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Spatiotemporal temperature distribution in the canopy of summer-to-autumn flowering chrysanthemum under different zone cooling methods**

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Abstract. Avoiding high-temperature stress effectively can ensure sufficient plant production in hot seasons. Therefore, we proposed the use of zone cooling to decrease the temperatures around the chrysanthemum canopy using a heat pump and duct at the bottom (base cooling), top (top cooling), and above (above-top cooling) the canopy. The spatiotemporal distribution of temperatures (air, leaf, and stem temperatures) was measured under the various zone cooling treatments applied, and compared with those under the treatments which were not subjected to cooling (no cooling) and were entirely cooled (entire cooling). The air temperature around the targeted cooling regions and some plant temperatures declined substantially under the base and top cooling treatments at night, but such a decline was not observed with the above-top cooling treatment. During the day, the cooled region under top cooling was directly affected by solar radiation, but this region was unaffected under the base cooling treatment. The cold air was maintained at the bottom. The results indicate that solar radiation substantially influenced spatiotemporal temperature distribution. Moreover, base cooling was found to be the most effective method during both day and night. Thus, this study examines the spatiotemporal temperature distribution under zone cooling methods in the chrysanthemum canopy, thereby advancing our understanding of the fundamental knowledge required for the establishment of a practical zone cooling system.

Keywords: thermocouples, greenhouse, heat pump, high temperature, *Chrysanthemum* × *morifolium* Ramat.

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INTRODUCTION

High temperatures often irreversibly hinder the growth and development of various plants worldwide (Wahid *et al.*, 2007). In particular, summer temperatures often exceed the optimum range for crops, and supra-optimal temperatures negatively affect the growth of common ornamental species (Warner and Erwin, 2006); for example, delaying flowering with increasing leaf numbers on snapdragon, calendula (Warner and Erwin, 2005), and chrysanthemum (Whealy *et al.*, 1987; Cockshull and Kofranek, 1994), and reducing the flower numbers in campanula (Niu *et al.*, 2001), leading to a decline in their commodity value.

In order to maintain the production of ornamental species even in the summer, cooling methods have been investigated worldwide (Cockshull and Kofranek, 1994; Warner and Erwin, 2006; Garner and Armitage, 2008). Moreover, there have been many studies concerning qualitative and quantitative improvements in ornamental species using heat pumps to cool the entire greenhouse, this has the effect of preventing abnormal flower formations and increasing the weight and length of the cut flowers (Higashiura *et al.*, 2020). However, cooling entire greenhouses requires a large amount of energy, especially during the day considering the cooling load required. Compared to that figure, less energy is needed to cool the entire greenhouse during the night because there is no solar radiation. Indeed, the positive effects of nighttime temperature control on plant productivity have been reported previously (Higashiura *et al.*, 2020). As a consequence, heat pump cooling has been limited to nighttime use for most ornamental species due to practical considerations (Muramatsu *et al.*, 2021). Nevertheless, a cooling method will also be necessary during the day because the daytime temperature is much higher than the nighttime temperature and can easily induce high-temperature stress. However, the cooling effect during the day is counteracted by solar radiation, this indicates that additional energy is required (Sethi and Sharma, 2007). Therefore, developing efficient cooling technologies to alleviate high-temperature stress is essential, not only during the night but also during the day.

Crop-localized environmental control is well known for being an efficient technology which uses less energy and has improved productivity as compared to the controlling environment at the scale of the entire greenhouse scale (Zhang *et al.*, 2020). For example, crop-localized controlling technologies were previously developed to increase tomato production by cooling around the shoot-tips (Kawasaki and Ahn, 2015), earlier flower bud differentiation was induced for strawberry cultivation through crown-cooling (Hidaka *et al.*, 2017), the strawberry yield was improved and also fuel use efficiency through the application of crop-localized CO_2 enrichment (Miyoshi *et al.*, 2017; Hidaka *et al.*, 2022; Zhang *et al.*, 2022). Therefore, zone cooling methods can be used to facilitate efficient cooling, leading to the alleviation of high-temperature stress for ornamental species.

The air temperature surrounding the plants varies with the exact location and time, and as a result, plant temperatures (leaf and stem temperatures) which substantially influence plant growth and development throughout the cultivation period (Matsui and Eguchi, 1971; Matsui and Eguchi, 1972; Blanchard and Runkle, 2010; Lambers *et al.*, 2019) also vary spatiotemporally (Kimura *et al.*, 2020). In order to determine these temperatures, radiation dynamics such as solar radiation and heat radiation from the soil surface generally plays an important role (Flerchinger *et al.*, 2009). Furthermore, the characteristics of the spatiotemporal distribution of these temperatures should be formed in different ways depending on the zone cooling methods. Therefore, in order to develop effective zone cooling technology, it is essential to clarify the short-term effects of zone cooling on the spatiotemporal air and plant temperatures which have not been investigated well in the past studies, and furthermore the long-term effects on plant growth and energy consumption should be established.

In this study, we focused on the short-term effects of applying zone cooling methods for chrysanthemum, which is the most common ornamental species in Japan and is affected by the high temperatures which occur in the summer when commercial demand reaches its highest point. The aim of this study was to elucidate the spatiotemporal distribution of temperatures (air and plant temperatures) around the chrysanthemum canopy under different zone cooling methods both during the day and at night, through multiple measurements of the air and plant temperatures using thermocouples (approximately 150). The targeted cooling points were distinguished by altering the height of the duct, *i.e.*, zone cooling with the duct at the bottom, top, and above the canopy. Additionally, these cooling methods were compared with conditions where cooling was not applied and also where cooling was applied around the entire canopy in order to characterize each zone more precisely in terms of the cooling effect.

