

Vertical Temperature Gradients in the Semi-Closed Greenhouses: Occurrence and Effects

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Abstract

Semi-closed greenhouses have been developed in which window ventilation is minimized due to active cooling, enabling enhanced CO₂ concentrations at high irradiance. Cooled and dehumidified air is blown into the greenhouse from below or above the canopy. Cooling below the canopy may induce vertical temperature gradients along the length of the plants. Our first aim was to analyze the effect of the positioning of the inlet of cooled and dehumidified air on the magnitudes of vertical temperature and VPD gradients in the semi-closed greenhouses. The second aim was to investigate the effects of vertical temperature gradients on assimilate production, partitioning, and fruit growth. Tomato crops were grown year-round in four semi-closed greenhouses with cooled and dehumidified air blown into the greenhouses from below or above the crop. Cooling below the canopy induced vertical temperature and VPD gradients. The temperature at the top of the canopy was over 5°C higher than at the bottom, when outside solar radiation was high (solar radiation >250 J cm⁻² h⁻¹). Total dry matter production was not affected by the location of the cooling (4.64 and 4.80 kg m⁻² with cooling from above and from below, respectively). Percentage dry matter partitioning to the fruits was 74% in both treatments. Average over the whole growing season the fresh fruit weight of the harvested fruits was not affected by the location of cooling (118 vs 112 g fruit⁻¹). However, during summer period the average fresh fruit weight of the harvested fruits in the greenhouse with cooling from below was higher than in the greenhouse with cooling from above (124 vs 115 g fruit⁻¹).

INTRODUCTION

Semi-closed greenhouses were developed to save energy. Greenhouse air is cooled and dehumidified by air treatment units and returned to the greenhouse through cooling ducts. Active cooling is combined with window ventilation if temperatures are too high to be controlled by the air treatment units with limited cooling capacity. Cooling ducts are normally placed beneath the growing gutters, because placement overhead or within crops either causes loss of light or interferes with cultivation procedures (Wells and Amos, 1994). However, cooling from below induces a vertical temperature gradient along the canopy (Qian et al., 2011a). The occurrence and magnitude of the vertical temperature gradient depend on the radiation (Suay et al., 2008), the cooling capacity, and temperature of the air blown into the greenhouse (Qian et al., 2011a). It may vary during a day and during the season. So far, hardly any research on the effects of vertical temperature gradients on crops has been conducted. The vertical temperature gradients might affect assimilate production, dry matter partitioning and fruit growth. Therefore we carried out an experiment with tomato crops in semi-closed greenhouses where a vertical temperature gradient was present or absent. The aims of this paper were firstly to analyze the effect of the positioning of the inlet of cool and dehumidified air on the occurrence and magnitudes of vertical temperature and VPD gradients in the semi-closed greenhouses, and secondly,

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to investigate the effects of vertical temperature gradients on assimilate production, partitioning, and fruit growth.

MATERIALS AND METHODS

Experiments were conducted in four adjacent semi-closed greenhouses with 350 W m⁻² maximum cooling capacity, located in Bleiswijk, The Netherlands. Each greenhouse measured 144 m² (15×9.6 m), with a gutter height of 5.5 m. Transmission of diffuse global light was 58.59%. Seven growing gutters, about 70 cm above the floor, with rockwool slabs, were oriented from east to west, of which five were double-row and two were single-row for border plants. Air conditioning was controlled by a standard horticultural computer (Hoogendoorn-Economic). Cooling capacity was controlled by adjustment of air speed and the temperature of the cooling water. This control was based on the difference between supply and return water temperature in the air treatment units. Air temperature set points for cooling and heating were identical for all the four greenhouses. Ventilation windows were opened if the cooling capacity was insufficient to keep greenhouse temperature below the critical level. Pure CO₂ was supplied at a maximum rate of 230 kg ha⁻¹ h⁻¹ during daytime with a set point of 1000 μmol mol⁻¹ for each greenhouse. Outside radiation, greenhouse CO₂ concentration, greenhouse air temperature and humidity were recorded automatically at a 5 min interval. In addition, temperature and humidity sensors (Hoogendoorn) were placed at four canopy heights in each greenhouse (3.5, 2.5, 1.2, and 0.3 m above the growing gutters, which were 0.7 m from the ground). The highest sensor (3.5 m) was above the top of the canopy. The lowest sensor (0.3 m) was between the lowest truss and the rockwool slab. The values of the two sensors in the middle (2.5 and 1.2 m) were averaged, representing the temperature and humidity at the middle of the canopy.

