Scientia Horticulturae 288 (2021) 110271

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

Vertical microclimate heterogeneity and dew formation in semi-closed and naturally ventilated tomato greenhouses

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ARTICLE INFO

Keywords:
Greenhouse ventilation
Sidewall curtains
Microclimate gradients
Protected crops

ABSTRACT

The extent of the vertical microclimate heterogeneity inside a greenhouse is mostly unknown, and it can strongly affect plant production and yield quality. Tomato crop was grown in a semi-closed greenhouse equipped with horizontal ventilation and sidewall curtains, which were only opened depending on microclimate conditions; and a naturally ventilated greenhouse equipped with sidewalls curtains that were kept open. Both greenhouses had a 1,000-m^2 area and a net size of 50-mesh, and were located in an arid climate zone in Israel. Vertical profiles of CO_2 concentration, actual vapor pressure, air, leaf and soil temperature, net CO_2 assimilation rates, stomatal conductance, and total fruit yield, fresh mass, and quality were monitored in both greenhouses for 13 days, in January 2018; CO_2 concentration, actual vapor pressure, and air and soil temperature were additionally monitored in the semi-closed greenhouse for seven days in December 2016, when the ventilation was inoperative, and in December 2017, with ventilation. The vertical air temperature gradient, along with the colder microclimate inside the naturally ventilated greenhouse, led to a lack of plant uniformity and yield loss. Closing the side curtains in the fanned semi-closed greenhouse had a beneficial effect on yield, however, with mixed results for quality, due to the higher air temperature and lower carbon dioxide levels at the upper canopy. Horizontal air circulation in the semi-closed greenhouse increased transpiration and assimilation, and increased dew occurrence at night, but did not reduce the vertical heterogeneity. Significant vertical gradients affect plant physiology, and closing the curtains in winter cultivation in semi-arid/arid climates has the potential to improve fruit yield and quality. However, it must be coupled with proper air circulation and, preferably, with CO_2 enrichment, or careful management of natural ventilation through side curtains, in order to maximize CO_2 replenishment while minimizing heat losses.

1. Introduction

In the last few decades, improvements in yield quantity and quality have been associated with the improvement of growth conditions in greenhouses, especially in Mediterranean and semi-arid areas where high air temperature and solar radiation can severely limit crop growth (Dorais et al., 2001; Rosales et al., 2006). However, a number of well-known problems, such as a decreasing plant assimilation rate and fruit growth, and changes in dry matter partitioning, are commonly attributed to the difficulty of microclimate management in the greenhouse (Savvas et al., 2008). Specifically, these problems could be due to the heterogeneity of microclimatic conditions inside the greenhouse,

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https://doi.org/10.1016/j.scienta.2021.110271
Received 28 October 2020; Received in revised form 12 April 2021; Accepted 11 May 2021

resulting in high variability of air temperature, such as that reported for semi-closed greenhouses (Qian et al., 2011). In these conditions, the greenhouse is kept closed, and the microclimate is maintained by using a ventilation or cooling system, which is supported by the use of sidewall windows, opened only during the critical periods of the day. Previous studies have looked into the extent of the vertical microclimate heterogeneity inside greenhouses and have shown a maximal vertical air temperature gradient of 11.6 °C m^{-1} (Zhao et al., 2001; Kutta and Hubbart, 2014), and little or no plant response for < 5 °C differences (Qian et al., 2012, 2015). In taller plants, this phenomenon has been observed in several species, and changes in air and leaf temperature difference of up to 2 °C m^{-1} have been shown to form differential physiological acclimation and changes in water use and the assimilation rate (Zweifel et al., 2002; Cermak et al., 2007; Bauerle et al., 2009). Still, little is known about the extent of the vertical microclimate heterogeneity and its impact on plant growth inside greenhouses, particularly in winter cultivations in semi-arid climates, where the management of the greenhouse microclimate is critical, and extreme, opposite conditions from the bottom to the top part of the greenhouse may occur, triggering plant acclimation to local microclimatic conditions.

Changes in air temperature and relative humidity, in combination with carbon dioxide concentration, strongly affect plant growth. In general, spots of high temperature (> 30 °C) at the upper part of the greenhouse, and low temperature (< 18 °C), associated with high relative humidity from the middle to the bottom of the greenhouse, may stress the plant and are related to a wide range of plant diseases, resulting in damage to photosynthesis and reduced fruit quality (Koskitalo and Ormrod, 1972; Peet and Welles, 2005; van Der Ploeg and Heuvelink, 2005; Hazra et al., 2007; Egel and Saha, 2015). Moreover, at night, when leaf temperature drops below the dew point temperature, dew forms on the leaf surface, increasing the risk of plant diseases (Jarvis et al., 1989; Cohen et al., 2005; Qian et al., 2011). On the other hand, high CO_2 levels have a strong and beneficial effect on photosynthesis rate, plant development timing, and growth (Dippery et al., 1995; Sage and Coleman, 2001) depending on the stage of leaf development (Besford et al., 1990), and the sink activity of the whole plant (Hicklenton and Jollife, 1980; Porter and Grodzinski, 1984; Peet et al., 1986), while lower carbon dioxide levels (< 200 ppm) can lead to a severe decrease in the assimilation rate. Soil temperature can also affect plant metabolism through changes in the plant respiration rate, shoot and root growth rates, root water uptake, and fruit color (Cooper, 1973; Nothmann et al., 1978).

Despite the improvement of the management of microclimate conditions inside a greenhouse due to the continuous development of greenhouse concepts, such as the implementation of evaporative cooling, sidewall curtains, forced ventilation systems, CO_2 enrichment, roof whitening, shade nets, and thermal screens, the increased initial investment, operational costs and the challenging management practices involved in these methods have forced some growers to make use of a semi-closed system, with sidewall curtains and/or ventilation systems that are used only during the critical periods of the day (Montero, 2006; Katsoulas et al., 2009; González-Real and Baille, 2006). In arid and semi-arid areas, the management of a greenhouse is quite complex. In general, the growing season comprises the coldest and wettest months of the year, and the high relative humidity and cold temperatures at night make it difficult to achieve optimal growth conditions. Usually there is no supplemental heating, and the main method of optimizing the temperatures is by closing the side curtains of the greenhouse when heating is needed and relying on natural ventilation for cooling and CO_2 replenishment, which creates a particular microclimate from the middle to the highest part of the greenhouse, i.e., increase of temperature, relative humidity and CO_2 levels, and decrease of wind speed, while the temperatures close to the ground remain low, which might be minimized through the use of an efficient and inexpensive air circulation system in order to equilibrate air flux within the plant canopy and increase the canopy's CO_2 exchange rate (Shibuya et al., 2006).

