Comparison of Climate and Production in Closed, Semi-Closed and Open Greenhouses

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Abstract

A (semi-)closed greenhouse is a novel greenhouse with an active cooling system and temporary heat storage in an aquifer. Air is cooled, heated and dehumidified by air treatment units. Climate in (semi-)closed greenhouses differs from that of conventional open greenhouses. The aims of our research were first, to analyze the effect of active cooling on greenhouse climate, in terms of stability, gradient and average levels; second, to determine crop growth and production in closed and semi-closed greenhouses. An experiment with tomato crop was conducted from December 2007 until November 2008 in a closed greenhouse with 700 W m^{-2} cooling capacity, two semi-closed greenhouses with 350 and 150 W m^{-2} cooling capacity, respectively, and an open greenhouse. The higher the cooling capacity, the more independent the greenhouse climate was of the outside climate. As the cooling ducts were placed underneath the plants, cooling led to a remarkable vertical temperature gradient. Under sunny conditions temperature could be 5°C higher at the top than at the bottom of the canopy in the closed greenhouse. Cumulative production in the semi-closed greenhouses with 350 and 150 W m^{-2} cooling capacity were 10% (61 kg m^{-2}) and 6% (59 kg m^{-2}) higher than that in the open greenhouse (55 kg m^{-2}), respectively. Cumulative production in the closed greenhouse was 14% higher than in the open greenhouse in week 29 after planting but at the end of the experiment the cumulative increase was only 4% due to botrytis. Model calculations showed that the production increase in the closed and semi-closed greenhouses was explained by higher CO_2 concentration.

INTRODUCTION

Energy consumption of Dutch greenhouse industry contributes to about 10% of the total national energy use and 79% of the total energy use of agriculture in the Netherlands (Lansink and Ondersteijn, 2006). For energy saving, closed and semi-closed greenhouses were innovated. A closed greenhouse has no window ventilation. Air is cooled and dehumidified by air treatment units (ATU), which mainly takes place in summer. Surplus heat as energy is stored in an underground aquifer and used in winter to warm the greenhouse (Opdam et al., 2005). A semi-closed greenhouse has a smaller cooling capacity than a closed greenhouse. Window ventilation is combined with active cooling when the temperature is too high to be managed by the active cooling system.

The greenhouse macro- and microclimates are distinctly different in (semi-)closed greenhouses compared to that of open greenhouses. A high CO_2 concentration (about 1000 ppm) is one of the typical climate characteristics of the (semi-)closed greenhouse (De Gelder et al., 2005), which increases the production in the (semi-)closed greenhouse (Heuvelink et al., 2008). In particular, combination of high CO_2 and high radiation that occurs during summer in a (semi-)closed greenhouse is impossible to be realized in an open greenhouse. However, there is little detailed information available on climate

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conditions that are realized by different cooling capacities in the (semi-)closed greenhouses. In addition, a simultaneous comparison of climate and production between a (semi-)closed greenhouse and an open greenhouse is necessary to analyze processes under similar outdoor climate conditions.

The aims of our research are first, to analyze the effect of active cooling on climate, in terms of stability, gradient and average levels, in closed and semi-closed greenhouses; and second, to determine the production increase in closed and semi-closed greenhouses. For this reason, we evaluated climate and crop growth and production in greenhouses with different cooling capacities.

MATERIALS AND METHODS

Four experimental Venlo greenhouses were located in Bleiswijk, The Netherlands. Each greenhouse was 144 m^2 (15×9.6 m), with a gutter height of 5.5 m. From these four greenhouses, one was a conventional open greenhouse; the other three had cooling capacities of 700, 350 and 150 W m^{-2} respectively, installed. The air conditioning was controlled by a standard horticultural computer (Hoogendoorn-Economic). Greenhouse air was extracted to the ATU by five ventilators placed at the top of each greenhouse. In the ATU the air was cooled and dehumidified, and subsequently blown into the greenhouse through five plastic ducts placed beneath the growing gutters. Each duct had six holes (16 mm diameter) per meter. Cooling capacity was adjusted based on a difference between supply and return water temperature in the ATU. Cooling was achieved by controlling air speed and water temperature with a minimum temperature of 9°C to obtain a desired greenhouse temperature. If temperature of the greenhouse air exceeded the set point for cooling (Table 1), cooling was used. When the cooling capacity could not cope with too high temperature, ventilation windows were opened to support cooling (Table 1). In the greenhouse with 700 W m^{-2} cooling capacity the cooling capacity was high enough to keep the windows closed during the experiment. Hence, this greenhouse was defined as a closed greenhouse. The greenhouses with 350 and 150 W m^{-2} cooling capacities represented semi-closed greenhouses, of which the latter one had more extended periods of window opening. Climate treatments started on 10 March 2008 (89 days after planting). Heating was done via the conventional heating pipes. Average temperature set points during treatment for heating in the greenhouses with 700, 350 and 150 W m^{-2} cooling capacities, and in the open greenhouse, were 19.3, 18.6, 18.1 and 17.9°C, respectively. Pure CO_2 was supplied with a maximum capacity of 230 kg ha^{-1} h^{-1} during daytime with a set point of 1000 ppm for all treatments. Outside solar radiation, greenhouse CO_2 concentration, greenhouse air temperatures and humidity at the top of the canopy and at the growing gutter were recorded automatically at a 5 min interval. Relations between outside solar radiation and greenhouse CO_2 concentration, vertical temperature gradient, and air humidity were established for the purpose of trend analysis only.