MATERIALS AND METHODS

The experiments were conducted in an N-S oriented plastic greenhouse (15 m long × 6.6 m wide × 4.6 m high) located at Fukuoka Agriculture and Forestry Research Centre (33°32′84″N, 130°71′22″E) on the 6th and 7th of August and also on the 25th of September, 2020. Four ridges (each 10.9 m long and 70 cm wide) were created in the greenhouse with loamy soil, and summer-to-autumn flowering cultivars of *Chrysanthemum* × *morifolium* Ramat., namely ‘Sei no issei’ were planted on the 25th of June, 2020 (Fig. 1). The plants were irrigated twice a day, early in the morning and in the evening, and N: P_2O_5: K_2O (13: 14: 8) fertilizer was applied at a rate of 2 g per plant. The plants were subjected to night-break (22:00-3:00) treatment with red-emitting LED lamps (FR-MP; D-market Inc., Osaka, Japan) from the 19th of July (24 DAP: days after planting) to the 31st of August (67 DAP), and then placed exposed to natural daylight after the 1st of September (68 DAP). The night air temperature was controlled at 19°C from 18:00 to 6:00, on the 29th of July (30 DAP) to the 25th of September (92 DAP) using heat pumps with an 11.2 kW output (PRV-AP112K; Hitachi

Fig. 1. Plants were grown on each ridge (10.9 m in length and 70 cm in width), and the measurements were performed in the plot surrounded by white lines at the east-side ridge. A 13.5 cm grid-like flower net with five rows was set on the canopy. Two plants were grown per grid, except in the middle row, where the duct for zone cooling was located.

Appliances Inc., Tokyo, Japan), these were installed northwest and southeast of the greenhouse. In addition, ventilation was applied during the day when the air temperature in the greenhouse exceeded 25°C.

Three different zone cooling treatments were applied to the canopy: base cooling, top cooling, and above-top cooling. A polyethylene duct with a 10 cm diameter was connected to the centre of the exhaust port of the heat pump, and other parts of the exhaust port were covered with Styrofoam board. Cold air was transmitted through the duct and discharged around the canopy through vent holes with a 6 mm diameter, the perforations were located at 10 cm intervals in four rows. From those 4 rows of vent holes, the cold air blew diagonally upward at 25°, 45°, 135°, and 155° from horizontal, respectively. Figure 2 shows a schematic of each zone cooling treatment. For base cooling, the duct was set on the ridge surface and the upward moving cold air cooled the lower parts of the plants (Fig. 2a). For top cooling, the duct was set on the middle line of the flower net (40 cm high for the experiment in August and 90 cm high for the experiment in September), and the upward moving cold air cooled the shoot-tips (Fig. 2b). For above-top cooling, a duct was hung above the canopy (1.7 m high) upside down, therefore the downward moving cold air cooled the shoot-tips (Fig. 2c). The wind speed inside the duct during cooling was approximately 6.0 m s^{-1}, and the air temperature inside the duct was approximately 8.0°C in the treatment plot. In order to evaluate these zone cooling methods and characterize them precisely, two other treatments were also applied to the canopy: a no-cooling treatment where cooling was not conducted, and the entire cooling treatment where the entire canopy was cooled with cold air directly from the entire exhaust port without using the duct.

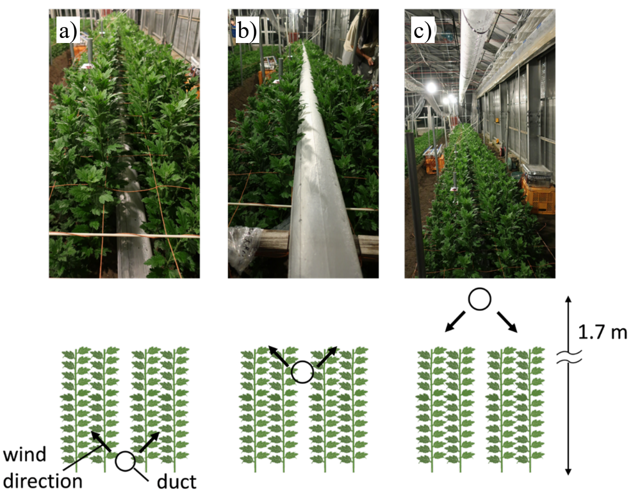

Fig. 2. Photographs and schematics of the zone cooling methods: (a) base cooling; (b) top cooling; (c) above-top cooling. The targeted cooling locations were distinguished by changing the height of the duct. The position of the duct was on the ridge surface for the base cooling, on the flower net depending on plant height for the top cooling, and above the canopy (1.7 m high) for the above-top cooling.

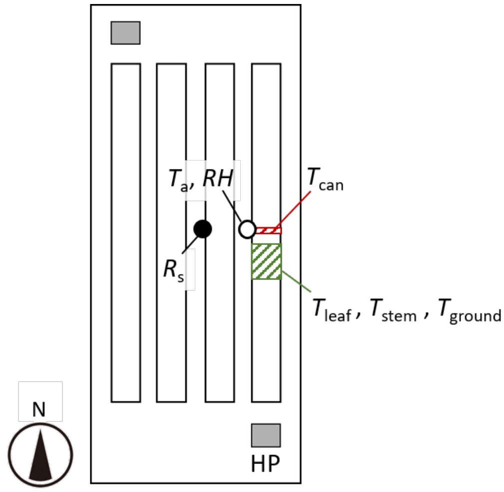

Fig. 3. Schematic of the greenhouse showing the measurement locations: solar radiation (R_s) was measured at ● point using a pyranometer at a height of 1.85 m, and air temperature (T_a) and relative humidity (RH) at ○ point using a temperature-humidity sensor at a height of 1.5 m. The air temperature in the greenhouse (T_{can}) was measured in the red shaded cross-section in the canopy by using multiple thermocouples, and the leaf, stem, and ground temperature (T_{leaf}, T_{stem}, and T_{ground}, respectively) were measured in the green shaded area with thermocouples.