Regardless of the understanding that vertical gradients within greenhouses are likely large enough to affect plant growth and yield quantity and quality, monitoring the microclimate conditions inside the greenhouse is usually only done at a representative height, close to the plant growth point (Gieling and Schurer, 1995), overlooking the magnitude and dynamics of vertical microclimate gradients. In this context, although some studies have evaluated certain microclimate gradients, mainly of air temperature, inside greenhouses, the characterization of the vertical distribution of other important climate variables, such as carbon dioxide composition, vapor pressure deficit, and soil temperature distribution, and their relation with physiological and morphological plant performances, in open and semi-closed/closed systems, has not yet been fully investigated. Here, we hypothesized that there is a difference in vertical microclimate gradients, dew formation, and fruit yield and quality, between a semi-closed greenhouse (SCGH), equipped with sidewall curtains combined with daytime horizontal air flow fans, and a naturally ventilated greenhouse (NVGH) with sidewall curtains that are constantly open.

2. Material and methods

2.1. Naturally ventilated and semi-closed greenhouses

Measurements were conducted during two growing seasons, September 2016 to April 2017, and September 2017 to April 2018 (Table A.1), in two adjacent greenhouses growing tomatoes in Israel's southern Negev Desert (31°36′ N, 35°09′ E): a semi-closed greenhouse that was either fanned (fanned SCGH) or non-fanned (non-fanned SCGH) and a naturally ventilated greenhouse (NVGH). The climate in the research site is arid, and the soil is loess. Drip irrigation in both seasons occurred three times per day, with a 2-mm application each event until December, and a twice-daily 2.5-mm application from January to the end of season. The irrigation water EC was from 1 to 1.5 dS m^{-1}. The two greenhouses had an area of 1000 m^2 each, and both were covered with a 50-mesh net (Fig. 1). The sidewall curtains of the NVGH were constantly open without a ventilation system (Fig. 1a); thus, the microclimate conditions followed the outside conditions. The sidewall curtains of the SCGH were kept closed, and were only opened when measurements at 2-m height indicated that the CO_2 concentration had decreased below 280 ppm, relative humidity (RH) reached 70%, and/or air temperature (T_{air}) was higher than 30 °C. The greenhouse was closed through the use of sidewall polyethylene curtains (Fig. 1b and 1c). The air circulation system was implemented through the use of a set of four ventilators installed at the end walls of the greenhouse at 4-m height, active from 8:00 to 16:00, during the 2017–2018 crop season. During the 2016–2017 crop season, the ventilation was not implemented.

2.2. Climate, soil, and plant monitoring

Vertical profiles of key microclimatic conditions were measured at the center of each greenhouse, at 0.1, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5-m heights (Fig. 2). CO_2 concentration (ppm) and actual vapor pressure (e_a: kPa) were monitored by an infrared gas analyzer system (CIRAS, PP Systems, Amesbury, MA, USA), through the use of an 8-valve (Aquative Plus actuator valve, Netafim, Tel Aviv, Israel) control system connected to plastic pipes placed at each height (Fig. 2a). T_{air} (°C) was measured by thermocouples inserted into the 1-cm diameter pipes protected by a black 9.5-mm-thick thermal insulation foam and covered by aluminum foil (Fig. 2a). Soil temperature (T_{soil}: °C) was measured by thermocouples placed at 4, 6 and 10-cm depths in three repetitions, positioned 20 cm from the plant (line). All measurements were continuously recorded every 30 min (Campbell Scientific, Logan, USA; Campbell CR1000), over 13 d (January 2018; Table A.1) at mid-season of the tomato crop when maximum plant height was reached. Saturated vapor pressure (e_s: kPa) was calculated using air temperature based on the Tetens formula (Murray et al., 1967). Hourly vapor pressure deficit (VPD: kPa) was

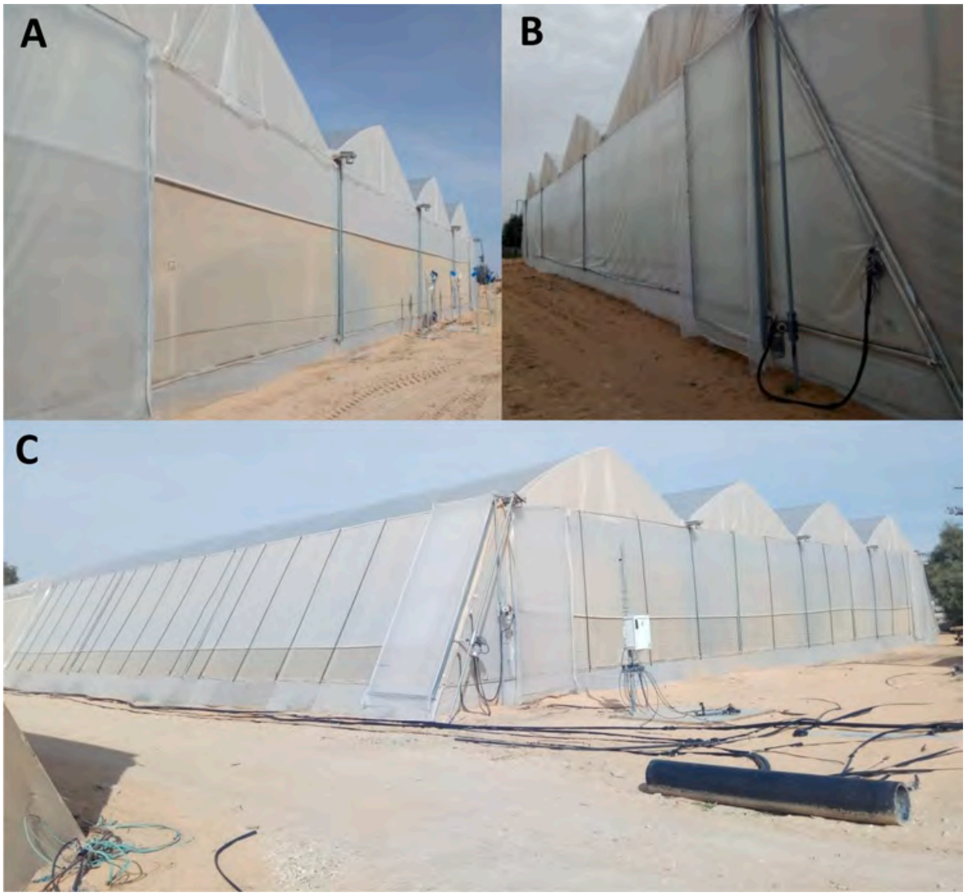

Fig. 1. Outside view of the naturally ventilated greenhouse (a), the semi-closed greenhouse with the lateral controller and curtains closed (b), and the general view of the semi-closed greenhouse during an opening event (c).

estimated by the difference between e_s and e_a. Hourly dew point temperature (T_{dew}: °C) was calculated using e_a (Bosen, 1958; Jensen et al., 1990). The times when the dew point temperature was equal to or lower than the leaf temperature (T_{leaf}: °C) were considered periods during which dew was formed. No T_{leaf} data was available for the NVGH; thus, dew was assumed to form when T_{air} was equal to or lower than T_{dew}. Hourly T_{leaf} values were recorded over a 13-d period (January 2018; Table A.1), in the fanned SCGH only, at 1, 2, and 3 m, through the use of self-constructed infrared temperature sensors (Fig. 2b).