Tomato plants, cultivar 'Capricia' (truss tomato) grafted on the rootstock 'Emperador', were planted in rockwool on 12 December 2007 with an initial stem density of 2.5 stem m^{-2}. In week 11 after planting, one plant out of each two developed an additional side shoot, to increase the stem density to 3.75 stems m^{-2}. Fruit harvest was started in the 14^{th} week after planting. Fresh weights of the harvested fruits were recorded weekly. Scenarios were calculated, by using the plant growth model INTKAM (Marcelis et al., 2009), to investigate the contribution of the climate factors to the final production increase. Calculation started by inputting the actual CO_2 concentration, air temperature and VPD of the open greenhouse. CO_2 concentration, then, was replaced by the actual CO_2 concentrations of the closed greenhouse, the semi-closed greenhouse with 350 W m^{-2} cooling capacity and the semi-closed greenhouse with 150 W m^{-2} cooling capacity, respectively. The same operations were done for air temperature and VPD.

RESULTS AND DISCUSSION

Carbon Dioxide

In summer, average day-time CO_2 concentration in the closed greenhouse with 700 W m^{-2} cooling capacity was greater than 1000 ppm, while it was about 600 ppm in the open greenhouse (Fig. 1). However, the total amount of CO_2 supplied to the open greenhouse was almost four times more than that of the closed greenhouse (Table 2). CO_2 concentration in the closed greenhouse was independent of solar radiation, whereas in the semi-closed greenhouse with 150 W m^{-2} cooling capacity and the open greenhouse CO_2 concentration decreased with increasing solar radiation (Fig. 2). The differences in CO_2 concentration and CO_2 supply rates between treatments were due to differences in window opening. During treatments, the average extents of lee side and wind side window opening of the closed greenhouse, the semi-closed greenhouses with 350 and 150 W m^{-2} cooling capacities, and the open greenhouse, were correspondingly 0, 6, 18 and 30% for lee side and 0, 0, 3 and 5% for wind side (0% is fully closed and 100% is fully open). Window ventilation during high radiation removed not only heat but also CO_2 and water vapour.

Temperature

Air temperature in the greenhouse showed a positive linear relation with solar radiation in all greenhouse types (the slope being about 0.03 J cm^{-2} h^{-1} °C^{-1} for the four greenhouses). Realized average day-time temperature (measured at the top canopy) were about 21.5, 21.2, 21.3 and 21.0°C for the closed greenhouse, the semi-closed greenhouses with 350 and 150 W m^{-2} cooling capacities, and the open greenhouse, respectively. Since the closed and semi-closed greenhouses had higher CO_2 concentrations compared to that of the open greenhouse, temperature in the closed and semi-closed greenhouses was controlled to a higher level to have higher development rate of crop. The vertical temperature gradient pattern differed remarkably between greenhouse types, especially when solar radiation was high (Fig. 3). As the cooling ducts were placed underneath the plants, cooling led to lower temperature at the bottom of the canopy than at the top of the canopy. In addition, the vertical temperature gradient also depended on the temperature and the speed of the air blown into the greenhouse from ATU and caused the fluctuation of the vertical temperature gradient (Fig. 3). Temperature affects the partitioning of photosynthetic assimilates indirectly by affecting rate of development, such as leaf initiation, truss appearance and fruit growth duration (Heuvelink, 1995; Adams et al., 2001; Pek and Helyes, 2004). During treatment, the average air temperature at the top canopy in the closed greenhouse was higher than that of the open greenhouse (21.8 vs. 21.4°C), plants in the closed greenhouse had more trusses than the plants in the open greenhouse (data not shown). However, the average air temperature around the ripening fruits in the closed greenhouse was lower than that of the open greenhouse (19.8 vs. 21.2°C), fresh weight of an individual ripe fruit in the closed greenhouse was higher than that in the open greenhouse (data not shown). The sensitivity of fruit to temperature is not equal at different fruit development stages (De Koning, 2000). In closed and semi-closed greenhouses with vertical temperature gradient, fruits experienced high temperature after anthesis but low temperature during ripening. Just after anthesis, temperature does not affect fruit size significantly, because of compensation between the effects of temperature on cell number and cell size (Bertin, 2005). In the last 1-2 weeks before maturity, lower temperature causes fruits to become larger due to longer growth period (Adams et al., 2001).