Micrometeorological elements in the greenhouse, such as solar radiation (R_s), air temperature (T_a), and relative humidity (RH), were measured using a pyranometer (PCM-01SD; PREDE Co., Ltd., Tokyo, Japan) and a temperature-humidity sensor (HMP60; Vaisala, Helsinki, Finland), respectively (Fig. 3). R_s was measured in the middle of the east-side ridge at a height of 1.85 m, and T_a and RH were measured at the centre of the greenhouse at a height of 1.5 m. These measurements were recorded at 1 min intervals using a data logger (MIJ-01, Environmental Measurement Japan Co., Ltd., Fukuoka, Japan).

In order to measure the spatiotemporal distribution of the temperatures in the canopy (air temperature (T_{can}), leaf temperature (T_{leaf}), and stem temperature (T_{stem})) and the ground temperature (T_{ground}), T-type thermocouples of copper-constantan wires were used. Two types of thermocouples with diameters of 0.20 and 0.32 mm (T-2-G-J2; Ninomiya Electric Wire Co., Ltd, Kanagawa, Japan; VT3; CHINO Co., Tokyo, Japan) were connected *via* miniature connectors (SMPW-T-F; OMEGA Engineering, CT, USA).

T_{can}, T_{leaf}, and T_{stem} were measured on the night of the 6th of August (42 DAP). T_{can} was measured in the analysed region (width: 90 cm, height: 67.5 cm), which was the vertical section in the middle of the east-side ridge (Fig. 3), using thermocouples arranged on an aluminium frame (AFS-2020-4; NIC Autotec, Inc., Tokyo, Japan) at 10 cm intervals horizontally and 13.5 cm vertically. By moving this frame the T_{can} values for the five experimental treatments were measured. All measurements were performed under no ventilation conditions to elucidate how the cold air from the duct spread around the canopy without any influence of convection due to ventilation. The data were recorded for 20 s at 1 s intervals using a data logger (midi LOGGER GL820; Graphtec Corporation, Yokohama, Japan). For each condition, data in the time range of 11-20 s was used to calculate averages, considering that the response time of the thermocouples was only 1.5-2.0 s. Based on the averaged data results, heatmaps were constructed using matplotlib in Python (version 3.7.3). T_{leaf} and T_{stem} were measured (n=5) at a 40-45 cm height, from the upper part of the plants using thermocouples attached to the leaves and stems with tape. Moreover, T_{ground} was measured (n=5) at a depth of approximately 3 cm, around the treatment canopy using thermocouples. These data were recorded at 1 min intervals using a data logger.

On the 25th of September (92 DAP), time-course changes in the spatial distribution of T_{can} were measured in the analysed region (width: 90 cm, height: 94.5 cm) under four experimental treatments, except for the above-top cooling treatment, using thermocouples arranged on two frames (one on the left of the analysed region and the other on the right). The measurements for each cooling treatment were conducted for 30 min, they consisted of 20 min under cooling and then 10 min after discontinuing cooling, under a no ventilated-condition. The T_{can} of the no-cooling treatment was also measured for 30 min. All data were recorded at 1 s intervals using the data loggers (midi LOGGER GL820 and midi LOGGER GL840). Heatmaps were constructed using matplotlib in Python version 3.7.3, based on calculated data averaged every minute. Moreover, T_{ground} was measured (n=5) at a depth of approximately 3 cm using thermocouples, the temperatures were recorded at 1 min intervals using the data logger. Finally, the results were examined by considering the values of R_s and T_{ground}.

Samples originating from ten plants were taken from the treatment area to evaluate the growth status for both experiments on the 6th of August (43 DAP) and on the 25th of September (92 DAP) during the period when the spatiotemporal temperature distribution was measured. Measurements were taken in terms of shoot length, the number of leaves, leaf area, and the dry weight of the plant (Table 1). The samples were taken apart and arranged on a white sheet in order to capture images to estimate leaf area. Then, it was calculated from the ratio of the leaf area to the photo area, by binarizing the images using imaging processing software (Image J, version 1.53, US). The dry weight was measured after the leaves and stems were fully dried at 80°C for 72 h.

Table 1. The average shoot length, number of leaves, leaf area, and dry weight of plants in the chrysanthemum canopy (n=10) (Means ± SD), measured on the 7th of August (43 DAP) and on the 25th of September (92 DAP), 2020

Month	Shoot length (cm)	Number of leaves ($plant^{-1}$)	Leaf area ($cm^2\ plant^{-1}$)	Dry weight ($g\ plant^{-1}$)
Aug	56.9±4.7	30.0±2.3	628.9±103.3	4.4±0.74
Sep	108.1±2.6	62.9±3.2	1312.2±150.3	12.0±1.9

RESULTS AND DISCUSSION

Figure 4 shows the spatial distribution of T_{can} under five experimental conditions at night. Their statistical characteristics at three different heights (low: 0-23.6 cm, middle: 23.6-47.3 cm, and high: 47.3-67.5 cm) are shown in Fig. 5. Under no-cooling treatment, T_{can} was uniformly distributed at approximately 29°C (Fig. 4a), and its spatial distribution exhibited an extremely slight temperature gradient (<1°C) with height (Fig. 5a). For the entire cooling treatment, T_{can} was relatively uniform at approximately 23°C, and the distribution did not have a remarkable temperature gradient with height (Figs 4b, 5b). Previous studies reported that growth delays in chrysanthemum are encountered if either the day or night temperature exceeds approximately 26°C (Karlsson *et al.*, 1989; Wilkins *et al.*, 1990). Moreover, it is widely known that the optimum temperature for chrysanthemum development is 20-25°C in Japan. Given these facts, under the no-cooling treatment T_{can} was above the optimum temperature; by contrast, under the entire cooling treatment T_{can} reached the optimum temperature, which can alleviate high-temperature stress for chrysanthemum.

