Modeling the Effect of the Position of Cooling Elements on the Vertical Profile of Transpiration in a Greenhouse Tomato Crop

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Abstract

Semi-closed greenhouse management may increase greenhouse productivity. However, it relies on the application of mechanical cooling. Cooling can be applied from above or below the canopy. The positioning of the cooling affects the vertical climate profile in the canopy. In order to determine how this affects the vertical profile of transpiration and crop temperature, in this work we used the energy balance of different crop layers to develop a modified "big leaf" model for its temperature and transpiration. The model was validated with data from a large greenhouse experiment (tomato) where the position of cooling elements and climate set-points ensured different vertical profiles of air properties. In particular, we had the combination of two positions of cooling elements (above and below the crop) and two temperature set-points; and a control (not cooled and naturally ventilated) compartment. For the validation we used measurements of crop temperature at different heights in the canopy and of transpiration of the whole crop. Finally we used the model to determine and discuss the effect of the various types of air conditioning on the vertical profile of transpiration within the crop. The compartment with natural ventilation had the highest simulated transpiration (which agreed with the measurements) and the largest uniformity of distribution of transpiration among layers. The least homogeneous distribution was with the cooling elements below, which had also the smallest total transpiration, which was 95% of the transpiration of the crop cooled from above.

INTRODUCTION

There are several advantages of reducing greenhouse ventilation, including reduced pest pressure; the chance of maintaining a higher carbon dioxide concentration and reduced heating requirements. Since this leads to a higher productivity (Heuvelink et al., 2008), a number of growers have built semi-closed greenhouses in The Netherlands. Only mechanic (rather than evaporative) cooling is compatible with reduced ventilation. Cooling can be applied from above or below the canopy. The positioning of the cooling affects the vertical climate profile in the canopy (Qian et al., 2012).

There are questions about the best management of climate and cooling strategy, with regard to the physiological processes in the crop (Heuvelink and Gonzalez-Real, 2008). In particular, with respect to the position of the cooling elements there is a trade-off to be made between positioning above the crop (which warrants the most uniform vertical temperature profile) and positioning below (which prevents light loss). The consequences for crop physiology are hardly known. It may for instance affect the vertical distribution of transpiration in the canopy, which in turn may affect transport of calcium and other processes. The aim of this paper is to analyse to what extent the vertical profile of temperature and humidity of the air affects the distribution of transpiration and temperature among various crop layers.

Before we can answer this question we need to be able to determine water relations of different layers of a crop. Unfortunately, it is hardly possible to measure transpiration of a single layer of a healthy crop. Our approach has been to use the energy balance of four superimposed crop layers to develop a model for its temperature and transpiration; then to validate the model with measurements of crop temperature at different heights in the canopy and of transpiration of the whole crop; and then to use the model to determine the effect of the various types of conditioning on the crop.

MATERIALS AND METHODS

The Experiment

The experiment is described extensively elsewhere (Dieleman et al., 2011) and here we only give the information relevant to this topic. On December 23, 2008, tomatoes (‘Cappricia’ on rootstock Emperador) were planted in five 144 m^2 compartments of the greenhouse research facility of Wageningen UR Greenhouse Horticulture, in Bleiswijk, The Netherlands. After an initial period to ensure similar development of the crops among compartments, treatments started on March 13, 2009. One compartment (control) had no cooling and was managed (ventilated) in a traditional way, that is: ventilators where open by a P-controller whenever air temperature exceeded the ventilation set-point. In the other four a cooling capacity of 350 W m^{-2} was installed, so that ventilation took place only if the greenhouse temperature exceeded the ventilation set-point, in spite of the operation of the coolers. In two compartments the cooling was achieved by cold air blowing over the crop, in the other two the cold air was distributed by perforated ducts installed under the hanging gutters supporting the crop. The temperature set-points for cooling/ventilation were the same in the control and in two of the cooled compartments (one for each cooling type), whereas in the other two the set-point was raised in a light-dependent fashion by up to 1°C. Besides the ventilated measurement box (Hoogendoorn, Vlaardingen, the Netherlands) positioned above the crop for air temperature and humidity that is the input for the climate control system, four such boxes where hanging in each greenhouse (within the canopy) about equally spaced between the one at the top of the canopy and the one at the level of the substrate (the hanging gutters, 75 cm above ground).