Two treatments were applied, namely cooling from below and above the canopy (Fig. 1). Each treatment was replicated in two greenhouse compartments. The difference between the realized daily average temperature between the two replicates was less than 0.5°C. In all the four greenhouses, air was extracted from the greenhouse by five ventilators placed at the top of the greenhouse, cooled and dehumidified in the air treatment units. In one treatment, treated air from the air treatment units was returned to the greenhouse through five plastic cooling ducts placed horizontally beneath the growing gutters. Each duct had six holes (16 mm diameter) per meter. In the other treatment, treated air from the air treatment units was returned at the top of the greenhouse through the ends of five blowers at the two ends of the greenhouse.

Truss tomato plants, cultivar ‘Cappricia’ grafted on the rootstock Emperor, were planted on rock wool slabs on December 23rd, 2008, at a plant density of 2.5 m⁻². Initially one stem per plant was maintained. In week 8 after planting, an additional side shoot was maintained at 1/3 of the plants, increasing stem density to 3.33 m⁻². Climate treatments started on 23rd March 2009. Fruit number was manually restricted to 6 fruits per truss. Weekly fruit harvests started in week 15 after planting. In each week, total harvested fresh weight and total number of harvested fruits from one double row were measured in each greenhouse. Fresh weights of individual fruits were calculated by dividing the total harvested fresh weight of the fruits by the total number of harvested fruits from the double row.

Destructive harvests were performed 0, 27, 40 and 46 weeks after planting. Fresh and dry weights (dried at 80°C for over 24 h) of leaves, stems and fruits were measured. Fresh weight and dry weight of the picked leaves and harvested fruits were recorded and added to the cumulative dry weights. Each compartment was divided into 3 blocks from north to south. Two plants were randomly selected from each block. In total, 6 plants (4 with a single main stem and 2 with side shoot) were selected from each compartment per periodic harvest. At each periodic harvest, the 2 plants with a side shoot were always selected from two different blocks. Dry matter production during summer was the difference of the measured values between week 40 and week 27.

The significance ($P < 0.05$) of treatment effect on dry matter production, partitioning and fruit production was tested through ANOVA. Analysis was done in Genstat 12.1.

RESULTS AND DISCUSSION

Climate

Outside global radiation and outside temperature fluctuated during the season (Fig. 2). Average climate conditions at top of the canopy were rather similar between the two treatments. Realized seasonal average values for day/night temperature, day-time CO_2 concentration, and VPD (measured at the height of the top of the canopy) were 21.6/17.2°C and 21.8/17.0°C; 814 and 833 ppm; 0.38 and 0.37 kPa of the treatments with cooling from above and from below, respectively. In the greenhouses with cooling from below, temperature difference between the top and the bottom of the canopy increased with increasing outside global radiation. (Fig. 3a). This difference was larger than 5°C when outside solar radiation was higher than 250 $\text{J cm}^{-2} \text{ h}^{-1}$ (Fig. 3a). VPD differences between top and bottom of the canopy also showed a positive correlation with outside radiation in the greenhouses with cooling from below (Fig. 3b). The temperature and VPD difference between the top and the bottom of the canopy also correlated with outside temperature in the greenhouses with cooling from below (Figs. 3c and d). In addition, the fluctuation of the vertical temperature and VPD gradients were caused by the temperature and the speed of the air blown into the greenhouse from the air treatment units.

The diel pattern of the solar radiation during a day lead to a diel pattern of the vertical temperature and VPD gradients (Figs. 4b and 5b). The magnitudes of vertical temperature and VPD gradients reached their maximum after midday when solar radiation was high (Figs. 4b and 5b). However, no distinct vertical temperature and VPD gradients were measured in the greenhouses with cooling from above (Figs. 3a, 3b, 4a, and 5a).

