Monitoring of Climate Variables in Semi-Closed Greenhouses

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Abstract

Growers and Dutch government have concluded a covenant in which they express the ambition to reduce the carbon footprint of greenhouse production in order to improve the energy neutrality of newly built greenhouses. Conditioned cultivation in (semi-)closed greenhouses is seen as one of the instruments to reach this goal. It is appointed in the covenant to arrive in 2011 at 700 ha and in 2020 at 2,500 ha semi-closed greenhouses. This paper describes the instruments used to monitor the results of conditioned cultivation in eight semi-closed greenhouses in practice. It addresses the monitoring process, the installations involved and highlights some of the measured data.

INTRODUCTION

Semi-closed systems are a very promising concept for agronomy. In his overview of regenerative, semi-closed agricultural systems, Pearson (2007) mentions eight reasons to shift from conventional open or leaky systems to more closed, regenerative systems: “Current systems cause overconsumption of environmental resources, contribute to climate change, rely on increasingly expensive fossil fuel, and result in environmental (e.g., groundwater) contamination. Moreover, the agronomic-urban interface is growing, as are markets for ecologically friendly produce, the need for low-input farming systems in low-income regions, and disenchantment with the subsidization of conventional agriculture” (Pearson, 2007).

The concept of conditioned cultivation in (semi-)closed greenhouses is widely accepted as a method to achieve a substantial contribution to the energy neutrality and durability in horticultural production (Ruijgrok et al., 2003). The semi-closed greenhouse concept claims to save energy by reduction of losses and by a - partly diurnal and partly seasonal - phase shift of heat (cold) usage and heat (cold) storage. Additional technical equipments (humidifiers, air conditioners, heat exchangers, fans, cold- and heat storage in sub-soil aquifers, double screens) are used to keep the air temperature and humidity within acceptable limits, even when the windows are closed (Bakker et al., 2006; Campen, 2006; de Zwart, 2008). Not only allow these techniques a shift of the climate to a different “spot in the Mollier diagram”, they also allow higher levels of CO_2 (≥1000 ppm) to be maintained (closed windows) at high global radiation (≥600 W/m^2). As a result of these adaptations production increases (~20% estimated by modelling).

These ambitious goals require a paradigm shift. Cultivation in semi-closed greenhouses differs in essence from growing in conventional greenhouses. Cooling and heating by air conditioning ducts introduces temperature and humidity profiles that differ from the ones introduced by conventional heating and ventilation systems. Questions on how plants react to the new climate conditions provoked researchers to re-invent greenhouse growing in these new circumstances (Buwalda et al., 2006; Dieleman et al., 2006; Raaphorst et al., 2008; Qian et al., 2011).

Novice users of semi-closed greenhouses are reluctant to follow strictly the cultivation rules that come with these new climate regimes. It forces growers to change

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their treatment of the crop and to set a different climate regime. Often these settings are in complete contradiction with their experience of many years of greenhouse growing (De Gelder et al., 2005, 2008a,b), causing growers not to apply the needed measures to their full extend. As a result the expected production increase is not reached. An energy transition project named "Synergy" was started to provide a scientific back-up for the first innovators, who invested in new (semi-)closed growing systems even before it was clear how to operate them. Communication of their experience in "recovering from mistakes made" to the first followers was initiated following the first phase of the Synergy project. Advisory trajectories were started with as slogan "Innovate together" (Bruls et al., 2007; Bakker et al., 2008; Hoes et al., 2008), where growers who apply conditioned cultivation are organised in study groups. Extension officers assist these growers to comprehend the reaction of the crop in relation to the new behaviour of the conditioned climate variables. Monitoring equipment is installed in all greenhouses concerned to facilitate this process. For reasons of objectivity and fidelity, care was taken that the measuring equipment has a high quality and is positioned in the same way (Bakker, 2006).

MATERIALS AND METHODS

A number of suppliers of technical equipment to the Dutch greenhouse industry started to develop each their own idea on how to build a semi-closed greenhouse and what kind of equipment is needed in it. Each of the innovative growers teamed up with one of these suppliers and started to adapt (part of) their newly built greenhouses to a specific semi-closed principle of operation. Each grower-supplier combination came up with their own approach on solving the cultivation problems with additional technical solutions, leading to a number of designs and combinations of conditioning equipments.