The Model

We modified an existing model for transpiration of greenhouse crops (Stanghellini, 1987, with the simplification proposed in Bontsema et al., 2007) to generate transpiration of four crop layers. The model is based on the Penman-Monteith method (Monteith, 1965) whereby the energy balance and the vapour and heat transfer equations of a crop (seen as a “big leaf”) are combined to yield the transpiration and the temperature of the “big leaf”. We segmented the crop in four layers, referring vapour and heat transfer of each one to the air dry and wet bulb temperatures measured in ventilated boxes in each layer. The leaf (or stomatal) resistance was determined for each layer as a function of the radiation reaching the layer (Stanghellini, 1987) and the boundary layer resistance was assumed to be constant and homogeneous. Leaf area was assumed to be equally distributed among the four layers, and we have calculated the net radiation (R_i, W m^{-2}) absorbed in layer i through:

$$R_i = 0.86\, R_{top}\left[\exp\left(-0.7\sum_{1}^{i-1} LAI_i\right) - \exp\left(-0.7\sum_{1}^{i} LAI_i\right)\right] \qquad \mathrm{W\ m^{-2}} \quad (1)$$

where layer 1 is the uppermost layer; LAI_i is the leaf area index of layer i and R_{top} is net radiation above the crop. Net radiation includes both solar radiation and exchange of long-wave radiation with all surrounding elements and other canopy layers. A large number of sensors would be required to determine net radiation in each canopy layer, given the large in-homogeneity of a tomato crop on a small scale, which prevents experimental verification. However, differences in temperature are relatively small within a greenhouse and the very hot or very cold greenhouse-elements (such as the heating pipes or the roof gutters) occupy only a relatively small fraction of the “horizon” of each layer. The cold greenhouse roof would probably be an important element for the uppermost layers, but we may assume that when it would be really cold, then the energy screen is closed. Therefore, it was decided to use one sensor to determine net radiation at the top of the canopy, with the assumption that the influences of other radiation sources are relatively small. The net radiation absorbed by each layer was then modeled, based on that one sensor.

The net radiation at the top of the canopy can better be determined as a function of sun radiation outside the greenhouse, rather than on the basis of a single sensor which may be not representative at all times; for instance, when the shadow (or the reflection) of a construction element passes over it. As a good correlation between solar (I_{sun}) and net radiation at top of the canopy (R_{top}) was found, we assumed that the intercept of the best-fit equation accounted well enough for the long wave exchange (among elements of nearly the same temperature anyhow) without the need for modeling.

$$R_{top} = 0.5 I_{sun} + 10 \qquad \text{W m}^{-2} \qquad (2)$$

Data available from the greenhouses with the cooling elements above would yield a slightly different equation (lower slope and intercept at times negative). The presence of the cooling elements, which intercept some sunlight, may explain the lower slope; the cooling elements, when operating may cause a net long-wave radiation flow from the canopy to the elements, which would explain the intercept at times negative. As there was a strong preference for not pre-determining the results through unverifiable assumptions about net radiation distribution, Eq. (2) was applied for each treatment.

As it is well known, the combination of the energy balance and the heat and vapour transfer equations can be solved to calculate both the leaf temperature and crop transpiration of each layer.

The Measurements

Crop water uptake was determined by weighing a 8-plant section of a substrate gutter, in each compartment. The weight of the plants was determined separately by pressure sensors on the rod from which the plants were hanging. The weight of the substrate and the weight of the hanging plants were measured and recorded each 30 s, which ensured (after filtering) reliable data over time intervals of 10 minutes or longer. Transpiration was determined as the difference in water uptake and fresh growth, and was between 88.5 and 92.5% of water uptake. We also measured leaf temperature, by means of a series of 5 thermocouples at each level, at three heights in the canopy: 1.15, 2.45 and 3.55 m, respectively, above the gutter, with a full-grown height of the canopy between 4 and 4.5 m. Due to the amount of work for ensuring good contact between leaf and thermocouple, this was done only during selected periods and not concurrently in the compartments.