Net CO_2 assimilation rates (An: μmol CO_2 m^{-2} s^{-1}) and stomatal conductance (gs: mol H_2O m^{-2} s^{-1}) of the fully matured leaves of each plant were collected around midday on January 2018, 130 days after transplanting (DAT) (Table A.1), when maximum plant height was reached. The gas exchange measurements were taken in leaves exposed to sunlight at 1, 2 and 3-m heights, classified as lower, middle, and upper canopy, respectively, using a portable infrared gas analyzer (IRGA) system (CIRAS-2, PP Systems, Amesbury, MA, USA) at an average photosynthetically active radiation (PAR) of 600 μmol m^{-2} s^{-1} and CO_2 concentrations of 300 and 370 μmol mol^{-1} for the fanned SCGH and NVGH, respectively. Temperature and relative humidity ranges were 15–25 °C and 25–35%, respectively. Fruits were harvested in December 2017 and January 2018, and fruit yield (kg m^{-2}) and average fruit fresh mass (g $fruit^{-1}$) were measured. Titratable acidity (TA: meq g^{-1} of fresh mass) of the fruits was determined by titrating the pulped juice samples with NaOH (AOAC Intl. 2000; Barret et al., 2007). Total soluble sugars (TSS:%) were determined in dried and powdered fruit samples according to Leyva et al. (2008).

To analyze the effect of ventilation on the formation of vertical microclimate gradients inside the SCGH, ventilation was not operated during the 2016–2017 season (non-fanned SCGH) and was operated during the 2017–2018 season (fanned SCGH). Climate measurements were taken over 7 d at the mid-growing season of the tomato crop (December 2016 and 2017; Table A.1; Fig. 2).

Hourly observations of air temperature (°C), relative humidity (%), and solar radiation (MJ m^{-2} day^{-1}) of the outside climate conditions near the greenhouses were measured at 2-m height. Hourly solar radiation was measured by a pyranometer (CM3, Campbell Scientific, Logan, USA), and air temperature and relative humidity were measured by a Vaisala HMP45C sensor (produced by Vaisala, Vantaa, Finland; and modified by Campbell Scientific, Logan, USA). December and January were the coldest and wettest periods in the tomato crop growing season, allowing us to better represent the effect of treatments in the non-fanned and fanned SCGH's during the critical winter period. Daytime periods were defined between 6:00 and 18:00 for both December and January periods.

2.3. Statistical analysis

Statistical analyses of climate variables (CO_2 concentration, T_{air}, T_{soil}, T_{dew}, e_a, e_s, and VPD) and plant traits (An and gs), obtained at different heights, were compared by using a multiple comparison test of the Multcompare procedure (MATLAB R2015b, MathWorks, Natick, MA) considering the Tukey test (α = 0.05 of significance). Fruit yield, fruit fresh mass, TSS, and TA were compared between greenhouses using JMP software, considering Student's *t*-test (α = 0.05 of significance) (SAS Institute Inc., Cary, NC). Hourly vertical patterns of CO_2 concentration, T_{air}, T_{soil}, T_{dew}, and VPD were obtained in MATLAB (MathWorks, Natick, Massachusetts, USA) by a linear interpolation of the average hourly values over all heights for the 13-d period.

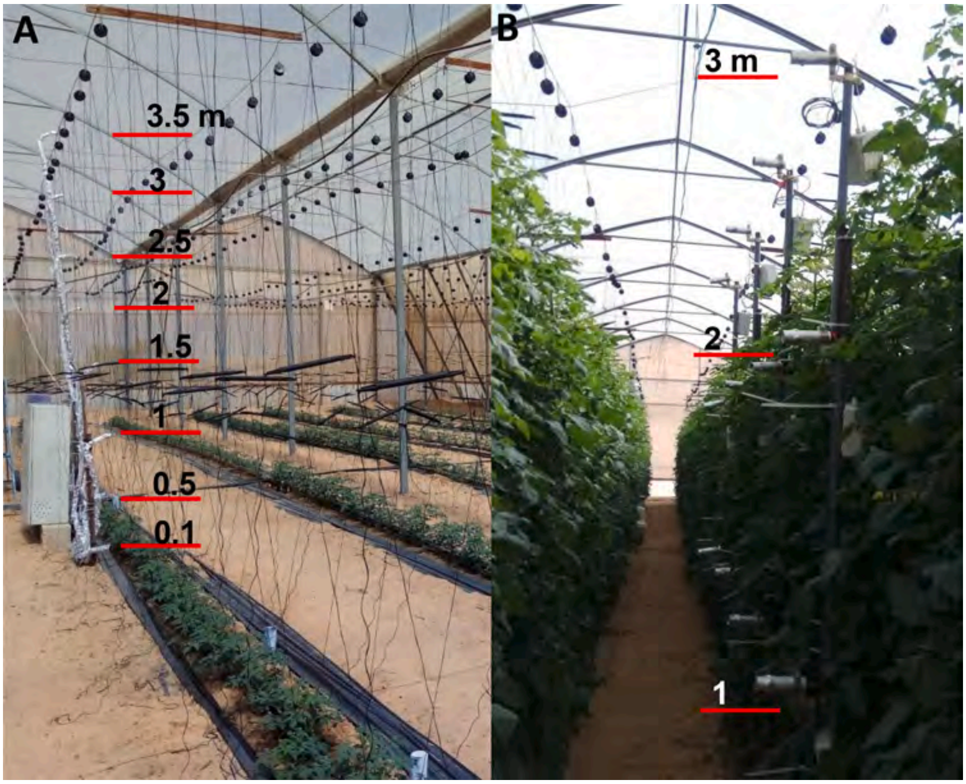

Fig. 2. Vertical distribution of thermally insulated pipes connected to the control box (a); and the distribution of the leaf temperature sensors (b).