In the base cooling treatment, the cold air concentrically spread from the duct, indicating that T_{can} gradually increased with height (approximately 19-27°C) from the ground to the top of the canopy (Fig. 4c). The temperature gradient was remarkably steep; T_{can} in the higher locations was almost the same as T_a (approximately 28°C) without a large range of temperature scattering, it exceeded the upper limit temperature for appropriate chrysanthemum growth (26°C); however, the average T_{can} in the middle and lower locations were approximately 26 and 23°C, respectively, and T_{can} in those locations were widely distributed with scatterings of 8°C (Fig. 5c), reaching an optimum temperature (20-25°C). Several zone cooling studies for horticultural crops have been conducted over a long period of time because zone cooling can promote plant growth efficiently as compared to cooling the entire canopy; in particular, base cooling is the most mainstream among the zone cooling methods that have been investigated previously (Lingle and Davis, 1959; Nkansah and Ito, 1995; Hidaka *et al.*, 2017; Liu *et al.*, 2022). For example, one of the beneficial effects of the base cooling method are improvements in root physiological activity and an increasing net photosynthetic rate of cyclamen (Oh *et al.*, 2007). There is also an increase in plant height, stem diameter, and dry weight for tomato with a much lower expenditure of energy as compared to cooling the entire canopy (Liu *et al.*, 2022). Moreover, zone cooling can cool the canopy efficiently regardless of the distance from the heat pump even in a larger greenhouse; while entire cooling might not cool

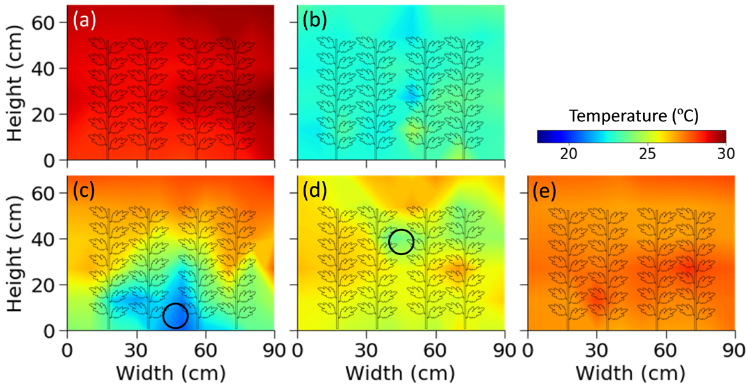

Fig. 4. Spatial distribution of the air temperature around the chrysanthemum canopy in the analysed region (width: 90 cm, height: 67.5 cm) under the five experimental conditions (a: no-cooling treatment, b: entire cooling treatment, c: base cooling treatment, d: top cooling treatment, e: above-top cooling treatment) on the night of the 6th of August, 2020 (42 DAP). The circles in the figure indicate the duct positions. The position of the duct at a height of 1.7 m was not shown for the above-top cooling treatment. The measurements were conducted from 20:00 to 23:30 on the 6th of August, 2020 (42 DAP).

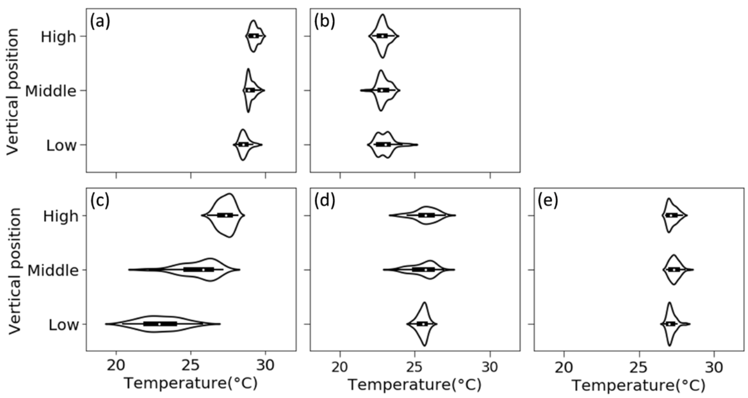

Fig. 5. Violin plots representing air temperature around the chrysanthemum canopy for each height (low: 0-23.6 cm, middle: 23.6-47.3 cm, high: 47.3-67.5 cm) under five experimental conditions (a: no-cooling treatment, b: entire cooling treatment, c: base cooling treatment, d: top cooling treatment, e: above-top cooling treatment) on the night of the 6th of August, 2020 (42 DAP). The data were calculated based on the heatmaps in Fig. 1. The surrounding lines are kernel density estimations showing the distribution range of the temperature. Each boxplot inside the surrounding lines shows the median and interquartile range.

the canopy far away from the heat pump. In fact, Zhang *et al.* (2022) reported that through crop-localized CO_2 enrichment, a higher CO_2 concentration was maintained even in the canopy far away from the CO_2 generator, whereas only the canopy close to the generator was maintained a high CO_2 concentration through entire CO_2 enrichment. Due to the findings mentioned above, the base cooling method in this study can be used to promote plant growth efficiently in the whole greenhouse by keeping T_{can} at the lower part of the canopy at the optimum temperature for chrysanthemum growth even if T_{can} at the upper part is out of the optimum range.