The difference in performance of the designs involved was not clear. Analysis of the measured climate data was used in evaluating the effect on the greenhouse climate of the different system designs. It was considered a good approach to firstly understand the problems that occur in climate and crop of a distinct group of innovators. Typical questions put forward by the innovator-growers were related to: how to use the equipment to optimise production and energy use, how to interpret the behaviour of the crop and how to implicate it in terms of new set points for control.

A project called "Monitoring of growing conditions in semi-closed greenhouses with different technical systems" was initiated with the purpose to generate knowledge from the experiences in eight greenhouses of the innovator-growers. It was the challenge to study in the monitoring project an example of each of the available technical solutions (Table 1):

- perforated air ducts to bring warm or cold air in the greenhouse (Fig. 1, right).
- cooling in the top of the greenhouse, below the crop or both.
- fogging equipment for cooling purposes.
- local or central heat exchangers and Air Conditioning Box (ACB) (Fig. 2).
- seasonal storage of warm and cold water by sub-soil aquifers and heat pumps.

Furthermore, two types of crop were chosen (4 tomato and 4 *Phalaenopsis*), which are quite different in: i) the reason for applying conditioning of the climate, ii) the growing technique applied and iii) the use of crop specific climate appendages.

Tomato was chosen as an example of a crop that fills the greenhouse and asserts itself on the climate. It is a tall crop that might suffer from vertical temperature differences. The main goal of applying semi-closed systems in tomato cultivations is to save energy and increase production by increasing the CO_2 level (Fig. 4).

Phalaenopsis was chosen as an example of a potted plant. Its shape is compact. The goal of applying semi-closed systems is to save energy and improve quality. *Phalaenopsis* is grown in two consecutive phases, a warm and a cold cultivation phase. Cooling is applied for more branches and nicer flowering.

Measuring System

During at least one year the eight greenhouses were monitored. Standard data from the greenhouse climate control computer were collected (e.g., CO_2 level, global radiation, temperature of the heating systems, position of windows and screens, use of artificial light, and outside weather conditions). Special attention was paid to the control of the heat exchangers (e.g., fan speed, inlet and outlet temperatures). Measuring boxes were placed at three vertical positions to quantify vertical profiles of temperature and humidity. A radiation sensor measured PAR-radiation at crop level; a WET sensor measured EC, temperature and moisture of the substrate (only tomato); and an IR camera measured plant temperature (Fig. 1, left). Artificial tomato-fruit mockups were positioned in the canopy of the crop to measure average fruit temperature in a close accordance with real fruits. When available, a traditional controlled (open) greenhouse was monitored as a reference.

Additional measurements were performed with a set of 30 wireless temperature and relative humidity sensors (Sownet, Model HT100, The Netherlands) to measure profiles of temperature and relative humidity in horizontal or vertical grids near air-conditioning ducts, heat exchangers and the ACB. Air movement was measured with acoustic air-movement sensors (Gill Instruments, 2006).

All data were collected and stored in databases of the web-server LetsGrow (Kempkes et al., 2009; www.letsgrow.com). Data retrieval programs were formulated in Matlab (version 7, The MathWorks Inc., Natick, USA), which take the data streams from the Letsgrow database and calculate at 5 min intervals the average of that data point with data points of the same time of day of a number of consecutive days before. This procedure removes artifacts in the data and shows specific data-patterns that remain untouched during several days. This procedure is very useful in the analysis of "what happened, as a result of a specific action". The data were used for the analysis of actions taken by the grower and the effect these actions had on the climate and the behavior of the crop. Results of these analyses were discussed with each individual grower on a weekly basis and once per month in two groups, one group for each crop type. Researchers used the data for additional analysis and dissemination of results.

RESULTS AND DISCUSSION

Growers in the project struggled to balance the plant responses by adjusting the settings of the systems (tomato) or how to manipulate the climate to dry the plants after water supply. The individual discussion was a kind of personal consultancy of the individual grower by the extension officer, often leading to a change in behavior of that grower and to the grower's "loosing fear for making mistakes". The group approach showed results towards identifying general problems, leading to a follow-up in research.

Figure 3 shows the cyclic temperature and vapor deficit of *Phalaenopsis* grower 7 (Table 1). The lower sensor is placed in between the greenhouse floor and the bottom of the growing table (Fig. 2 right). At this level during heating the warm air and during cooling the cold air is distributed. This explains the trend of the temperature below the table during the day. At night time the greenhouse still needed some heating and during daytime cooling. The set point line (setp.) shows the target temperature of the greenhouse air temperature at middle level sensor, which was just at the top of the plants. The small difference in temperature between middle and high sensors means a high level of mixture of the air above the growing tables, which was a result of the properties of this system setup. In general, these temperature differences were small.