RESULTS AND DISCUSSION

Calculated and measured profiles of leaf temperature are shown in Figure 1 for both positions of the cooling elements and for two different periods. Results are shown only for the top and bottom canopy layer, for clarity. The model reproduces quite well the trend, and it correctly accounts for the periods of operation/non operation of the cooling systems. Figure 2 shows the calculated and measured profiles of transpiration in different weather conditions, for the control treatment. The values for each layer are stacked, in order to allow comparison with measured transpiration of the whole crop. The model seems to reproduce the measured values rather well, although some of the assumptions − in particular the night-time behaviour of calculated vs measured values − suggests that the assumption of constant long-wave radiation exchange may not hold under all circumstances. Figure 3 shows the results of the same days for both positions of the cooling elements (the two compartments having the same climate set-points as the control). The figure shows that cooling from below results in less total transpiration than cooling from above, particularly during sunny days. In addition, it makes clear that the contribution of the two lowermost layers to total transpiration is smaller than with cooling from above.

Summary results are given in tables. Table 1 shows an analysis of the results for the crop temperature calculated for each treatment. The treatments that were meant to have the same air temperature did result in the same crop temperature as well. The effect of the increased temperature set-point (last two rows of Table 1) was smaller on the crop than on the air, which is to be expected. As an indicator of the effect of the treatments on the temperature gradients within the crop we have calculated for each time point the standard deviation of the temperature of the 4 canopy levels (a large standard deviation means there are large differences between canopy levels) and in the table the average of all standard deviations is shown. Indeed the control treatment had the lowest variation and the cooling below the largest, slightly mitigated by a rise in temperature. The two rightmost columns show the results exclusively for the periods when the cooling was concurrently operating in all four compartments. The effect of cooling elements below on the temperature profile becomes even more obvious. However, it may be slightly more surprising that cooling from above does not result in a more uniform climate than natural ventilation (open greenhouse).

Table 2 shows the effect of the treatments on crop transpiration. The model reproduces the measured trend, whereby the control treatment transpired the most, followed by the two with raised temperature and then the others. In both cases, cooling elements above gave more transpiration than cooling elements below. Transpiration was the most uniformly distributed in the open compartment and the least in the bottom-cooled ones.

Obviously, the cooling is operating when there is an abundance of sun radiation. As Figure 1 shows, under sunshine the uppermost layer is much warmer than the lowermost, even with cooling from above. This means that the contribution of sun energy to crop processes is much more relevant than that of air properties. In such condition crop transpiration is driven more by available energy than by the properties of the surrounding air, so that the effect of profiles of air temperature and humidity is relatively small. Therefore the vertical inhomogeneity caused by cooling from below is smaller for transpiration than for air properties, although it is still larger than with natural ventilation or cooling from above.

CONCLUSIONS

A simple multi-layer “big leaf” model is able to reproduce correctly the measured vertical profile of leaf temperature under various configurations of cooling systems. The sum of the crop transpiration calculated for each layer also corresponds satisfactorily with measured transpiration of the whole crop. The compartment with natural ventilation had the highest transpiration due to lower VPD and the largest uniformity of distribution of transpiration among leaf layers. As expected, the least homogeneous distribution was with the cooling elements below, which had also the smallest transpiration.

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Tables

Table 1. Calculated average leaf temperature (°C) averaged over 4 canopy levels in the five treatments, from Aug 26th to Sept 19th. The standard deviation (σ, °C) is the mean of the standard deviation of the 4 level values, calculated at each time interval. The two columns on the right are calculated for the periods when the cooling was operating in all compartments (1500 of the 3600 data points of the whole period).

		Whole period		Cooling only	
		Mean	Mean of σ over layers	Mean	Mean of σ over layers
Open		18.6	0.36	19.8	0.52
Cooling	above	18.7	0.39	19.9	0.52
	below	18.6	0.69	19.9	1.02
	above (+1°C)	19.2	0.41	20.5	0.55
	below (+1°C)	18.9	0.59	20.2	0.95

Table 2. Effect of the treatments on crop transpiration (g m^{-2} min^{-1}) and its profile over the four canopy levels, for all periods when cooling was concurrently operating in the four compartments, from Aug 26th to Sept 19th, 2009. The mean standard deviation over levels is calculated as in Table 1. The rightmost four columns tell which fraction of the total transpiration took place in each layer.