Vapour Pressure Deficit

VPD of the air inside the greenhouses with higher cooling capacity was less dependent on outside radiation (Fig. 4). When radiation induced a temperature rise in the greenhouse, VPD strongly increased in the open greenhouse. Realized average day-time VPD (measured at the top canopy) was about 0.4 kPa for the closed greenhouse and semi-closed greenhouse with 350 W m^{-2} cooling capacity, 0.5 kPa for the semi-closed greenhouse with 150 W m^{-2} cooling capacity, and 0.6 kPa for the open greenhouse. In general, VPD within the range of 0.2-1.0 kPa has little effect on crop growth and development in tomato (Grange and Hand, 1987). However, 11, 6, 3 and 1% of the time VPD was higher than 1 kPa, and 5, 5, 10 and 4% of the time VPD was lower than 0.2 kPa, in the open greenhouse, the semi-closed greenhouses with 150 W m^{-2} and 350 W m^{-2} cooling capacities, and the closed greenhouse, respectively. When VPD exceeds 1 kPa, it might promote water stress and stomatal closure, leading to a reduction of photosynthesis and transpiration (Grange and Hand, 1987; Leonardi et al., 2000). On the other hand, too low VPD may also cause physiological disorder by reducing transpiration, following by less uptake of water and nutrient (Adams, 1991; Del Amor and Marcelis, 2006).

Production

The early cumulative production in the closed greenhouse, the semi-closed greenhouse with 350 W m^{-2} cooling capacity, the semi-closed greenhouse with 150 W m^{-2} cooling capacity were 14, 10 and 6%, respectively, higher than that in the open greenhouse (Table 2). The final cumulative production in the semi-closed greenhouses with 350 and 150 W m^{-2} cooling capacities were, respectively, 10 and 6% higher than that in the open greenhouse (Table 2). However, the final cumulative production in the closed greenhouse was only 4% higher than that in the open greenhouse, due to infection of botrytis firstly detected in week 29 after planting. Infected stems were removed to prevent spreading of botrytis, which caused a diminished increase of the production in the closed greenhouse. It was also the reason for a lower actual yield increase in the closed greenhouse in some other studies (Heuvelink et al., 2008). Stem infection by botrytis increased as a function of air humidity, especially high humidity and wound spots on the stems providing a favourable condition for the development of botrytis (Eden et al., 1996). However, high humidity is not a likely reason for the botrytis problem in the present experiment, since the semi-closed greenhouse with 150 W m^{-2} had an even higher percentage of time with high humidity, around the wound spots caused by leaf picking on the stem, than that of the closed greenhouse.

The crop model estimated the increase of production by 5, 11 and 15% when CO_2 concentration increased by 4, 10 and 14%, respectively. These data fitted the observation well, suggesting that the difference in CO_2 concentration can fully explain the difference in production. The model assumed no acclimation of photosynthesis and production to long term exposure to high CO_2. However, acclimation of photosynthesis and production to high CO_2 concentration may occur (Besford et al., 1990; Peet et al., 1986). Dieleman et al. (2006) found in current Dutch greenhouse systems, photosynthesis and production did not show adaptation to high CO_2 concentration.

CONCLUSIONS

In conclusion, the higher the cooling capacity, the more independent its interior climate is of the outside climate. In addition, the active cooling from below the canopy introduced new macro and micro climate conditions in the greenhouse. For example, vertical temperature gradient, combination of high radiation and high CO_2 concentration. Future work will be done to quantify the relations between climate factors and crop physiological processes, such as photosynthesis and transpiration.

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Tables

Table 1. Average temperature set points to start cooling, to open lee side windows and wind side windows in the greenhouses with 700, 350 and 150 W m^{-2} cooling capacities, respectively, and in the open greenhouse.

