in the greenhouse. Due to this lack of generality it is difficult to make a sound business case for commercial development. Secondly, as the process control computer is vital for the control of the greenhouse and any disturbance of the continuity can have detrimental effects on the crop, computer companies are reluctant to implement complex models in the core process control software. Thirdly, as long as not implemented it is hard to convince growers of the value of model-based knowledge and there will be no demand for such applications.

The aim of the current study was to demonstrate the potential of models implemented in real-time greenhouse process control. An architecture of the process control computer system was developed that allows for easy implementation of such custom software without risk for control continuity. Then, as example, model predicted transpiration was compared with transpiration determined by a weighing system.

A transpiration model (Van Beveren et al. 2015) was calibrated and validated with historical data from a commercially grown tomato crop. Subsequently, the transpiration model was incorporated to software, to predict crop transpiration and compare predicted with measured transpiration values. It is assumed that the predicted transpiration represents the behavior of a well-functioning plant under the same climate conditions as the plants measured by the weighing system. When the measured transpiration differed significantly from the predicted value, the system initiated a warning to alert the grower. Further, it was assumed that lower crop transpiration than predicted was caused by closing of the stomata. Stomatal resistance was predicted by the model as well as calculated from the measured transpiration. Subsequently, a photosynthesis model (Gijzen, 1988) was applied in order to evaluate the effect of stomatal closure on carbon dioxide uptake. Details of the transpiration and photosynthesis model are described in another paper (Tsafaras and De Koning, in preparation).

Real time evaluation was carried out during the first months after implementation at two commercial nurseries.

Materials and Methods

Greenhouses

In the present study data were obtained from two commercial greenhouses; one located in Pijnacker (The Netherlands) and the other in Texas (USA). The growers provided historical data for calibration and validation of the transpiration model. The implementation and real time evaluation of the developed software was performed in both sites, at two greenhouses in each site.

1. Greenhouse in the Netherlands

The Venlo-type greenhouses were equipped with heating, fogging and CO_2 enrichment systems. One greenhouse (A) was covered with single glass where the second (B) was fully double-glazed with special coatings for higher light transmission and diffusion. In addition, greenhouse B had bigger panes and less construction elements compared to greenhouse. An overall transmissivity of both greenhouses was assumed to be 75%, constant in time (personal communication with grower). In both greenhouses tomatoes (Solanum lycopersicum) were grown in hydroponic system with plant density 3.5 stems per square meter, transplanted in the beginning of December 2013. Different varieties were grown in each greenhouse; plume tomatoes (cv Elanto) in greenhouse A and truss tomatoes (cv Prunus) in greenhouse B.

2. Greenhouse in Texas

The greenhouse in Texas was also Venlo type, equipped with heating, fogging, wetted pad wall and exhaust fans and CO_2 enrichment systems. There were shading screens with transmissivity 80%, closing when outside radiation intensity exceeded 450 W.m-2. Both greenhouses (C and D) were similar, with overall transmissivity equal to 75%. The crop was transplanted in October 2013 with a density of 3.6 stems per square meter.

Measuring equipment

Both greenhouses are controlled with a Ridder process computer, which was used to provide the data needed. Solar radiation was measured with a radiation sensor included in the weather stations of the growers (Hukseflux LP02). Greenhouse air temperature and relative humidity were measured with an Ektron III aspirated measuring box (Ridder). The measuring boxes were placed at the same height as the top of the plants, about 4.5 m, in the middle of the greenhouses and close to the gutter weighing systems. Canopy temperature was measured with an infrared sensor (Royal Brinkman) from an area around 10 m^2, also close to the gutter weighing systems.