3. Results

3.1. Fanned semi-closed vs. naturally ventilated greenhouses

Both greenhouses experienced sub-optimal T_{air} ($18\,^{\circ}C \geq T_{air} \geq 30\,^{\circ}C$) over all heights at certain periods during the day and/or night. In the fanned SCGH, the temperature range was closer to the optimal conditions ($27\,^{\circ}C \geq T_{air} \geq 21\,^{\circ}C$), but the CO_2 concentrations were severely reduced from the bottom to the top of the canopy ($CO_2 \leq 300$ ppm), when compared to the NVGH ($P < 0.05$). Large variability of CO_2 concentration, T_{air}, VPD, and T_{dew} was observed across the heights sampled in the NVGH and fanned SCGH. CO_2 concentrations in the fanned SCGH were lowest (< 300 ppm) at 3.5-m height and highest (360–380 ppm) at 0.1-m height (Fig. 3a). T_{air} and VPD reached the lowest ($T < 20\,^{\circ}C$ and VPD < 1 kPa in both greenhouses) and highest ($T > 25\,^{\circ}C$ and VPD > 2 kPa in the fanned SCGH; and $25\,^{\circ}C \geq T \geq 20\,^{\circ}C$ and $2 \geq \text{VPD} \geq 1.5$ kPa in the NVGH) values at 0.1 and 3.5-m heights (Fig. 3b, 3c, 3f and 3g). In the NVGH, the CO_2 concentration was less heterogeneous, varying from 380 to 400 ppm (Fig. 3e). In the fanned SCGH, the T_{air} equated to the outside air temperature at night, while actual vapor pressure remained slightly higher, resulting in a high dew point temperature (Fig. 3h), suggesting an increased likelihood for dew occurrence.

A significantly different plant performance was observed across heights and between the greenhouses ($P < 0.05$; Fig. 4). On average, at midday, the air temperature inside the fanned SCGH was significantly higher (Fig. 3b), the air was relatively drier (Fig. 3c), and the CO_2 concentration lower (Fig. 3a) from the bottom to the top of the canopy, resulting in higher water demand by increased stomatal activity ($P < 0.05$) (Fig. 4b). Due to the higher air temperatures in the fanned SCGH (Fig. 3b), the assimilation rate was greater than in the NVGH (Fig. 4a), and even though stomatal conductance at 2 m was about half that measured at 3 m (Fig. 4b), similar assimilation rates were observed for these heights. The fruit yield and fresh mass in the fanned SCGH were greater by 0.71 $kg\,m^{-2}$ and 3.70 g $fruit^{-1}$, respectively (Fig. 4c and 4d). However, significantly lower total soluble sugars and higher, albeit non-significantly, titratable acidity, by 1.20% and 0.0021 meq g^{-1} of fresh mass, respectively (Fig. 4e and 4f), resulted in a mixed effect on fruit quality.

3.2. Vertical microclimate heterogeneity inside fanned semi-closed and naturally ventilated greenhouses

At noontime, in the middle of the canopy (1.5–2 m height), the fanned SCGH was, on average, with a 70 ppm lower CO_2 concentration, 5 °C warmer (Fig. 5b) and 1.5 kPa drier (Fig. 5c) than the NVGH.

At nighttime, the fanned SCGH experienced fast cooling, mainly from middle to top canopy (1.5–3.5 m height) which resulted in the NVGH being up to 6 °C warmer and up to 0.9 kPa higher VPD for a period of about 2 h after sunset (Fig. 5b and c). For the rest of the night, the fanned SCGH was up to 2.1 °C cooler (Fig. 5b), 0.5 kPa moister (Fig 5c), mainly from the middle to the top of the canopy (1.5–3.5 m height), and 56 ppm richer in CO_2 (Fig. 5a), mainly from the bottom to the middle of the canopy (0.1–2 m height), than the NVGH.

At the top of the canopy, the average T_{air} was around 9 °C higher than at the bottom of the canopy (Fig. 5g) in both greenhouses at noontime, thus representing the most significant vertical gradient in the greenhouses. Similarly, on average, the top of the canopy was drier than the bottom by 1.6 and 0.9 kPa for the fanned SCGH and NVGH, respectively (Fig. 5h). Significant differences in the gradients of T_{dew} were accordingly found between the two greenhouses (Fig. 5i) from the middle to the upper canopy. At night, the T_{air} differences over all heights were smaller and more evident at the upper canopy, being 0.5 °C and 1.5 °C lower for the NVGH and fanned SCGH. The vertical gradients of CO_2 concentration were more evident in the fanned SCGH where they reached an up to 144 ppm difference, while in the NVGH, they reached up to 61 ppm (Fig. 5f). On average, CO_2 at the top of the canopy was 40 ppm and 11 ppm lower than at the bottom of the canopy for the fanned SCGH and NVGH, respectively. Our results show that the vertical heterogeneity of T_{air} was similar between greenhouses (Fig. 5g), and that the T_{dew} behaved in an opposite way; in the fanned SCGH, T_{dew}