		Mean	Mean of σ over levels (g m^{-2} min^{-1})	Low	Mid-low	Mid-high	High
				(%)			
Open		3.20	0.34	16	19	26	39
Cooling	above	2.51	0.29	14	18	28	40
	below	2.42	0.39	11	15	28	46
	above (+1°C)	2.62	0.33	14	18	27	41
	below (+1°C)	2.52	0.39	11	15	27	46

Figures

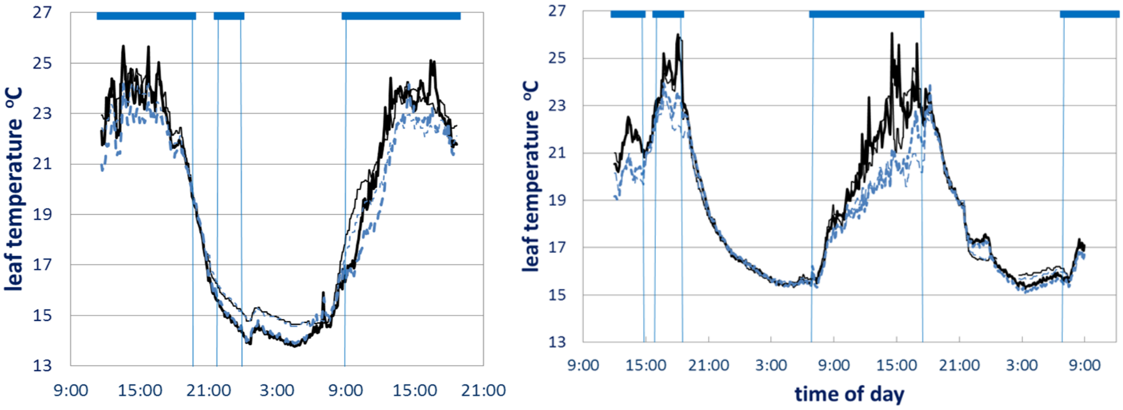

Fig. 1. Measured and calculated leaf temperature in the top and bottom layer of the canopy during different days. Left: the cooling elements were above the crop; right: cooling elements were below the crop. The operation of the cooling is also indicated. The gradients (both measured and calculated) were much smaller when the cooling was not operating.

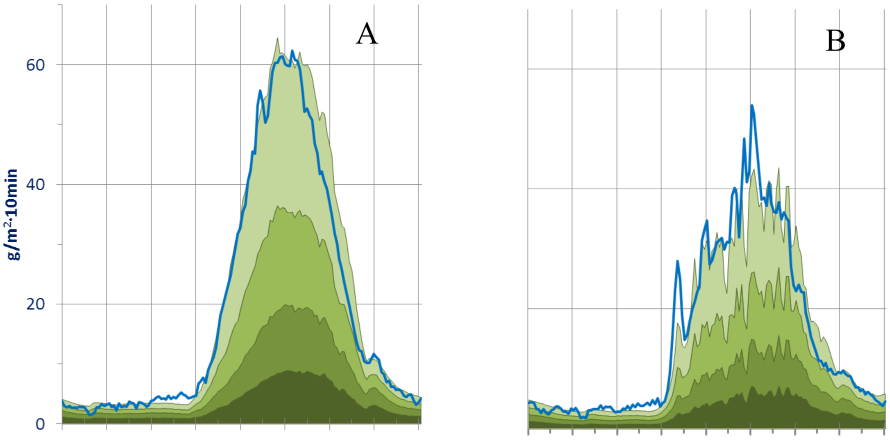

Fig. 2. Stacked plots of calculated transpiration (control compartment) in the four canopy layers, the darkest is bottom, for a sunny day (A) and a cloudy day (B). The thick line is the measured transpiration of the whole crop. The x-axis is 24 hours.