Under the top cooling treatment, cold air is spread diagonally above the duct, and T_{can} decreased to 23.5-26°C (Fig. 4d). With regard to temperature variation at the respective heights, T_{can} at the high and middle height was similar, it ranged from 23.5 to 28°C (Fig. 5d). Although T_{can} at the lower location had a lower degree of scattering, the average T_{can} was almost the same as those for the middle and the high locations. The average T_{can} for each height did not reach the upper limit temperature at which a growth delay in chrysanthemum does not occur (Karlsson *et al.*, 1989; Wilkins *et al.*, 1990). Kawasaki *et al.* (2011) investigated the local heating of tomato shoot-tips with an air duct and found that the surface temperatures around the shoot-tips increased locally, which lead to an increase in the commercial fruit yield and to a decrease in fuel consumption by 26%. In this experiment the temperature gradient with height was not as conspicuous as that reported by Kawasaki *et al.* (2011). It is generally considered that controlling the shoot-tip temperature is the most effective way of inducing a beneficial result because the temperature at this location is the primary factor that controls the rate of plant development (Tardieu *et al.*, 2000). However, not many studies concerning the control of shoot-tip temperature have been conducted due to the difficulties in implementing this method as the shoot-tip positions are elevated with elongation growth (Kawasaki and Yoneda, 2019). Therefore, top cooling at night may be effective in terms of lowering the temperature locally to achieve the optimum temperature with the possibility of less energy consumption, although it has the disadvantage of necessitating the movement of the duct upward, corresponding to plant growth.

For the above-top cooling treatment, T_{can} in the analysed region decreased little and was distributed uniformly at 26.5-28°C (Fig. 4e). Only a slight gradient was observed, although the upper part of the analysed region was slightly cooler than the middle and lower parts (Fig. 5e). All T_{can} values under the above-top cooling treatment were above the optimum temperature. Incidentally, this cooling method is the most convenient one to use as compared to other zone cooling methods because, by simply suspending the duct above the canopy, one can control T_{can} around the shoot-tips without moving the duct as the plants grow. Kawasaki and Ahn (2015) applied a similar cooling method during the night and found that this cooling effect decreased the air temperature around the shoot-tips by 2°C, leading to an increase in pollen viability, fruit number, and fruit weight. However, in our experiment, the cold air only spread faintly around the entire canopy and did not lower T_{can} enough in spite of the convenience of this above-top cooling system. This result may be attributed to the fact that the distance between the duct and the canopy was much larger in this experiment as compared to the previous one performed by Kawasaki and Ahn (2015), and the cooling capacity was insufficient to cool the canopy locally.

T_a, T_{can}, T_{leaf}, and T_{stem} under the five experimental conditions at night are shown in Fig. 6. Under the no-cooling treatment, T_{can} and T_a were almost the same (approximately 29°C); however, T_{leaf} and T_{stem} were 1°C lower than these values (Fig. 6a), which were still above the optimum temperature for chrysanthemum (20-25°C). Previous studies reported similar results that plant temperatures at night are generally somewhat lower than the air temperatures due to radiational cooling (Matsui and Eguchi, 1971; Aubrecht *et al.*, 2016). Moreover, the data scatterings of T_{leaf} and T_{stem} were almost negligible. Under the entire cooling treatment, all measurement indices were affected to a significant extent by cooling, compared with those under the no-cooling treatment (Fig. 6b). Although T_a was measured at the centre of the greenhouse, which was close to the heat pump and the targeted canopy, it was also directly affected by cooling. All of the measured T_{leaf} and T_{stem} values were within the optimum temperature range. Considering that plant temperatures are strongly affected by the air temperature (Matsui and Eguchi, 1971) and directly influence plant growth (Kawasaki and Yoneda, 2019), entire cooling during the night can ensure the sufficient growth of chrysanthemum by decreasing plant temperatures.

In the base cooling treatment, T_{can}, T_{leaf}, and T_{stem} declined compared with T_a (27.5°C), and some T_{leaf} values in particular dropped to the optimum temperature (20-25°C), whereas all T_{stem} values did not reach the optimum range with the extremely slight range of data scattering (Fig. 6c). A remarkable decline in some T_{leaf} values may be caused by the heat capacity of the leaves being less than that of the stems as leaves have a thinner structure and a smaller volume. Another reason may be the measurement positions. T_{leaf} and T_{stem} were measured in the upper part of the plants at a height of 40-45 cm, based on the consideration that controlling the shoot-tip temperature is the most effective means for facilitating plant growth (Tardieu *et al.*, 2000). However, the leaves close to the shoot-tips were too small to allow for the use of thermocouples. Therefore, the measurement position of T_{leaf} was somewhat lower (approximately 40 cm high) than that of T_{stem} (approximately 45 cm high), which means that T_{leaf} was measured closer to the duct, and this may be the cause of the difference between T_{leaf} and T_{stem}. T_{leaf} and T_{stem} around the base of the canopy may have been reduced