Crop transpiration was determined by Ridder ProDrain® gutter weighing. It measures continuously the irrigation (WIrrigation) and drain (WDrain) water weight in separate load cell weighing buckets. The slab and the plants are hanging from a bar about 3.5 m above the gutter. Slab (gutter and substrate) (Wslab) and crop weight (Wcrop) are measured with use of load cells. From changes in each of those four weights, transpiration rate is calculated as:

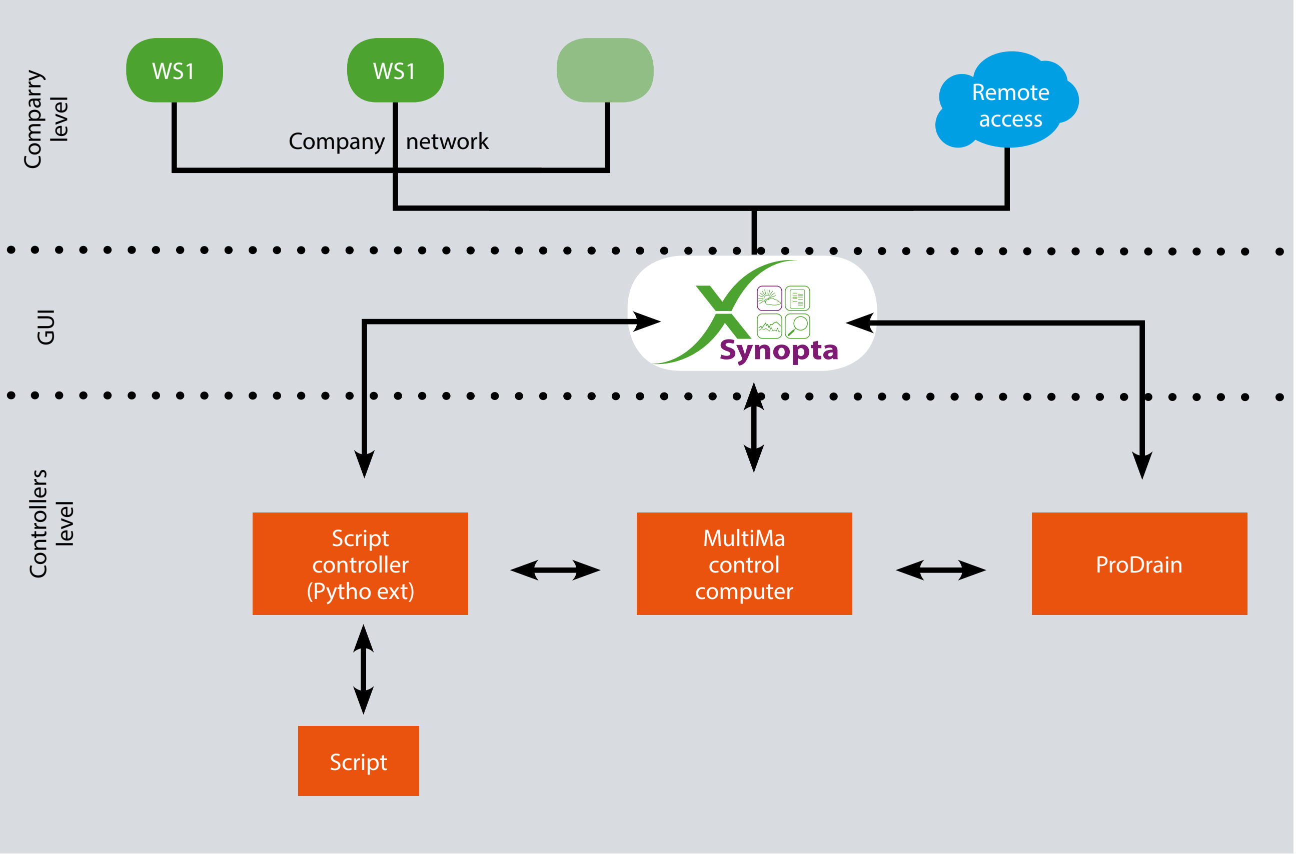
$$\varphi\_transp=d(W\_Irrigation)/dt-d(W\_Slab)/dt-d(W\_Drain)/dt-d(W\_Crop)/dt$$

The calculated data are filtered by specific software removing noise and disturbances from crop handling.