Assimilate Production and Partitioning to the Fruits

During the whole growing season, no significant difference in dry matter production and partitioning were found between the two treatments (Table 1). In addition, dry matter production and partitioning in the period from July to September were analyzed separately, since the vertical temperature gradient reached its maximum value during this period. In this period, no significant difference in dry matter production and partitioning were found between the two treatments (Table 2). It confirms that a vertical temperature gradient has no effect on dry matter production and partitioning.

Light, CO_2 concentrations and temperatures at the top of the canopy did not differ between treatments, most likely resulting in identical leaf photosynthesis rates in short term. The lower leaves in the greenhouse with cooling from below experienced lower air temperatures than those in the greenhouse with cooling from above (Fig. 4). Leaf photosynthesis has an optimum response to temperature (Acock, 1991) under both high light (Yamori et al., 2010) and high CO_2 (Cannell and Thornley, 1998). However, these lower leaves experienced low light conditions, since most of the light had been intercepted by the leaves above. Under these low light conditions, temperature in the range of 24 to 38°C is not likely to have a distinct effect on leaf photosynthesis rate (Qian et al., 2011b). In summary, no difference in canopy photosynthesis rate was expected between treatments, which would explain the non-significant treatment effect on dry matter production (Table 1).

Leaf initiation rate increases linearly with increasing temperature (Adams et al., 1997). Temperatures at top of the canopy in the both treatments were comparable (Fig. 3) Therefore, no difference in canopy development (leaf initiation rate) was found between the two treatments. LAI did not differ between treatment in week 0, 27, and 40 after planting. However, the final LAI measured in week 46 after planting in the treatment with cooling from below ($1.97 \text{ m}^2 \text{ m}^{-2}$) was higher than that in the treatment with cooling from above ($1.58 \text{ m}^2 \text{ m}^{-2}$).

Truss initiation rate was the same in both treatments (final truss number was 32 trusses in both treatment). Fruit number was manually restricted to 6 fruits per truss. Weekly average fruit harvest rate during the whole growing season was 14.2 (s.e.m. = 0.03) fruits m⁻² week⁻¹ in the greenhouses with cooling from above and 13.8 (s.e.m. = 0.13) fruits m⁻² week⁻¹ in greenhouse with cooling from below. No difference in total number of harvested fruits was found between the two treatments (Table 1) Fraction of dry matter partitioned to the fruits was 74% in both treatments (Table 1). Temperature influences sink strength of plant organs directly, but if the sink strength of all plant organs responds proportionally to temperature, dry matter partitioning does not change with temperature (Heuvelink, 1995). In this experiment, the lower plant parts experienced lower temperatures in the greenhouse with cooling from below compared to those in the greenhouse with cooling from above. However, all plant organs (leaf, stem and fruit) at the bottom of the plant experienced the same low temperature, which did not influence dry matter partitioning among organs. In other words, the ratio of dry matter between fruits, leaves and stems at a certain canopy height is stable.

Fruit Growth

Fresh weight of individual fruits was the only harvest-related character that differed significantly between treatments during summer (Tables 2), but not during the whole growing season (Table 1). The higher fresh fruit weight is the combined effect of small, although non-significant, differences in assimilate production and dry matter partitioning and decreased number of fruits (Table 2). Temperature affects fruit growth (Adams et al., 2001) and development (De Koning, 2000). The sensitivity of fruit growth and development rate to temperature depends on the developmental stage of the fruit. During the first week after anthesis, higher temperatures increase fruit development rate, and therefore shorten the time to maturity (De Koning, 1994). However, temperature does not affect fruit size in this stage because of compensation between the effects of temperature on cell number and cell size (Bertin, 2005; De Koning, 1994). This is followed by a period during which temperature hardly affects fruit growth and development rate (Adams et al., 2001; De Koning, 1994). In the last 1-2 weeks before harvest stage, temperature leads to strong reduction of fruit development rate and therefore increasing fruit growth duration (Adams et al., 2001; De Koning, 1994). In this experiment, fruit growth duration in the greenhouses with cooling from below was about 1 day longer than that of the greenhouses with cooling from above. Lower temperatures might lead to higher fresh fruit weight due to the longer growth duration (De Koning, 1994). Therefore, the lower temperature at the bottom of the canopy in the greenhouse with cooling from below might explain the larger fruits in these greenhouses compared to greenhouses with cooling from above.