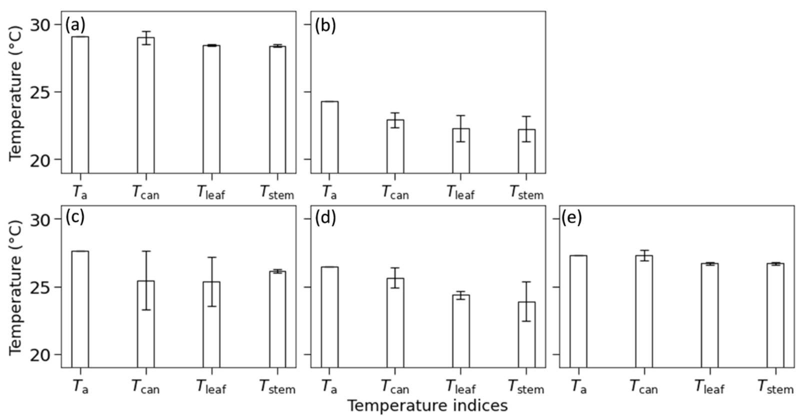

Fig. 6. Air temperature in the greenhouse (T_a), average air temperature in the treatment canopy (T_{can}), leaf temperature (T_{leaf}), and stem temperature (T_{stem}) under five experimental conditions (a: no-cooling treatment, b: entire cooling treatment, c: base cooling treatment, d: top cooling treatment, e: above-top cooling treatment) on the night of the 6th of August, 2020 (42 DAP). T_a was measured at a height of 1.5 m from the centre of the greenhouse, T_{can} was the average of the air temperatures calculated based on the heatmaps of Fig. 1. T_{leaf} and T_{stem} were the average of the five different observed temperatures measured by thermocouples (φ: 0.20 mm). The columns of T_{can}, T_{leaf}, and T_{stem} show ±standard deviations of the entire populations.

to the optimum temperature, although this was not clarified in this study, such temperature conditions can promote the uptake of water and mineral nutrients (Klock *et al.*, 1996) and hence promote plant growth (Xu and Huang, 2000). Thus, base cooling can reduce some plant temperatures in the upper parts of plants to its optimum range, especially T_{leaf}, nevertheless it should be noted that the measurement positions were far from the cooling duct. Further study is required to elucidate the plant temperature characteristics around the base of the canopy in order to achieve a better understanding of this cooling effect.

In the top cooling treatment, T_{can} declined by 1°C as compared with T_a (26.5°C) with some data scattering (Fig. 6d). By contrast, cooling greatly influenced both T_{leaf} and T_{stem}, both of which did not exceed the upper limit temperature for appropriate chrysanthemum growth (26°C). Plant temperatures can be substantially affected by the measurement positions because the measurements are taken at the upper part of the canopy close to the shoot-tips where cooling is locally targeted. The measurement positions may cause some data scattering of T_{leaf} and T_{stem}, but the details remain unclear. Kawasaki and Yoneda (2019) reported that maintaining the shoot-tip temperature at the optimum level, and not at other temperatures, generally improved the differentiation rate of both leaves and flower buds. Thus, the top cooling method can be used to reduce the plant temperatures at the upper part of the canopy to less than the upper limit, and this may possibly also reduce the shoot-tip temperature, leading to an improvement in plant tissue differentiation.

In the above-top cooling treatment, no conspicuous temperature decline was observed, and the results of each measurement index were almost at the same level (Fig. 6e). All T_{leaf} and T_{stem} values exceeded the upper limit temperature for appropriate chrysanthemum growth (26°C). Moreover, the temperature relationships among all four of the measured indices were similar to those under the no-cooling treatment. Thus, this cooling method cannot be effective enough to alleviate high-temperature stress for chrysanthemums. Based on these results, the above-top cooling treatment was not conducted during the day.

The time-course changes in R_s and the spatial distribution in T_{can} during the day are shown in Figs 7-10. Under the no-cooling treatment, T_{can} was uniformly distributed throughout the experimental period, ranging from 26-29°C (Fig. 7), which was above the upper limit temperature for appropriate growth in chrysanthemums (Karlsson *et al.*, 1989; Wilkins *et al.*, 1990). In addition, T_{can} increased when R_s exceeded 500 W m^{-2}, because R_s generally affects the air temperature distribution in a greenhouse with low wind speed and predominant natural convection (Kimura *et al.*, 2020), thereby indicating that T_{can} corresponded with the amount of R_s.

Under the entire cooling treatment, T_{can} at the lower half of the canopy gradually decreased, and the entire canopy was within the optimum temperature range (20-25°C) 10-15 min after the treatment began when R_s remained at less than 100 W m^{-2} (Fig. 8). Afterwards, T_{can} at the upper location gradually increased corresponding to the increase in R_s, and exceeded the optimum temperature, whereas the temperature at the lower location remained relatively low. In general, the light intensity in the canopy decreased exponentially through the leaf layers (Monsi and Saeki, 2005). Considering that the average height of this canopy was 108.1 cm, R_s in the lower part should be much less than that in the upper part. Hence, the entire cooling method can decrease T_{can} in the canopy as a whole when R_s is quite low, however, a relatively large value for R_s increases T_{can} especially in the upper part of the canopy, counteracting the cooling effect.

Under the base cooling treatment, T_{can} around the duct was remarkably low and R_s fluctuated between 100 and 600 W m^{-2} (Fig. 9). At a height of 0-40 cm T_{can} remained low, with scattering in the range of 17 to 25°C during the cooling period regardless of R_s, this was a relatively appropriate temperature range considering that the optimum temperature for Japanese chrysanthemums is in the 20-25°C range.