Implementation in process control computers

The programming language Python 3.3.5 was used to implement the described mathematical algorithms in a script file, which was running through a separate controller in the process control system. The script controller was able to transfer data from and to other parts of the system (figure 1) but its function was independent so possible failure of the script controller would not affect the function of the rest of the system i.e. the control of the greenhouse. Input values for the model (radiation intensity, air temperature and relative humidity, canopy temperature, shading screen position and measured transpiration rate) were imported from MultiMa process computer. The script controller was also connected with the management software of Ridder process computers (Synopta). All measured and calculated values were stored in Synopta every minute. In addition, through Synopta, the script controller was accessible either through the working stations (WS) in the company network or through remote access.

Figure 1. System architecture including scriptcontroller, greenhouse process controller (MTA), Prodrain controller and Synopta user interface.



LAI was estimated from the measured night transpiration (Tsafaras and De Koning, in preparation). Then the LAI value and climate data were used as input for the prediction of transpiration. Measured and predicted transpiration were compared real time and a warning was activated in case a difference greater than a threshold value was detected for a certain time period. Threshold value and time period could be set by the grower. Finally, based on the values of stomatal conductance, photosynthesis rate was predicted through the photosynthesis model. Photosynthesis comparison expresses the actual photosynthesis rate as a percentage of the predicted photosynthesis rate. The software module was implemented in the aforementioned greenhouses in The Netherlands and Texas. Predicted transpiration and photosynthesis as well as intermediate variables were available real time at the Synopta user interface. The stored values were used to analyze predicted transpiration as well as detected differences between measured and predicted.