Treatment	Cooling (°C)	Open lee side windows (°C)	Open wind side windows (°C)
700 W m^{-2}	20	28	29
350 W m^{-2}	19	22	25
150 W m^{-2}	18	20	23
Open		19	22

Table 2. Early cumulative fruit production in week 29 after planting, final cumulative production in week 48 after planting, and total amount of supplied CO_2 in the greenhouses with 700, 350 and 150 W m^{-2} cooling capacities, respectively, and in the open greenhouse. Values between brackets indicate increase compared to open greenhouse.

Treatment	Early production (kg m^{-2})	Final production (kg m^{-2})	Supplied CO_2 (kg m^{-2})
700 W m^{-2}	28 (14%)	57 (4%)	14
350 W m^{-2}	27 (10%)	61 (10%)	30
150 W m^{-2}	26 (6%)	59 (6%)	46
Open	24	55	55

Figures

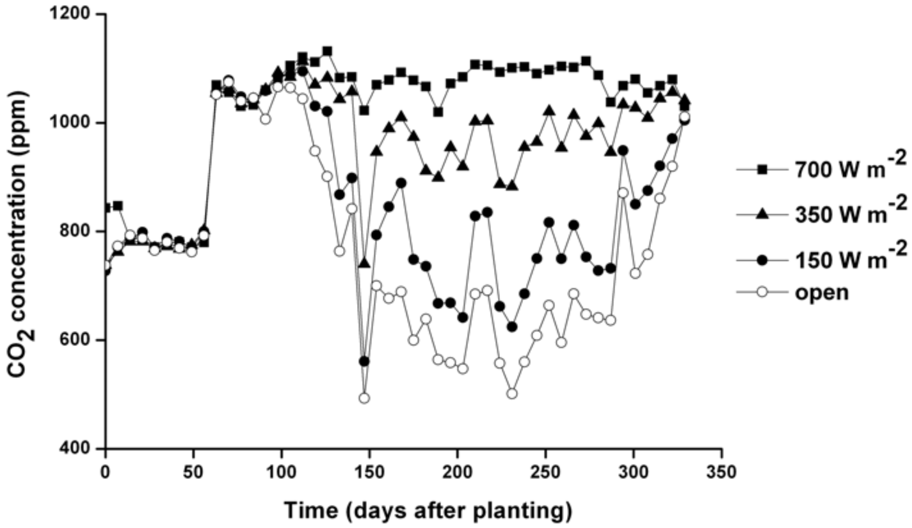

Fig. 1. Weekly average daytime CO_2 concentrations in the greenhouses with 700 W m^{-2} (■), 350 W m^{-2} (▲), and 150 W m^{-2} (●) cooling capacities, respectively, and in the open greenhouse (○).

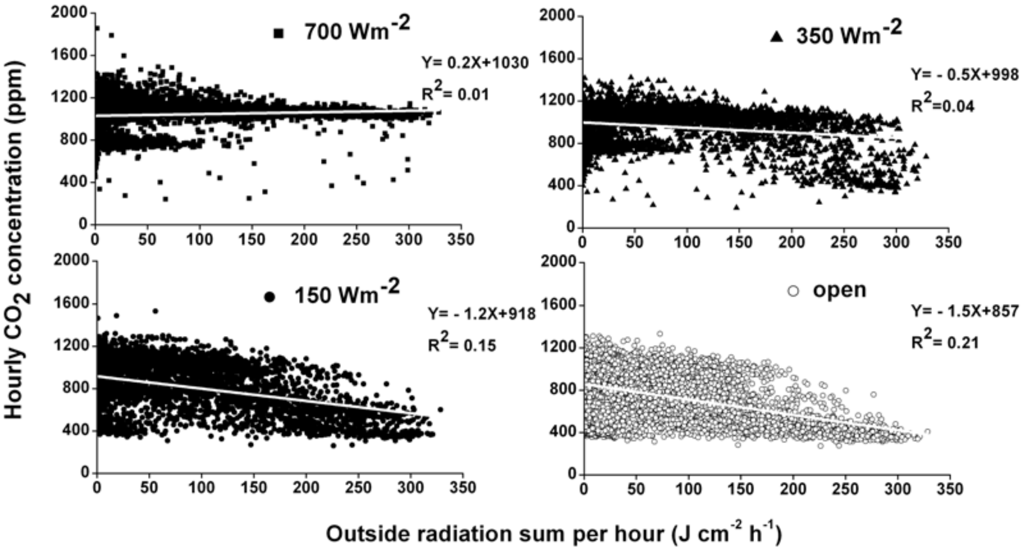

Fig. 2. Relation between outside radiation sum and CO_2 concentration in the greenhouses with 700 W m^{-2} (■), 350 W m^{-2} (▲), and 150 W m^{-2} (●) cooling capacities, respectively, and in the open greenhouse (○). White line indicates the fitted linear curve.