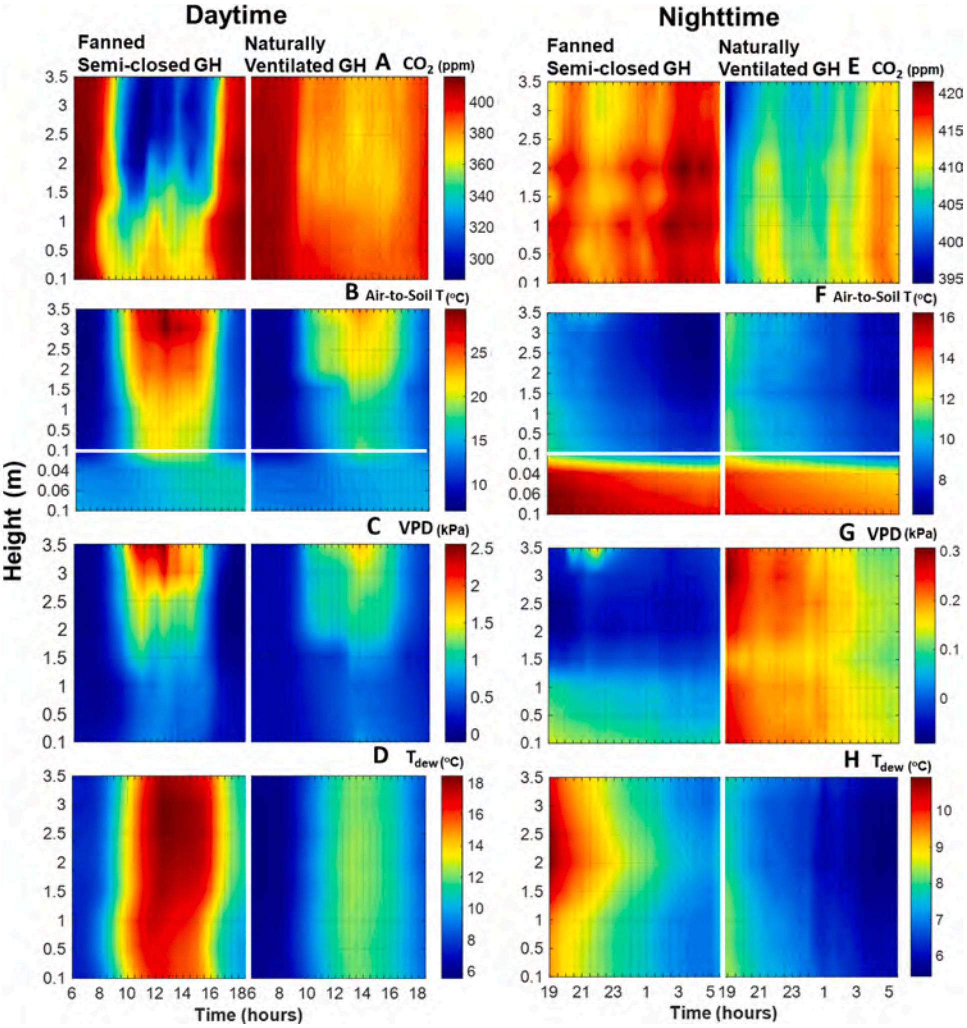

Fig. 3. Vertical CO_2 concentration (a and e), air-to-soil temperature (b and f), vapor pressure deficit (c and g), and dew temperature (d and h) variation map for daytime and nighttime periods inside the fanned semi-closed and naturally ventilated greenhouses for January 2018. Each hour point represents an average over the 13-d period of the experiment.

increased with height, while in the NVGH, it generally decreased at night (Fig. 5i).

T_{air} and T_{leaf} were almost always lower than the dew point temperature in the fanned SCGH at night. Over the 13-d period of the experiment, 96.5, 105.5, and 9 h of dew occurrence were observed at the top, middle, and bottom of the fanned SCGH, respectively, which occurred mainly between 20:00 and 6:00 (Fig. 6), when the curtains were open. In the NVGH, there was a small chance for dew occurrence at 3-m height for less than 1 h during the observation period.

T_{leaf} was lower than T_{air} during the day in the fanned SCGH, with the gradients increasing with height, reaching an up to 11.5 °C difference at 3-m height. Even though the T_{air} gradients between 3 and 1-m height were higher than 7 °C at noontime, the T_{leaf} gradients were smaller than 2 °C. These results highlight the importance of proper air circulation, by which the plant can regulate its temperature to a high degree and maintain favorable conditions.

3.3. Non-fanned vs. fanned semi-closed greenhouses

Even though the outside conditions were similar during the two seasons, lower T_{air} (Fig. 7a), poorer CO_2 concentrations (Fig. 7b), higher e_a (Fig 7c), and lower VPD (Fig. 7d) were observed at noontime in the SCGH when the horizontal air circulation system (hereafter fan system) operated.

No condensation was observed when the fan system did not operate (Fig. 8a), while when the fan system operated, e_a condensed almost immediately after opening the side curtains at 16:00 (Fig. 8b). This suggests that the condensed water in the fanned SCGH evaporated overnight, resulting in lower T_{air} and higher e_a than outside T_{air} and e_a, respectively (Fig. 8c and d). This effect seemed to be amplified by the fact that during the 2017–2018 crop season, outside night VPD and wind speed were higher (Fig. A.2). In contrast, the non-fanned SCGH followed the outside climate conditions at night (Fig. 8c and d).

Vertical T_{air} gradients were higher at the levels close to the ground due to rapid heating from the soil, and decreased with increasing height (Fig. 9a). However, in the fanned SCGH, the level with the highest gradient was observed in the middle of the greenhouse, and the top level cooled for most of the day (Fig. 9a). Despite this, the average T_{air} gradients were similar between greenhouses, and it was evident that the fans did not reduce the overall vertical T_{air} gradient in the SCGH (Fig. 9b).

4. Discussion

Our results show the extent of the vertical heterogeneity in microclimate conditions in the fanned SCGH and NVGH, and the significant effect it has on plant physiology and production. Despite the vertical heterogeneity in the fanned SCGH, daytime air temperature was not a

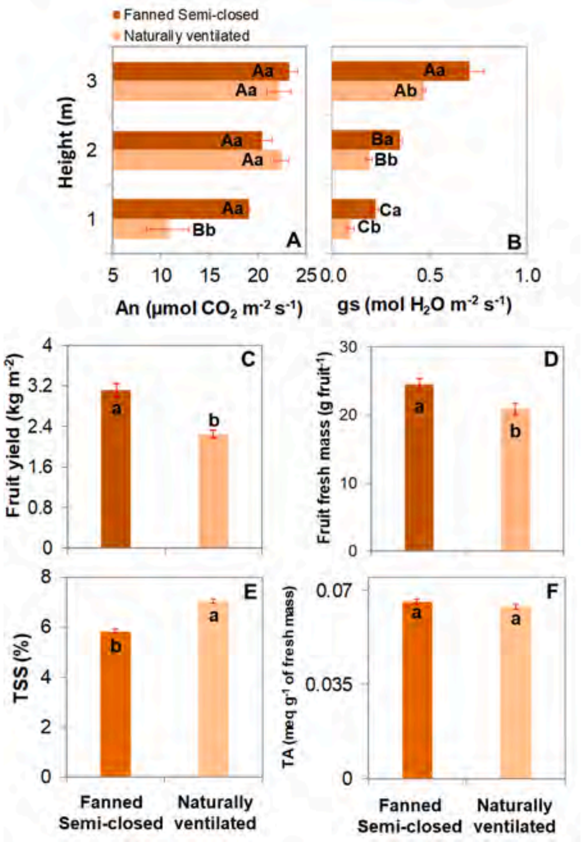

Fig. 4. Height variation of net assimilation rate (a) and stomatal conductance (b), and average fruit yield (c), fruit fresh mass (d), total soluble sugars (e), and titratable acidity (f) for the fanned semi-closed and naturally ventilated greenhouses. Each point represents average values of the repetitions. Standard error bars are shown ($n = 4$). Different capital letters indicate significant differences between heights at the $P = 0.05$ level. Different lowercase letters indicate significant differences between the fanned semi-closed and naturally ventilated greenhouses at the $P = 0.05$ level.

limiting factor for plant growth at the lower canopy, resulting in the increased fruit yield and size. Even under reduced light conditions, the lower leaves in the fanned SCGH experienced assimilation rates similar to the higher canopy, probably due to favorable air temperature and higher CO_2 concentration than at the top of the canopy. The balance between air temperature and CO_2 concentration is crucial to support assimilation activity (Cannell and Thornley, 1998), which strongly affects fruit growth and development (de Koning, 2000). In contrast, air temperature at the lower canopy was a limiting factor in the NVGH, resulting in lower assimilation rates. Moreover, even under high temperatures at the upper canopy in the fanned SCGH, leaf temperature was lower and mostly within the optimal range ($15\ ^{\circ}C \leq T_{leaf} \leq 25\ ^{\circ}C$).