Results

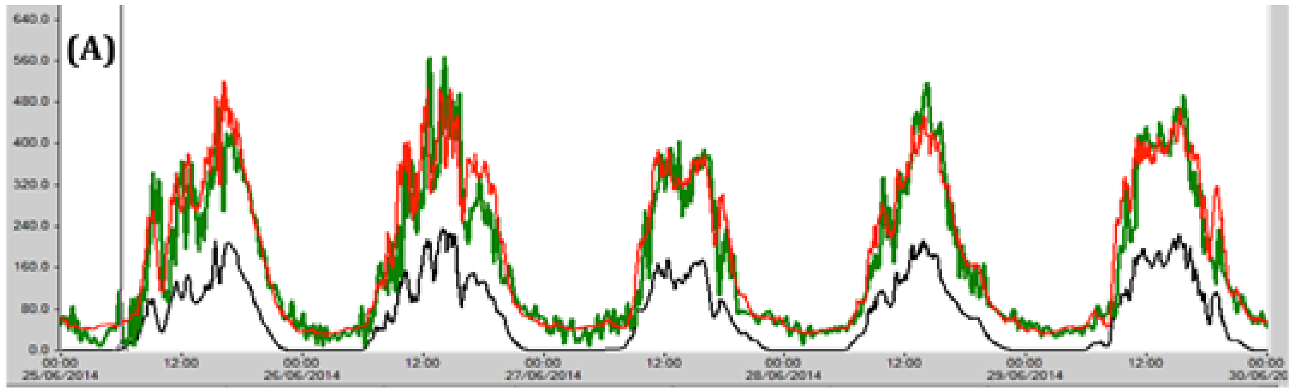
Validation of transpiration model

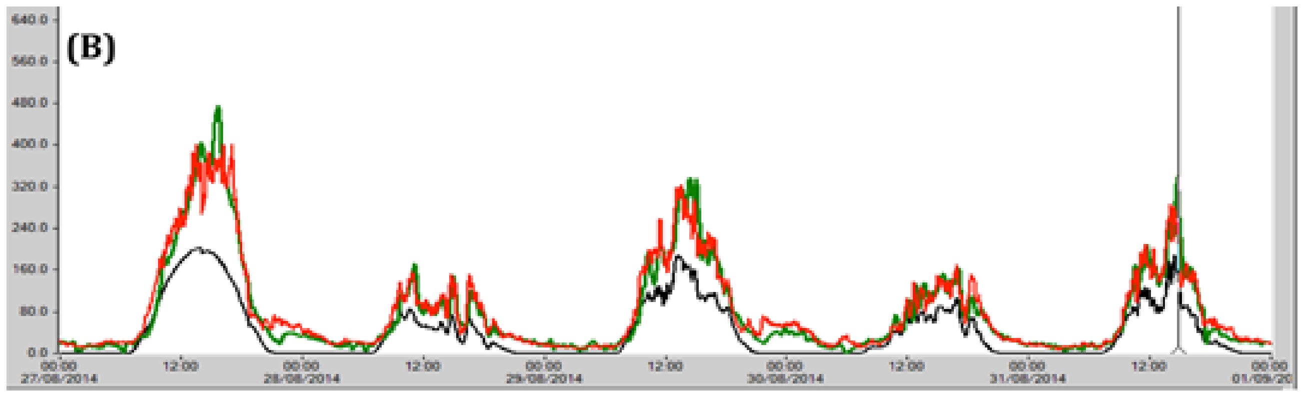
The validation and the calibration of the transpiration model were carried out with historical data from April and May 2014, from greenhouse A in The Netherlands. Firstly, the model was calibrated for the characteristics of a tomato crop by adjusting a crop specific parameter in the model (Tsafaras and De Koning, in preparation). Then, the model was tested over a wide range of the climatic variables. During the simulated days the daily radiation sum varied from 4 to 24 MJ.m-2, the temperature of the greenhouse air varied between 14 and 31 °C and the relative humidity was in the range 65-97 %. Comparing the theoretically calculated with the measured transpiration rate, high correlation was shown (Correlation coefficient and the Normalized Root Mean Square Error (NRMSE) were 0.91 and 0.10 respectively for hourly values and 0.92 and 0.10 respectively for cumulative daily values). The model succeeded to predict with fair accuracy both the variations of transpiration rate caused from changes of the climate variables and the cumulative daily transpiration over the full range of radiation, temperature and humidity levels.

Implemented model in commercial process control

The climate differed considerably between the two locations. The average daily radiation sum in Texas was about twice as high as in The Netherlands. The greenhouse air temperature was on average about 5 °C higher in Texas than in the Netherlands. The relative humidity was similar in the two locations, both during the day and night, except of the case of the double glazed compartment of the Dutch greenhouse where it was always higher.

The model predicted crop transpiration adequately during both sunny and dark days in both locations. The variation of transpiration with radiation intensity was predicted very well both within and among the days. Screenshots of representative graphs of historical data are presented in figure 2.