CONCLUSIONS

Cooling from below the canopy induced vertical temperature and VPD gradients, which increased with outside radiation. At high radiation levels temperature at bottom of the canopy was 5°C lower and VPD was 0.7 kPa lower than at the top of the canopy. No vertical temperature and VPD gradients were detected in greenhouses with cooling from above. The vertical temperature gradients had no effect on assimilate production, partitioning, and fresh fruit weight averaged over the whole growing season. However, vertical temperature gradients increased fresh fruit weight in summer, when the vertical temperature gradients were large.

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Tables

Table 1. Dry matter production, partitioning and fruit production during the whole growing season (December 2008 - November 2009).

| Treatment | Dry matter production (kg m ⁻²) | Dry matter partitioning (%) | Fruit dry matter content (%) | Harvested fruit number (fruits m ⁻²) | Fresh fruit weight (g fruit ⁻¹) |
|---------------|---|-----------------------------|------------------------------|--|---|
| Cooling above | 4.64 | 73.9 | 5.3 | 556 | 112.1 |
| Cooling below | 4.80 | 74.2 | 5.4 | 542 | 117.8 |
| P-value | 0.07 | 0.53 | 0.49 | 0.13 | 0.06 |

Table 2. Dry matter production, partitioning and fruit production during summer (July 2009-September 2009).

| Treatment | Dry matter production (kg m ⁻²) | Dry matter partitioning (%) | Fruit dry matter content (%) | Harvested fruit number (fruits m ⁻²) | Fresh fruit weight (g fruit ⁻¹) |
|---------------|---|-----------------------------|------------------------------|--|---|
| Cooling above | 1.55 | 75.5 | 5.3 | 200 | 115.0 |
| Cooling below | 1.38 | 77.5 | 5.5 | 196 | 123.9 |
| P-value | 0.39 | 0.65 | 0.21 | 0.43 | 0.02 |

Figures

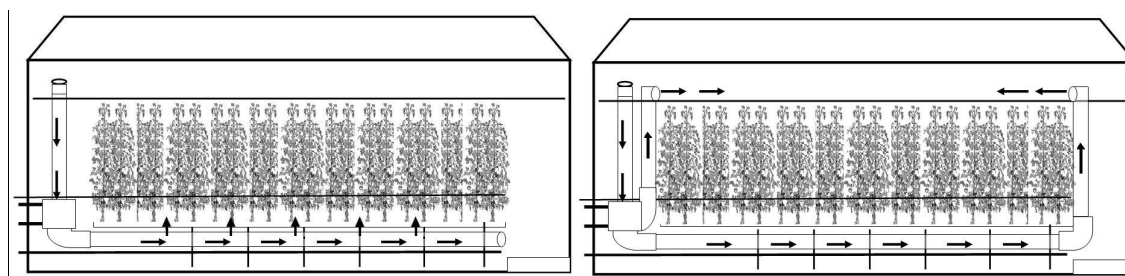


Fig. 1. Layout of the greenhouse with cooling below the gutter (left) and the greenhouse with cooling above the canopy (right).