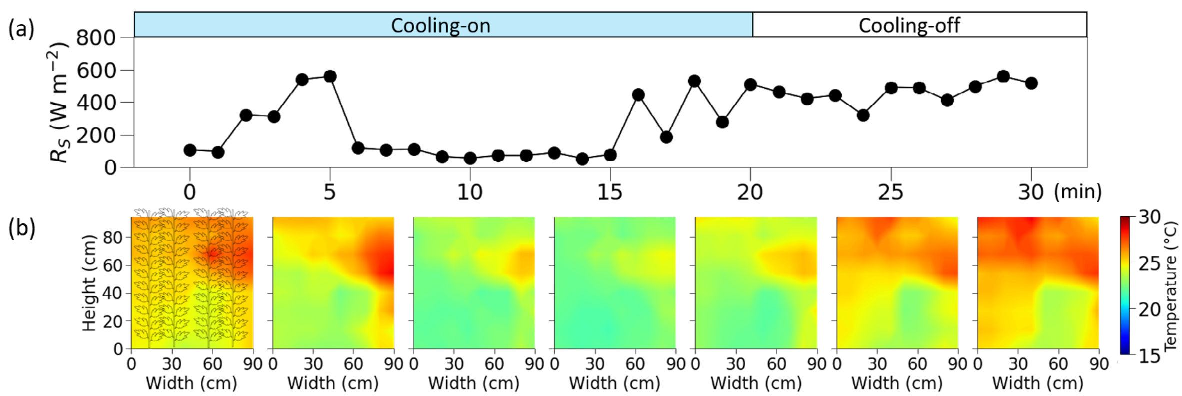

Fig. 7. Time-course changes in (a) solar radiation (R_s) and (b) spatial distribution in the analysed region (width: 90 cm, height: 94.5 cm) of the air temperature around the chrysanthemum canopy under the no-cooling treatment during the day. The 'Cooling-off' part of the figure shows the period when the air conditioning was completely turned off. R_s was measured from the centre of the greenhouse (1.85 m high). The experiment was conducted from 11:53 to 12:23 on the 25th of September, 2020 (92 DAP).

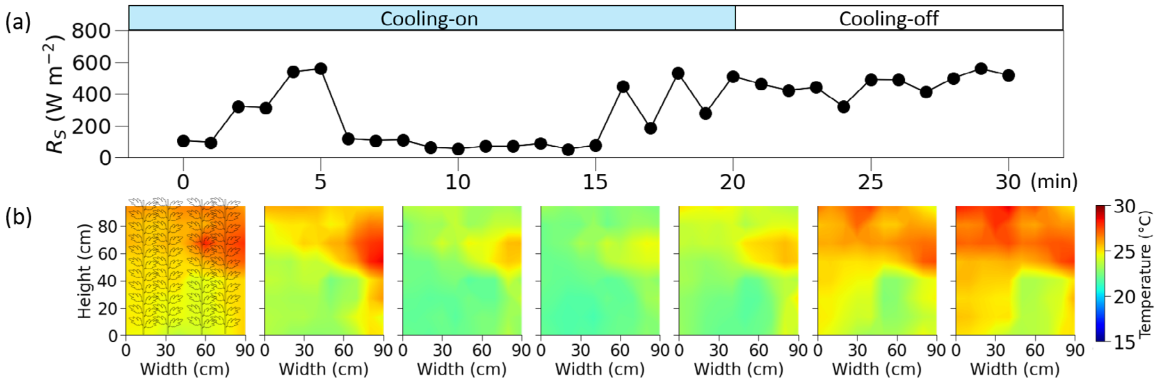

Fig. 8. Time-course changes in (a) solar radiation (R_s) and (b) spatial distribution in the analysed region (width: 90 cm, height: 94.5 cm) of the air temperature around the chrysanthemum canopy under the entire cooling treatment during the day. R_s was measured from the centre of the greenhouse (1.85 m high). The experiment was conducted from 9:50 to 10:20 on the 25th of September, 2020 (92 DAP).

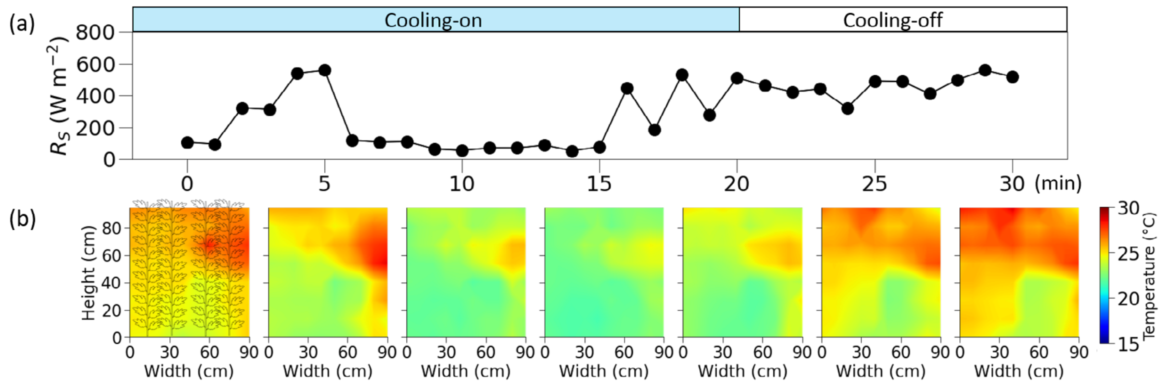

Fig. 9. Time-course changes in (a) solar radiation (R_s) and (b) spatial distribution in the analysed region (width: 90 cm, height: 94.5 cm) of the air temperature around the chrysanthemum canopy under the base cooling treatment during the day. R_s was measured from the centre of the greenhouse (1.85 m high). The experiment was conducted from 10:21 to 10:51 on the 25th of September, 2020 (92 DAP).