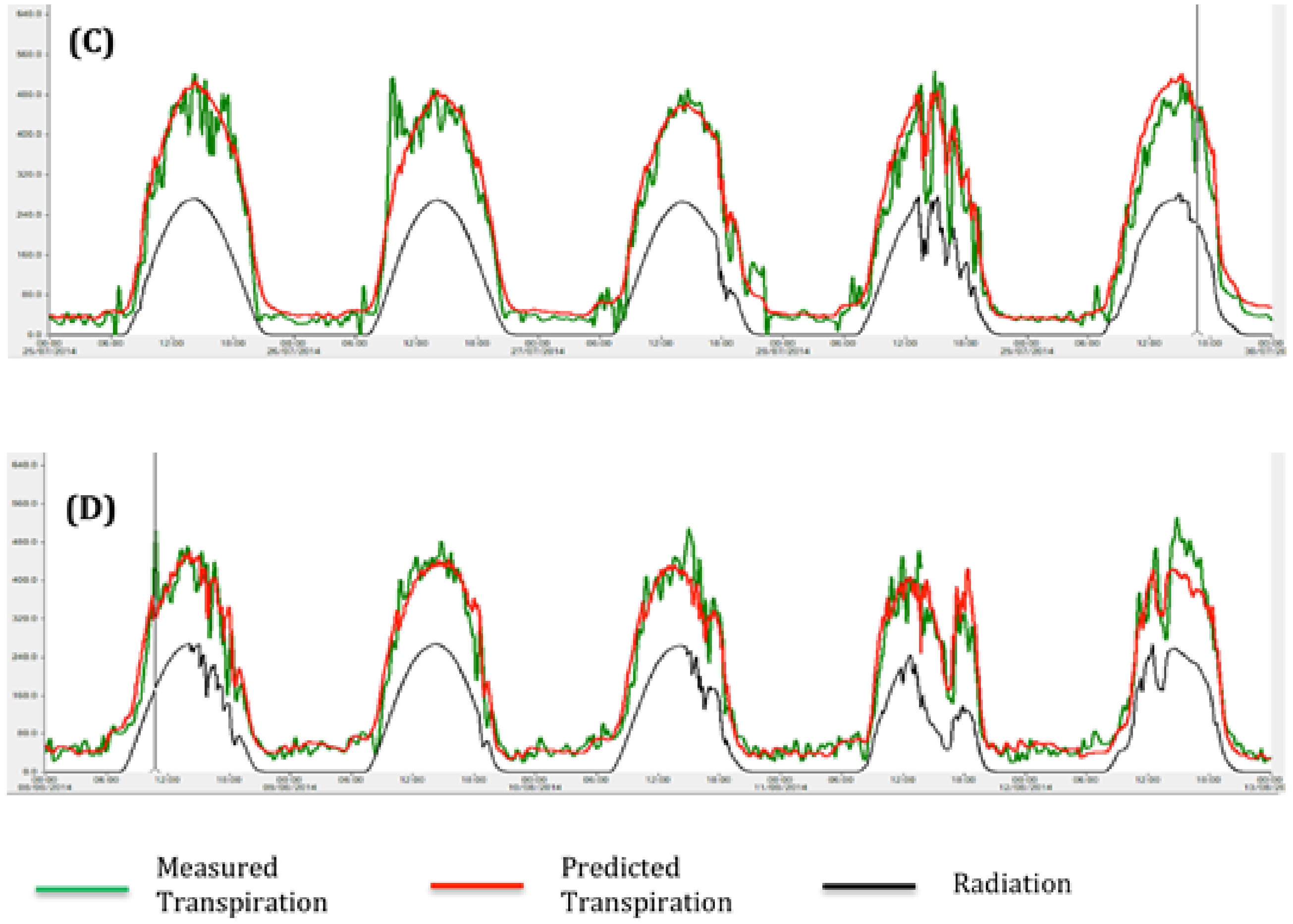


Figure 2. Measured (green line) and predicted (red line) transpiration rate (grams m-2 h-1) of tomato crop grown in commercial greenhouses in The Netherlands (A and B) and Texas (C and D). Radiation intensity is shown in the graphs (black line) in a scale from 0 to 2400 W m -2. The figures are taken as screenshots from the process computers of the growers.

Occasionally the measured transpiration differed significantly from the predicted. The first example (figure 3) shows a serious reduction of measured transpiration compared to the predicted between 14:00 and 16:00 hour. Also photosynthesis seems to be seriously affected as indicated by the relative photosynthesis rate compared to the predicted from the greenhouse environmental conditions.

In the second example (figure 4) a periodic reduction occurred in the late afternoon. Here it seems that transpiration was restricted by the availability of water in the root substrate as after each irrigation cycle transpiration reached the predicted level. Photosynthesis rate was calculated to be up to 20% less than expected, as a result of stomata closure.