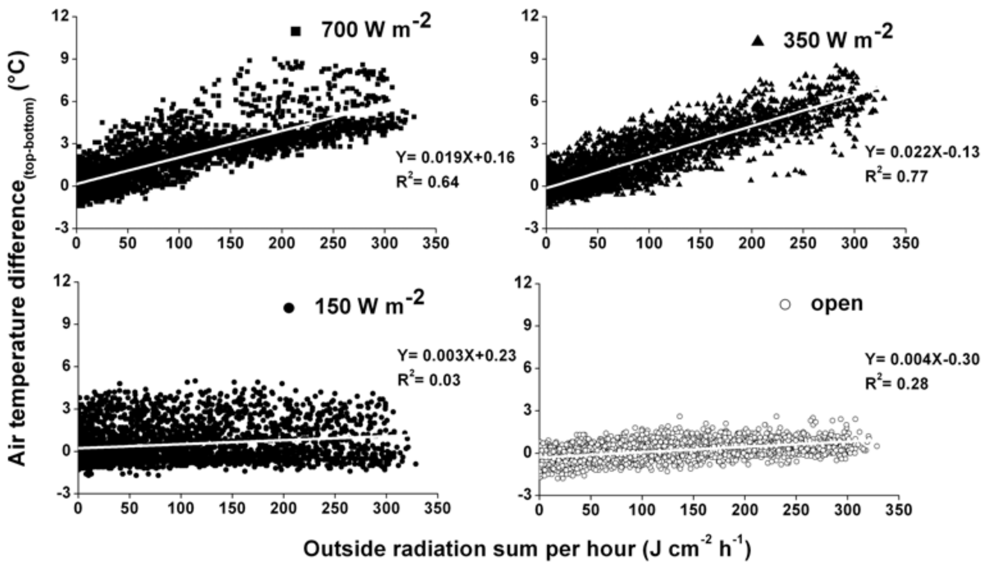

Fig. 3. Relation between outside radiation sum and vertical temperature gradient (air temperature difference) in the greenhouses with 700 W m^{-2} (■), 350 W m^{-2} (▲), and 150 W m^{-2} (●) cooling capacities, respectively, and in the open greenhouse (○). Air temperature difference is the difference between the air temperatures measured at the height of the top canopy (top) and at the height of the growing gutter (bottom). White line indicates the fitted linear curve.

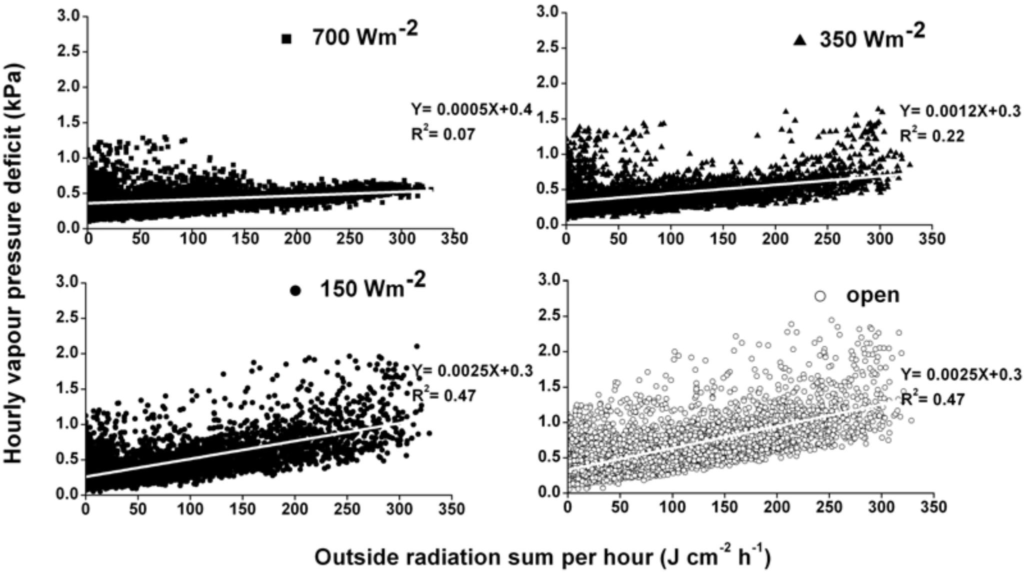

Fig. 4. Relation between outside radiation sum and vapour pressure deficit in the greenhouses with 700 W m^{-2} (■), 350 W m^{-2} (▲), and 150 W m^{-2} (●) cooling capacities, respectively, and in the open greenhouse (○). White line indicates the fitted linear curve.