The relationship between production in the open and semi-closed greenhouse is shown in Table 2. A weighted CO_2 level is used in the production model of Nederhoff (1994) to calculate the effect in production due to radiation and CO_2 level. The weighing was done according to an experimental formula as in Equation 1.

$$250 < CO_2[ppm] < 1000 \;\rightarrow\; CO_{2-effective}[\%] \approx 100 \cdot (1 - (\frac{1000}{CO_2} \cdot 0.15 - 0.15)) \qquad (1)$$

Differences between predicted and measured production were probably caused by other effects on growth than just CO_2 and climate, such as diseases, deficiencies, predators and crop treatment, which is especially true for grower 3. The data in Table 2 show that for the growers 1 and 4 the predicted production is reasonably in line with the measured production. The difference in the results of grower 2 can be explained by the different tomato cultivars used in the open and semi-closed greenhouse.

Figure 4 shows that in winter time the differences in CO_2 levels between open and closed greenhouses are small. Due to a high CO_2 production (i.e., the high heat demand of the greenhouse) and the small ventilation rate, availability of CO_2 is not the limiting factor. Hence, in summer time, Figure 4 shows differences to be larger. Then the CO_2 demand is higher, because of the higher ventilation rate in the conventional greenhouse and the CO_2 availability is limited because of a low heat demand. Figure 4 (top-left) shows that grower 1 has the highest overall CO_2 levels, which is easily explained by the fact that his greenhouse is completely closed (no windows at all). Moreover, Figure 4 shows that in summer time the 1000 ppm mark is never even approached, justifying the term semi-closed greenhouse.

Figures 5 and 6 show cyclic temperatures and vapor deficits of tomato grower 2 (Table 1) in the conditioned and conventional compartment respectively. During daytime, the temperature distribution above the crop in the conditioned compartment differs in size and in direction in comparison with the conventional greenhouse (approx. 2°C). During daytime the conventional greenhouse shows hardly any temperature difference between the top of the plant (high) and the substrate (low). In the conventional greenhouse the open windows will bring “cool” air into the greenhouse from above, resulting in low temperatures at the top of the crop. Large window openings cause turbulence and mixing of the greenhouse air, which results in smaller vertical temperature differences. In closed greenhouses, where, in this case, input of cold air is from below, the mixing of greenhouse air is less because cold air will not rise and turbulence is small (closed windows). The resulting vertical temperature gradient is larger in comparison with the conventional greenhouse and of opposite sign. During nighttime, when there is no cooling, the temperature in both greenhouses is equally distributed.

In the conditioned greenhouse the vapor deficit is always lower (more humid), as is shown in the diagram at the right of Figures 5 and 6. During daytime the vapor deficit in the conventional greenhouse is high (more dry) because of the high ventilation rate and the exchange of dry outside air with humid greenhouse air.

CONCLUSIONS

The differences between nurseries in the vertical distribution of temperature and humidity are caused by a different lay-out of the systems. The vertical temperature gradient decreases when the balance between cold brought in from above and from below shifts towards more cold inserted from above. The vertical temperature gradient fluctuates more in the semi-closed greenhouses of the monitoring project than in conventional greenhouses. In the conditioned greenhouse the vapor deficit tends to be lower (more humid) than in the conventional greenhouse.

Because *Phalaenopsis* plants are short compared to the height of the greenhouse, vertical temperature differences over the crop are small and independent of the installation setup.

In summertime higher CO_2 levels are reached, because windows are closed due to application of cooling systems, however much less than the level of 1000 ppm that was hoped for.

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Tables

Table 1. Technical equipment in tomato (1-4) and *Phalaenopsis* (5-8) greenhouses.

Grower	Decentralized ACB, free exhaust **above** the crop	Centralized ACB, distribution by ducts **below** the crop	Decentralized ACB, free exhaust **below** the crop	Fogging system
1	X	X		
2		X		X
3		X		
4	X			X
5			X	
6			X	X
7		X		
8	X			X

Table 2. Effect of CO_2 use on tomato crop production in standard and semi-closed greenhouses in relation to radiation (during high radiation effect largest), columns 2 and 3 show the weighted effect, expressed in %, and calculated and realized production increase (%), columns 4 and 5 in 2008.