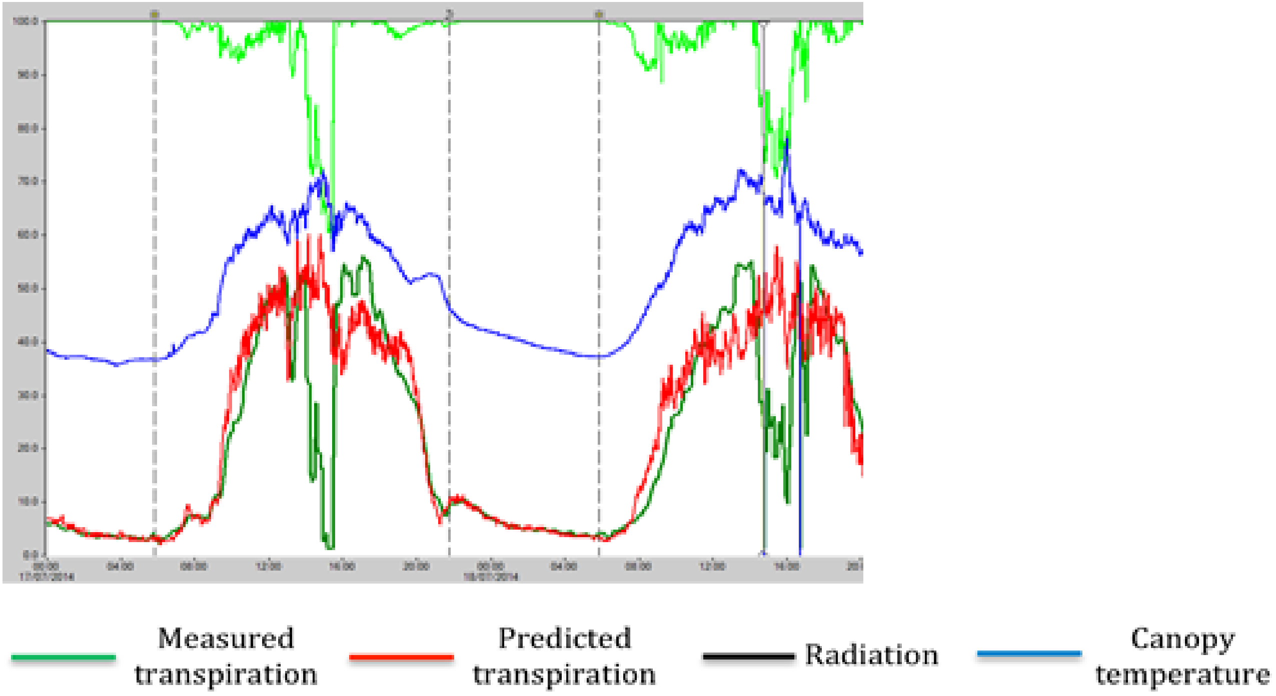
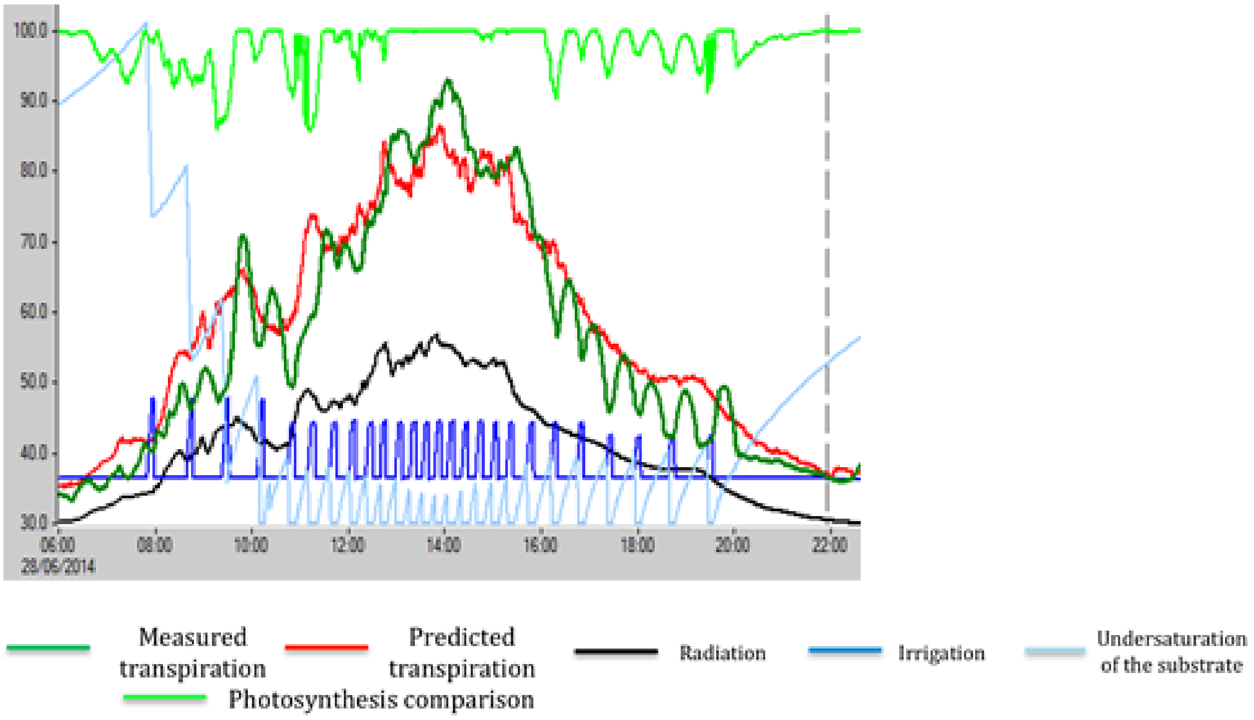