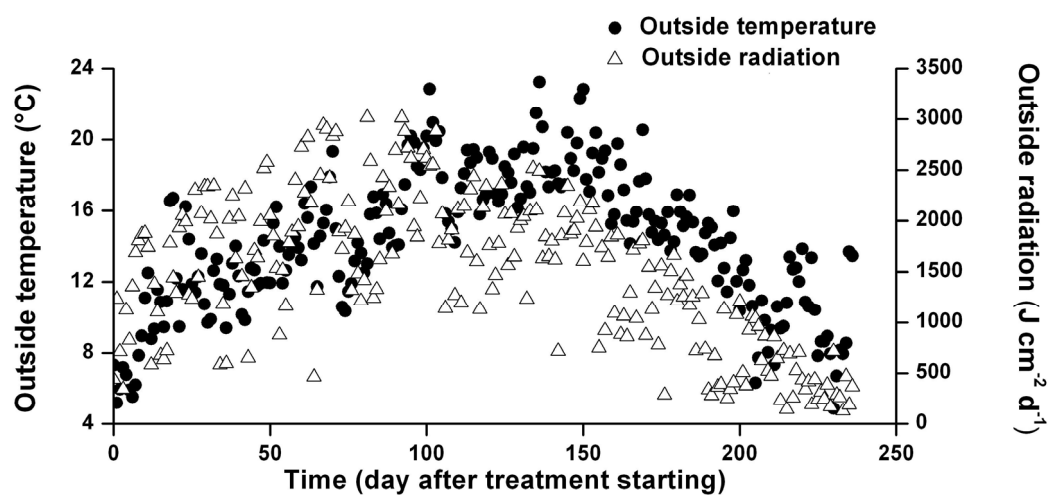


Fig. 2. Daily average of the outside temperature (●) and outside solar radiation (Δ) during the treatment period (23 March 2009 is considered as 0 day after treatment starting).

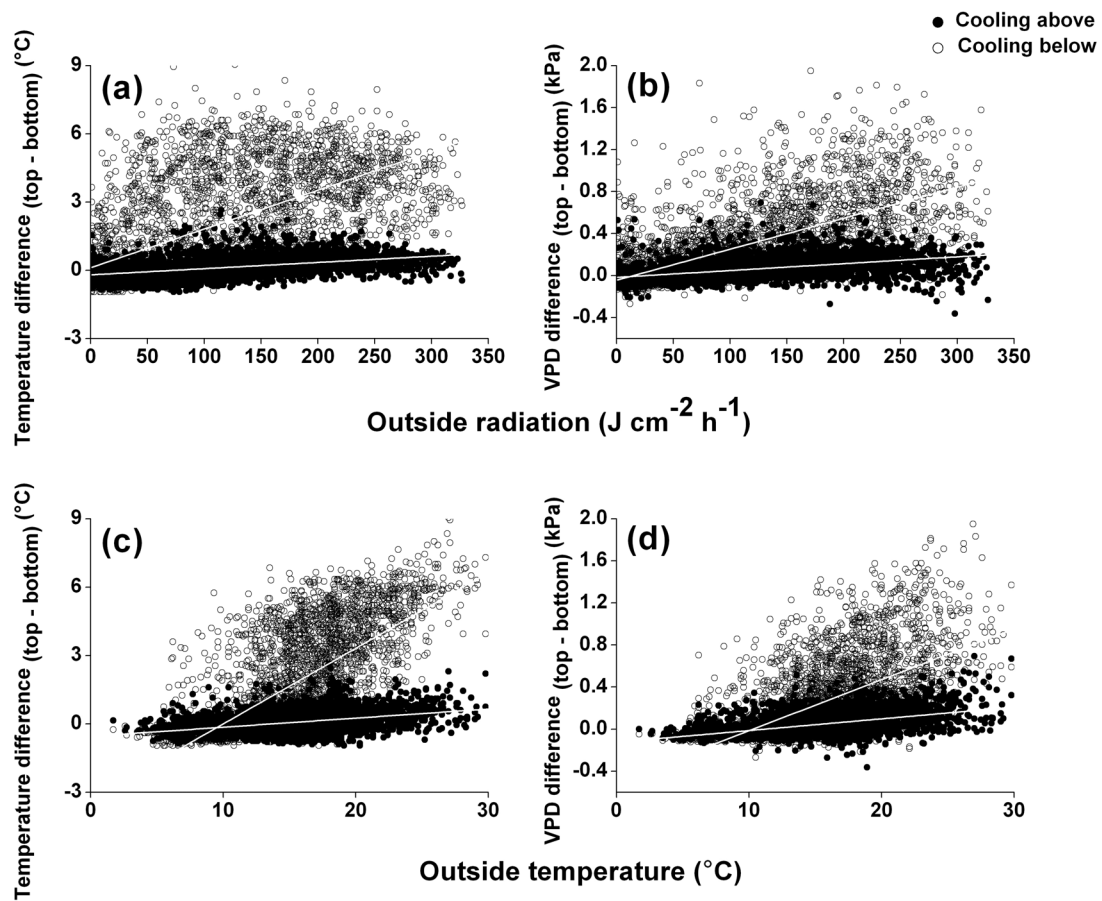


Fig. 3. The relationship of hourly outside radiation and outside temperature with hourly temperature difference between top and bottom of the canopy (a, c) and VPD difference between top and bottom of the canopy (b, d) in the greenhouse with cooling from above (●) and the greenhouse with cooling from below (○). Each data point is the average of the values from two replicates. White lines indicate the fitted linear curves.