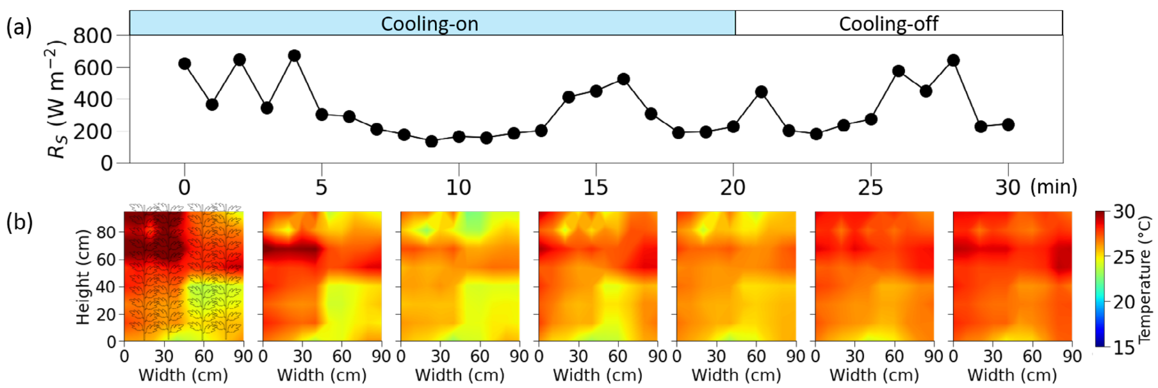

Fig. 10. Time-course changes in (a) solar radiation (R_s) and (b) spatial distribution in the analysed region (width: 90 cm, height: 94.5 cm) of the air temperature around the chrysanthemum canopy under the top cooling treatment during the day. R_s was measured from the centre of the greenhouse (1.85 m high). The experiment was conducted from 10:52 to 11:22 on the 25th of September, 2020 (92 DAP).

T_{can} at the targeted cooling region was not directly affected by R_s although T_{can} at the upper location corresponded to the R_s. Previous studies have reported the effectiveness of base cooling using a water circulation system during the day, for example, it enhances photosynthetic capacity and improves turfgrass growth in creeping bentgrass (Xu *et al.*, 2002) it also improves root growth and increases the number of flowers in paprika (Kwack *et al.*, 2014). Therefore, base cooling during the day could also be useful for the chrysanthemum canopy by producing an optimum T_{can} value at the lower part of the canopy despite the level of R_s, which would improve both vegetative and reproductive growth to ensure the appropriate degree of plant production. In addition, due to the prevention of high R_s levels in the lower part of the canopy (Monsi and Saeki, 2005), which was the target region for cooling, a low T_{can} value was maintained even after cooling was discontinued, thereby indicating the potential for further energy savings by maintaining the cold air not only during the treatment but also after its discontinuation.

Under top cooling treatment, the region at a height of more than 70 cm was cooled remarkably well, ranging from 22 to 25°C, when R_s was between 150 and 250 W m^{-2} in an elapsed time of 5-13 min (Fig. 10). Other than during these cooling periods, T_{can} in the analysed region even in the cooling targeted location exceeded the optimum temperature for chrysanthemum growth and T_{can} rose further after cooling was discontinued, which may be the cause of a flowering delay by suppressing reproductive growth (Nozaki and Fukai, 2008). Considering that R_s in the upper location is generally higher than that in the lower location (Monsi and Saeki, 2005), the targeted cooling region in this treatment is directly affected by R_s and the cold air in the upper location could not be maintained when R_s was above around 250 W m^{-2}. Therefore, the top cooling method may be unsuitable during the day because T_{can} was outside the optimum temperature range due to R_s, although this method may decrease T_{can} to the optimum temperature during the night.

Only the spatiotemporal temperature distribution during the day and night has been discussed so far. However, the temperature distribution may also be affected by the heat radiation from the soil surface (Flerchinger *et al*., 2009). For each measurement during the night, T_{ground} at a depth of 3 cm was 27.4°C (no cooling), 25.5°C (entire cooling), 25.6°C (base cooling), 25.6°C (top cooling), and 27.4°C (above-top cooling); T_{ground} under the entire, base and top cooling treatments was almost 2°C lower than that of the no-cooling and the above-top cooling treatments. Assuming that these T_{ground} values reflect the temperature of the soil surface, the heat radiation from the soil under the entire, the base and the top cooling treatments was about 10-11 W m^{-2} lower as compared to those of other treatments, which might cause differences in the effect of heat radiation from the soil surface on the spatiotemporal temperature distribution changes among the treatments but they would not be so substantial. By contrast, T_{ground} at a depth of 3 cm was found to be 21.7°C (no cooling), 21.3°C (entire cooling), 20.8°C (base cooling), 21.1°C (top cooling) using measurements performed during the day. The T_{ground} difference between each treatment was less than 1°C, indicating that the heat radiation from the soil surface was not remarkably different. Therefore, in this study, it is likely that there was little difference in the impact from heat radiation among the treatments during the day, even if the heat radiation from the soil surface affected the temperature around the canopy.

CONCLUSIONS

1. This study demonstrated the spatiotemporal distribution of temperatures (air and plant temperatures) around the chrysanthemum canopy under three different zone cooling methods. The cooling of each zone was characterized, focusing on the targeted cooling region, temperature distribution, and the treatment time during the day.

2. The base cooling method was shown to be efficient because the lower part of the canopy and some of the plants were cooled adequately both during the day and night, with the possibility of energy-saving efficiency occurring. The top cooling method was also effective at night, with a decline in air and plant temperatures around the targeted cooling region, but it was not adequate during the day as the temperatures were shown to be substantially affected by solar radiation. The above-top cooling method proved inadequate as it only slightly changed the air and plant temperatures even at night.

3. This experiment only focused on the short-term effects of zone cooling on the spatiotemporal temperature distribution. Further research is required, especially concerning the efficient base and top cooling methods in order to assess the long-term effects of such cooling methods on energy consumption and both qualitative and quantitative plant production to establish the practical utility of zone cooling systems.

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