Figure 3. Measured (green line) and predicted (red line) transpiration rate (grams m-2 h-1) of tomato crop grown in a commercial greenhouse in The Netherlands. The figure is taken as a screenshot from the greenhouse process computer.

Figure 4. Measured (green line) and predicted (red line) transpiration rate (grams m-2 h-1) of tomato crop grown in a commercial greenhouse in The Netherlands. The figure is taken as a screenshot from the greenhouse process computer.



Discussion

Without adjusting parameters the model predicted the transpiration of the tomato crop very well under different climatic conditions as well for different cultivars. Therefore the transpiration model seems robust for general application in tomato. Implemented in the greenhouse process computer at commercial nurseries, when a difference was noticed between predicted and measured transpiration, the computer warned the grower for unexpected behavior of his crop.

Due to the architecture of the greenhouse control system, implementation of the models was without risk of control continuity. Therefore the models could be implemented at commercial nurseries even after limited tests on stability. The architecture with individual software modules (script controller) showed to be very suitable for adding custom software for control or monitoring to the greenhouse control computer. For the grower the system appeared user friendly as the script controllers are fully integrated in the user interface of the control computer. This made the added functionality very approachable and will enhance the use of it. As the added software wouldn't affect the control even when it fails, modules may be implemented by others than the manufacturer of the control computer. E.g. researchers may test model applications and optimizations and consultants may add their specific control strategy. Although in the present study the script controller only received in-line data from the control computer, the data exchange can also be bi-directional where the script controller may influence control settings and serves therefore as a smart client. In order to get the grower acquainted first the smart client may advise the grower without changing settings. In this mode the grower can compare the advice with his own settings. Such comparison is facilitated by storage of all data from the control computer as well as the script controller in the same user interface.

This paper shows the results of implemented transpiration and photosynthesis models. Many other applications can be imagined with other models, e.g. based on the energy, water or CO_2 balance in the greenhouse. The presented integrated intelligence in the greenhouse process computer introduces a new generation greenhouse control where others may add applications to the greenhouse process computer.

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