Our results are partially consistent with previously reported assimilation rates and plant production obtained in a semi-closed tomato greenhouse equipped with a cooling system in a temperate climate (Qian et al., 2012). According to the authors, the assimilation rates, and dry matter production and partitioning at the lower part of the canopy did not differ much from those at the higher canopy, but the lower canopy presented significantly different fruit fresh mass. It is known that fruit size and mass typically increase under lower temperatures due to the longer growth duration (de Koning, 1994; van Der Ploeg and Heuvelink, 2005; Zhen et al., 2020); however, the lower fruit fresh mass observed in the NVGH might have been related to the sub-optimal temperatures, which were mostly 15–20 °C at noontime, up to 10 °C lower than in the fanned SCGH. As a result of the trade-off between fruit yield and quality (Kanayama, 2017), a decrease in total soluble sugars

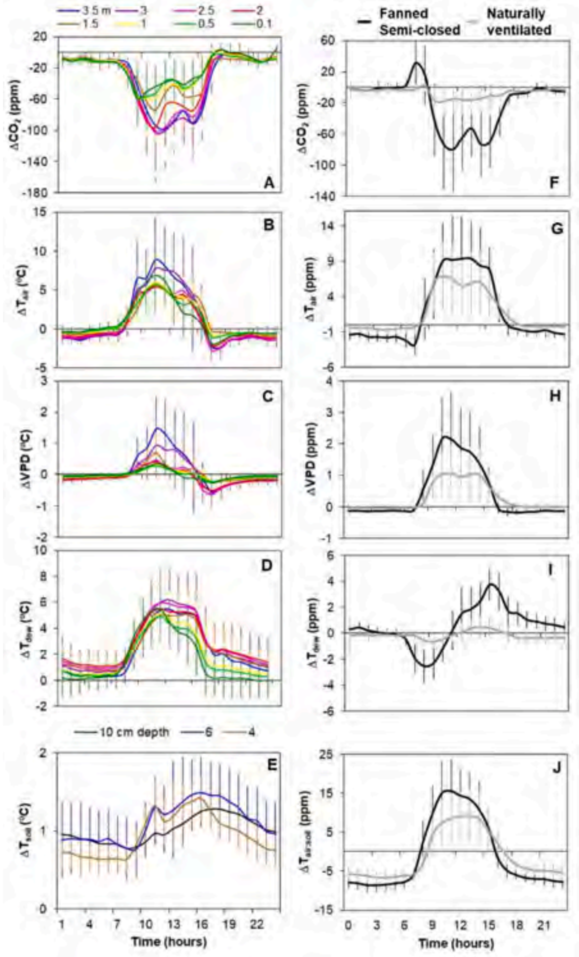

Fig. 5. Changes over height of daily average CO_2 concentration (a), air temperature (b), vapor pressure deficit (c), dew point temperature (d), and soil temperature (e) between fanned semi-closed and naturally ventilated greenhouses; and average hourly changes from 3.5 to 0.1-m height of the carbon dioxide mixing ratio (f), air temperature (g), vapor pressure deficit (h), and dew point temperature (i); and, from 3-m height to 0.1-m depth air-to-soil temperature (j) for fanned semi-closed and naturally ventilated greenhouses, for January/2018. Each point from a to e represents the daily average climate difference (Δ) from fanned semi-closed to naturally ventilated greenhouses at each height. Each hour represents average values of 13-days data series of climate variables. Standard error bars are shown.

and an increase in titratable acidity were observed in the fanned SCGH. The dependence of sugar content on atmospheric CO_2 concentration may also explain the reduced sugar content in the fruits in the fanned SCGH (Behboudian and Tod, 1995), where CO_2 was lower than in the NVGH. Even though VPD increased with height, which is proven to impair stomatal activity (Zhang et al., 2012), the stomatal conductance increased with height for both greenhouses. It seems that, for our conditions, the lower CO_2 levels at the top of the canopy had a strong impact on stomatal conductance (Ainsworth and Rogers, 2007), compared to the increase in atmospheric water demand (Fig. A.1).

High heterogeneity of dew occurrence was observed inside the fanned SCGH, which calls for a thorough study of the distribution of dew formation (and duration) along the canopy height, as opposed to previous studies where dew was monitored at one, presumably representative, height (Gieling and Schurer, 1995; Seginer and Zlochin, 1997; Cohen et al., 2006). The larger day-night temperature variation and low nighttime temperatures, mainly at the middle and upper canopy, might have increased the chance of the occurrence of nighttime dew in the fanned SCGH. Our findings are supported by the general mechanism

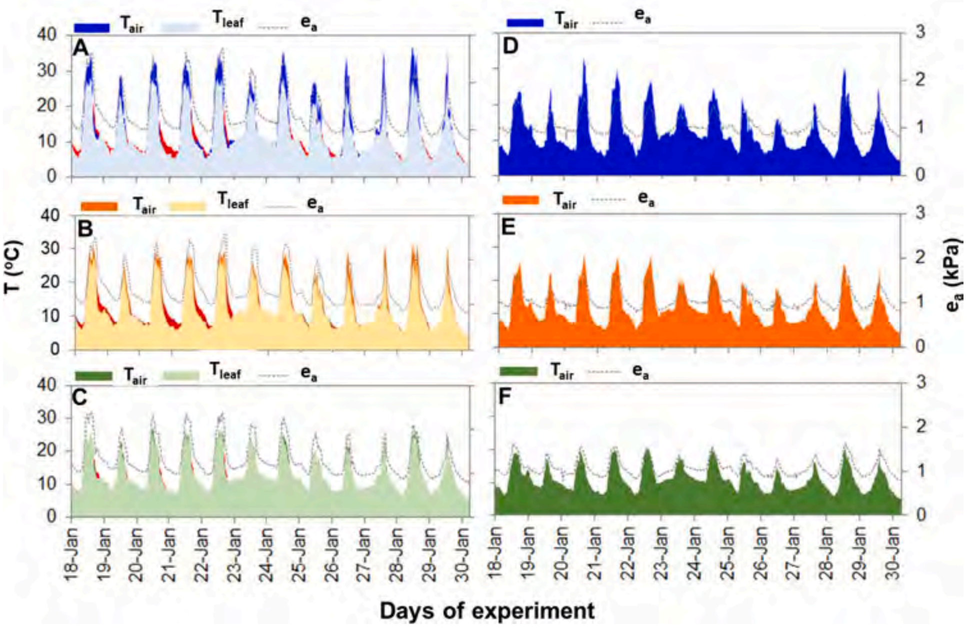

Fig. 6. Hourly changes in leaf temperature (T_{leaf}), air temperature (T_{air}), actual vapor pressure (e_a), and dew occurrence (red area) at 3-m (a, d), 2-m (b, e), and 1-m heights (c, f) for the fanned semi-closed (a to c) and naturally ventilated greenhouses (d to f). The red areas refer to the dew occurrence (T_{leaf}-T_{dew} for the fanned semi-closed greenhouse, and T_{air}-T_{dew} for the naturally ventilated greenhouse).