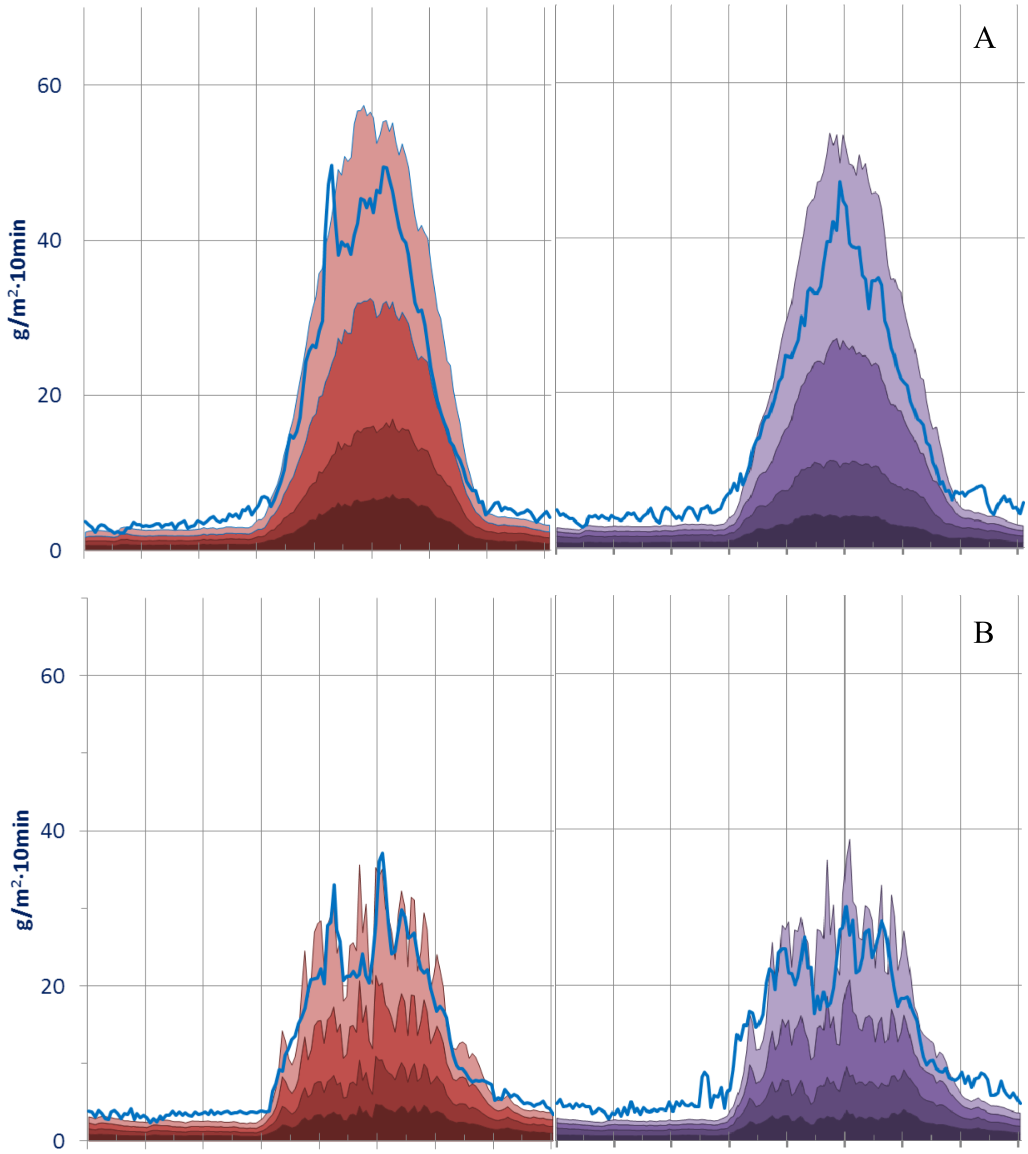

Fig. 3. Stacked plots of calculated transpiration in the four canopy layers, the darkest is bottom, for the same sunny (A) and cloudy (B) days as Figure 2. Left panels: cooling elements above the crop; right panels: cooling elements below. The thick line is the measured transpiration of the whole crop, in each compartment. The x-axis is 24 hours.