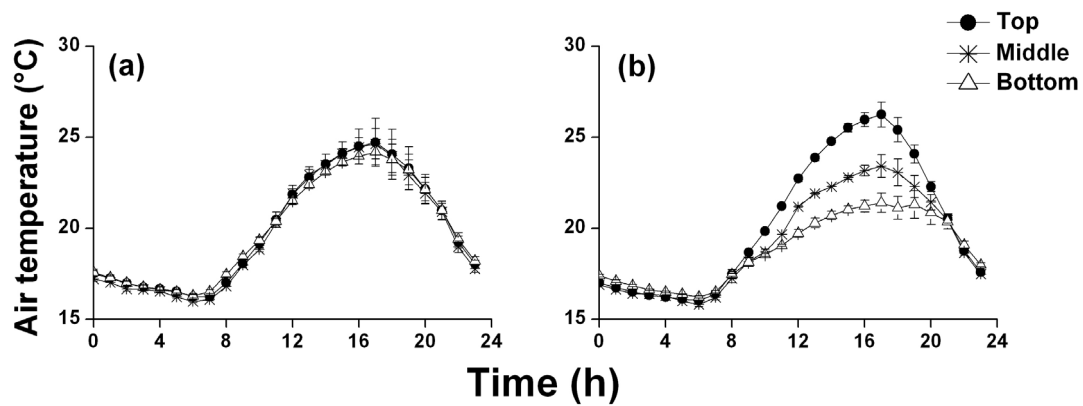


Fig. 4. Average diel air temperature at the top (●), middle (Δ) and bottom (*) of the canopy from July to September 2009 in the greenhouses with cooling from above (a) and from below (b). Top of canopy is 3.5 m, and bottom of canopy is 0.3 m above the gutter. The values of middle of the canopy were the average values measured at 2.5 m and 1.2 m above the gutter. Vertical bars indicate the s.e.m.

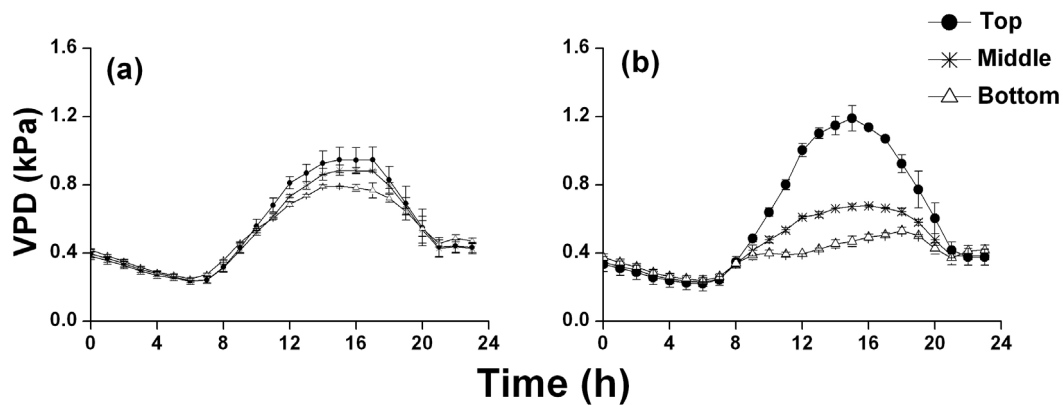


Fig. 5. Average diel vapour pressure deficit at top (●), middle (Δ) and bottom (*) of the canopy from July to September 2009 in the greenhouses with cooling from above (a) and from below (b). Top of canopy is 3.5 m, and bottom of canopy is 0.3 m above the gutter. The values of middle of the canopy were the average values measured at 2.5 m and 1.2 m above the gutter. Vertical bars indicate the s.e.m.