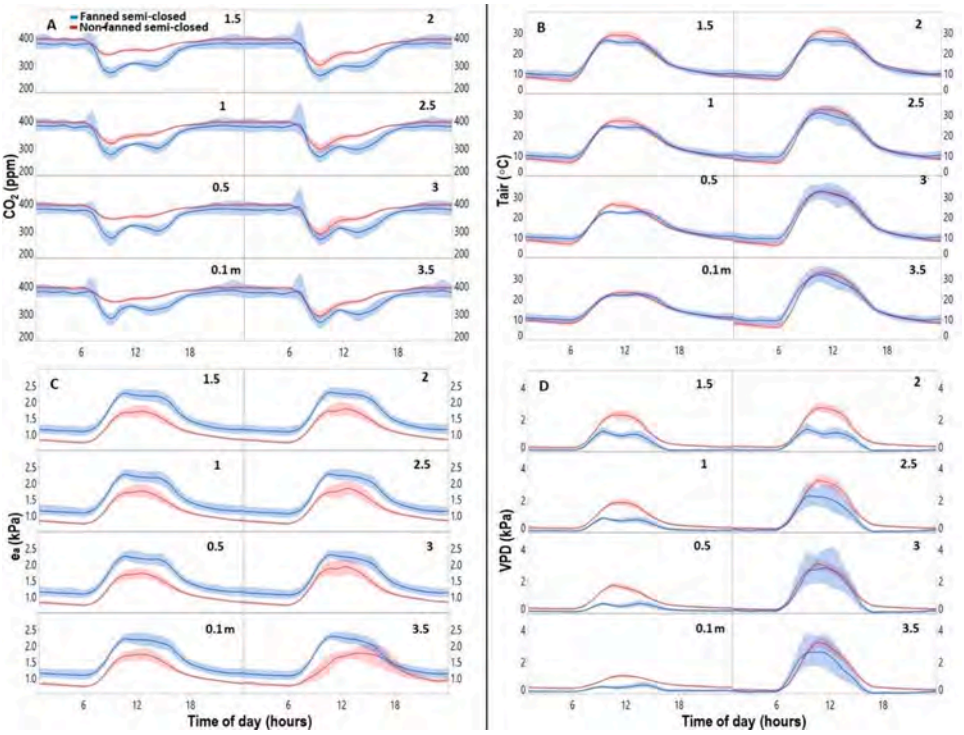

Fig. 7. Diurnal profile of CO_2 concentration (a), air temperature (b), actual vapor pressure (c), and vapor pressure deficit (d) from 3.5 to 0.1-m height, inside the fanned and non-fanned semi-closed greenhouses. Each hour point represents the average over the 7-d period of the experiment. Measurements shown for the non-fanned semi-closed greenhouse represent 7 d during the first week of December 2016; and for the fanned semi-closed greenhouse, they represent 7 d during the first week of December 2017.

stated by Jarvis et al. (1989), who showed that the greater the nighttime humidity and day-night temperature variation, the more dew is deposited on the leaf surface. Thus, opening the wall screens of the greenhouse earlier could be a way to reduce both the humidity and the hours of likely dew occurrence. However, careful management would be needed in these conditions, as opening the greenhouse walls may also increase the vapor pressure deficit and the plant transpiration rate, which tends to decrease the water use efficiency and may increase the need for irrigation in the fanned SCGH.

Particularly in tomato, most of the vegetative growth occurs at the top and middle of the canopy; thus, the higher chance of dew at this canopy level would be related to the increased risk of leaf disease outbreaks, such as gray leaf and white mold (Egel and Saha, 2015), which reduce the photosynthetic activity through direct effects on the green leaf area. However, the maintenance of the assimilation rate at the middle and upper canopy indicates no significant negative effect of dew on plant physiology. From the middle to the bottom of the canopy, where most of the fruit growth occurs, the chance of dew occurrence was

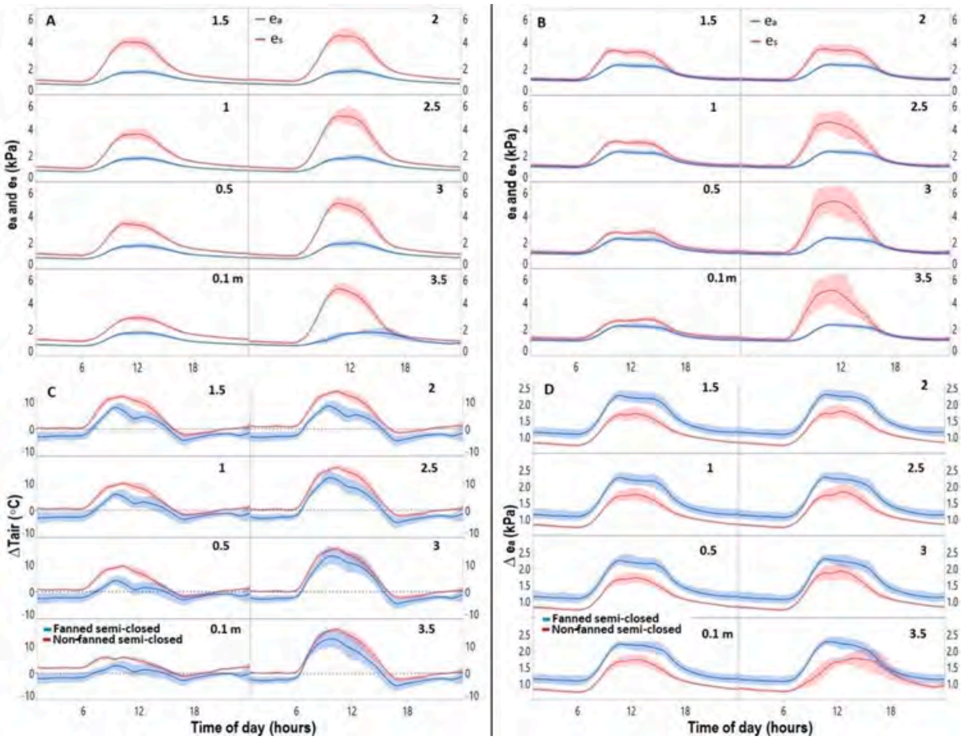

Fig. 8. Diurnal profile of saturated vapor pressure and actual vapor pressure inside the non-fanned semi-closed greenhouse (a), and inside the fanned semi-closed greenhouse (b), from 3.5 to 0.1-m height; difference between inside and outside (in-out) air temperature (c), and actual vapor pressure (d) from 3.5 to 0.1-m height, inside the fanned semi-closed and non-fanned semi-closed greenhouses. Each hour point represents an average over the 7-d period of the experiment. Measurements shown for the non-fanned semi-closed greenhouse represent 7 d during the first week of December 2016; and for the fanned semi-closed greenhouse, they represent 7 d during the first week of December 2017. Outside measurements are for the same time period for each respective crop season. Dashed lines highlight the zero line.

lower than at the top of the canopy. Compared to the NVGH, the negative effect of dew occurrence was not sufficient to surpass the positive effect of the higher T_{air} on plant growth. Even under high dew occurrence in the fanned SCGH, the T_{air} around 20–23 °C and the CO_2 supply of around 340–380 ppm, from the middle to the bottom of the canopy, were able to maintain the assimilation rate.