Grower	CO_2 effective (%)		Production increase (%)	
	Standard	Semi-closed	Calculated	Realized
1	86.1	89.0	3.4	~4
2	84.2	88.2	4.8	~10
3	79.7	89.9	12.8	~0
4	85.1	90.0	5.8	~8

Figures

Fig. 1. Sensors situated in a greenhouse with a tomato crop (left) and air ducts of a decentralized system below the crop (right).

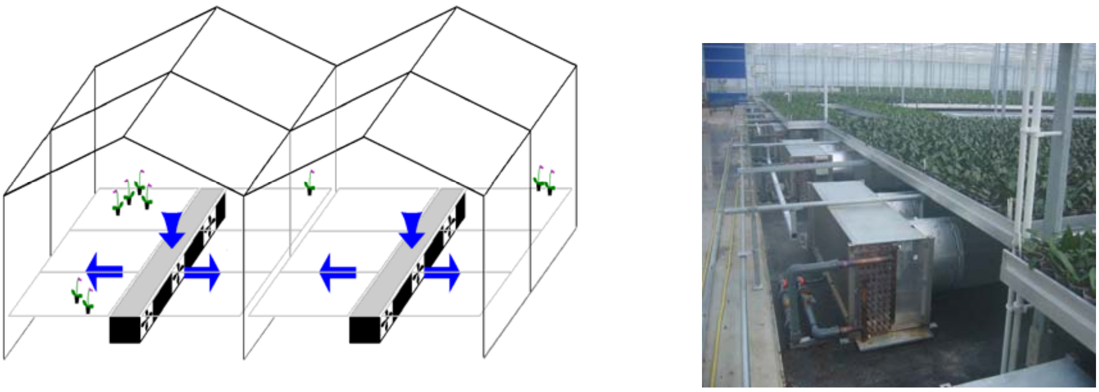

Fig. 2. Moving benches with pot plants (*Phalaenopsis*) and the air conditioning system consisting of decentral ACBs (left) and central ACBs with perforated air ducts (right).

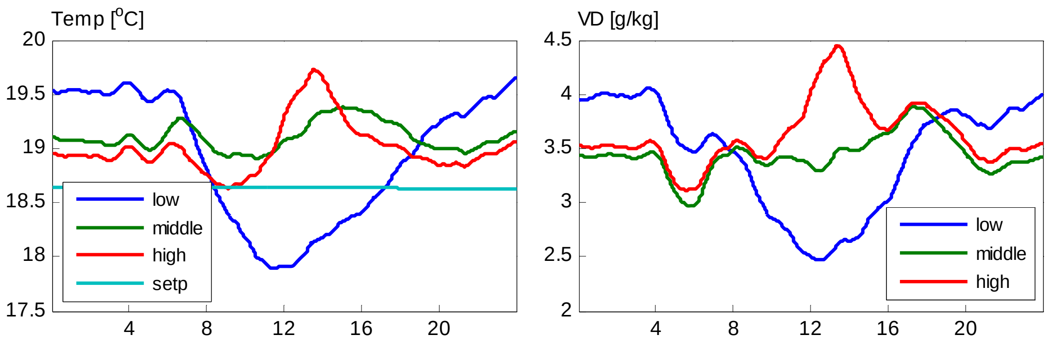

Fig. 3. Cyclic temperature (left) and vapor deficit (right) of grower 7 from 1 till 31 May 2009.