The fans used in the experiment managed to mix the air enough to change its expected heating pattern, thus increasing the assimilation and transpiration rates, but had no effect on the vertical air temperature gradient in the fanned SCGH. A strong inversion pattern, with similar gradients, was observed both when the fans were operating (fanned SCGH) and when they were not (non-fanned SCGH). The upper canopy was cooler in the fanned SCGH mainly due to the position of the fans, also resulting in higher actual vapor pressure and lower CO_2 levels, which are strongly related to the increase of stomatal conductance and fruit quality in these conditions. According to Qian et al. (2011) the cooling or ventilation systems are normally placed in specific points, such as the bottom or upper part of the canopy, and, depending on the position and capacity of the cooling and ventilation, they can induce vertical air temperature gradients along the plant canopy. It seems that the vertical force applied by the fans at the upper part of the canopy (4 m height) was not strong enough to counter the buoyancy forces of the air. The inability of horizontal air flow fans, located at the upper canopy, to eliminate vertical climate heterogeneity had been reported by Kittas et al. (2001). Greenhouse cultivation in the Mediterranean is mostly based on the assumption that an economic optimum can be reached with low-tech and low-cost greenhouse systems (Pardossi et al., 2004). Thus, many greenhouses in Israel are fanned semi-closed greenhouses with only side openings and no roof opening, resulting in significant vertical climate gradients with a direct impact on plant photosynthetic activity and fruit yield. Our results suggest that for winter cultivation, under Mediterranean and arid climates in semi-closed greenhouses, vertical air circulation would be more appropriate, and would allow better air flow through the plant canopy and efficient use of the solar energy absorbed during the day. During the day, the highest temperatures were observed at the top of the greenhouse and the lowest at ground level, which caused an increased heat flux leaving the greenhouse, through its covering, and a reduced heat flux into the soil, compared to a scenario in which heat was evenly distributed (fanned SCGH). If the air temperature was evenly distributed, more heat would flow into the soil and less would flow out through the roof cover, making the greenhouse more efficient at storing solar energy and improving conditions for root activity. Even though closing the curtains during the day had disadvantages, it still caused a significant increase of 27% in marketable fruit yield. Thus, coupling vertical air flow with closed curtains could increase the economic return even further. This strategy could fit the Mediterranean approach of low-cost and low-tech production, as circulation fans do not require high power consumption or an initial investment relative to other greenhouse systems.

5. Conclusion

In the fanned semi-closed greenhouse, the vertical gradients in air temperature, vapor pressure deficit, and the carbon dioxide mixing ratio that developed during the day mostly dissipated at night. The lower temperatures inside the naturally ventilated greenhouse led to a lack of plant uniformity and to yield loss. Even though significant air temperature gradients existed, plant leaf temperature experienced much lower gradients as the plant was able to self-regulate the temperature, under increasing transpiration from the bottom to the top of the canopy. The use of curtains, coupled with circulation fans, increased nighttime humidity and the chance of dew formation. High T_{air} from the top to the bottom of the canopy, and the CO_2 supply from the middle to the bottom of the canopy were able to maintain the assimilation rate, and positively affected fruit yield and fruit fresh mass, however, with mixed results for fruit quality. We concluded that air circulation is vital, and that vertical air flow is probably preferred, as horizontal air flow has been proven not to affect the vertical temperature gradients. We further concluded that closing the curtains in winter cultivation in semi-arid/arid climates has the potential to improve yield and quality but must be coupled with proper air circulation and, preferably, with CO_2 enrichment, or careful management of natural ventilation through side curtains, in order to maximize CO_2 replenishment while minimizing heat losses.

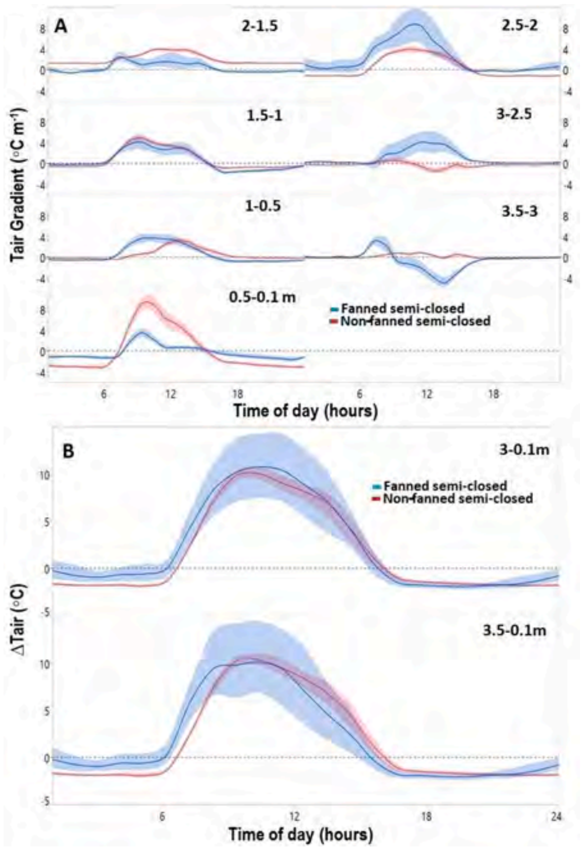

Fig. 9. Diurnal profile of vertical air temperature gradients (a) and maximal temperature difference (b), over different levels, inside the fanned semi-closed and non-fanned semi-closed greenhouses. Each hour point represents an average over the 7-d period of the experiment. Measurements shown for the non-fanned semi-closed greenhouse represent 7 d during the first week of December 2016; and for the fanned semi-closed greenhouse, they represent 7 d during the first week of December 2017. Dashed lines highlight the zero line.

Credit author statement

Daniela Jerszurki: Conceptualization, Methodology, Formal analysis, Writing - Original Draft. **Tal Saadon**: Formal analysis, Writing - Original Draft. **Jingbo Zhen**: Formal analysis. **Nurit Agam**: Writing - Review & Editing. **Eran Tas**: Supervision. **Shimon Rachmilevitch**: Supervision. **Naftali Lazarovitch**: Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the Israeli Ministry of Agriculture and Rural Development (Eugene Kandel Knowledge Centers) as part of the Root of the Matter – The Root Zone Knowledge Center for Leveraging Modern Agriculture.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scienta.2021.110271.

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