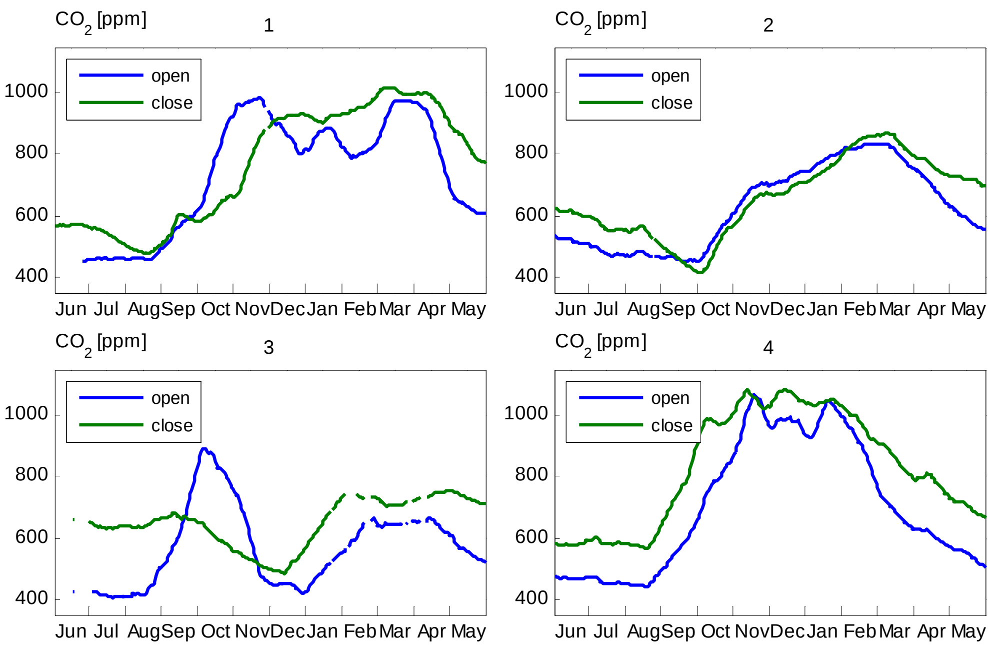

Fig. 4. Daily average CO_2 level during daylight for the open and closed greenhouses of the 4 tomato growers from June 2008 till June 2009.

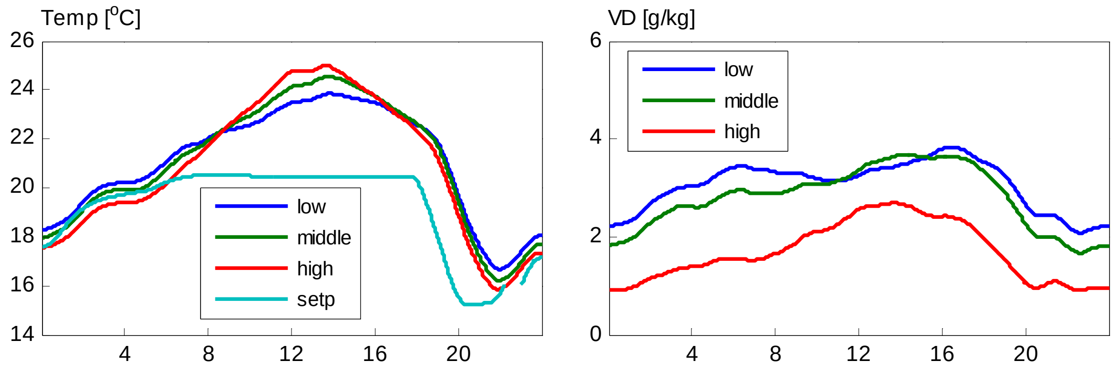

Fig. 5. Cyclic temperature (left) and vapor deficit (right) of the conditioned compartment of grower 2 (Table 1) from 1 till 31 May 2009.

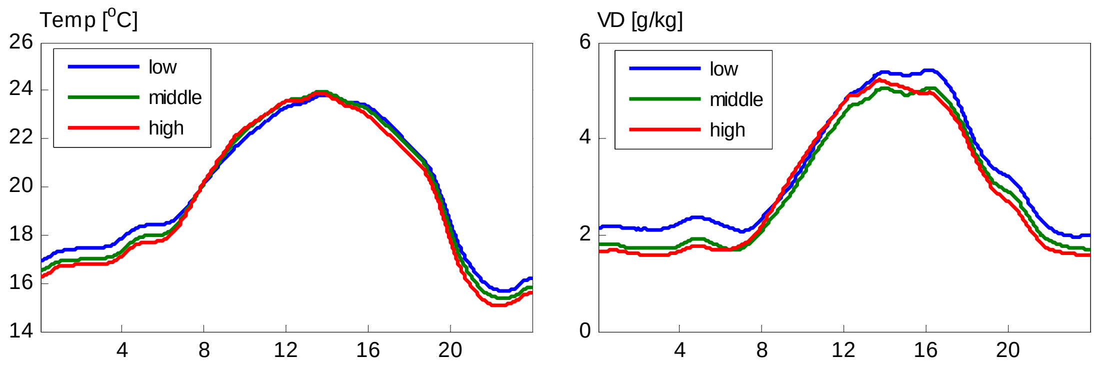

Fig. 6. Cyclic temperature (left) and vapor deficit (right) of the conventional controlled compartment of grower 2 (Table 1) from 1 till 31 May 2009.