Estimation of Photosynthesis Loss Due to Greenhouse Superstructures and Shade Nets: A Case Study with Paprika and Tomato Canopies

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Abstract. In horticultural greenhouses, the photosynthetic photon flux density (I) is inevitably lower than that outside because of interference from greenhouse superstructures (e.g., reflection and absorption of radiation by greenhouse coverings and superstructures). In addition, during hot seasons in many regions, I can be lowered by shade nets installed to reduce excessive radiation. These reductions in I can cause a decrease in the canopy photosynthetic rate (A_c), potentially leading to crop yield losses. This study investigated to what extent A_c is reduced inside a modern greenhouse and under a shade net in comparison with that outside. A simple A_c model (i.e., canopy-scale photosynthesis-light curves) was parameterized based on the measurements of A_c and I for paprika and tomato canopies using the open-chamber method. In addition, based on the measurements of I , linear regression models were derived that related outside I (I_{out}) with I inside arch-roofed, single-span greenhouses [enveloped with a diffuse ethylene tetrafluoroethylene (ETFE) film; I_{in}] and I under shade nets (composed of aluminum and polyester strips; I_{sh}). An A_c simulation using these models indicated that on a typical sunny summer day in Japan, A_c inside the greenhouses and under the shade nets ($A_{c,in}$ and $A_{c,sh}$, respectively) corresponded to 91% and 52% of A_c outside ($A_{c,out}$) for the paprika canopy (for the tomato canopy, $A_{c,in}$ and $A_{c,sh}$ corresponded to 90% and 48% of $A_{c,out}$, respectively). The simulated A_c loss was more serious on a cloudy day because of the linear A_c - I response under low I conditions ($A_{c,in}/A_{c,out}$ and $A_{c,sh}/A_{c,out}$ were 69% and 13%, respectively, for the paprika canopy). The loss of $A_{c,sh}$ may be alleviated by limiting the shading period to only midday hours.

In modern horticultural crop production, wherever root-zone environments are optimally managed, canopy photosynthesis

becomes the primary determinant of crop growth and yield, as suggested by numerous CO₂ enrichment experiments (Ainsworth and Long, 2005; Nomura et al., 2021b; Prior et al., 2011). Thus, farm managers and growers aim to optimize the canopy photosynthetic rate (A_c) through various means (e.g., by controlling the aboveground greenhouse environment and leaf area). To optimize A_c , it is important to have a reasonable estimate of A_c under a given environmental condition.

Sufficient photosynthetically active radiation (PAR ; radiation within a wavelength of 400–700 nm) is indispensable for canopy photosynthesis, as it drives the “light reaction,”

the first step in the photosynthetic reaction. However, in a greenhouse, incoming PAR can be quite different from the PAR outside, depending on the type of greenhouse cover (Baeza et al., 2020; Giacomelli and Roberts, 1993; Pearson et al., 1995). Depending on the transmissivity of the cover material, the photosynthetic photon flux density (PPFD; I) in the greenhouse can become considerably lower than that outside. In addition, some cover materials have diffusing properties, making incoming radiation more uniform (Hemming et al., 2008) and improving A_c (Li et al., 2014). Furthermore, greenhouse superstructures (e.g., ridges, trusses, and beams) can block and reduce the incoming PAR (Giacomelli and Roberts, 1993; von Elsner et al., 2000). These complicating factors and their interactions determine I inside a greenhouse.

In temperate and subtropical regions (e.g., many parts of Japan), incoming radiation can bring excessive energy into a greenhouse from late spring to early autumn. This radiation not only warms up the greenhouse but also reaches human workers, raising the apparent temperature (i.e., the temperature equivalent perceived by humans) to an unbearable point. To reduce such excessive radiation, modern greenhouses are often equipped with movable shade nets below the roofs (Castellano et al., 2008). These shade nets can be extended to cover the entire greenhouse area and create a shade, decreasing both the actual and apparent temperatures. Such shade treatment is expected to become more important in greenhouse horticulture, as global warming is rapidly progressing (Bisbis et al., 2019). An obvious drawback of these shade nets is the reduction in PAR and A_c (Hernández et al., 2015, 2019; Kitta and Katsoulas, 2020; López-Marín et al., 2012; Masabni et al., 2016). Because A_c is closely related to crop yield, inappropriate use of shade nets may result in reduced crop yield. In practice, however, shade nets are often used without considering their effects on A_c , and quantitative information on the loss of A_c due to shade-net operations is lacking.

The purpose of the present study was to assess to what extent the A_c of horticultural fruit vegetables is reduced due to greenhouse superstructures and shade nets in comparison with that outside. To achieve this objective, we first investigated the A_c of paprika (*Capsicum annuum* L.) and tomato (*Solanum lycopersicum* L.) canopies with the commonly used open-chamber method and then obtained model parameters for a simple empirical canopy photosynthesis model representing the response of A_c to I . Next, we measured I outside and inside greenhouses and under shade nets (I_{out} , I_{in} and I_{sh} , respectively) and derived regression models that related I_{out} with I_{in} and I_{sh} . The effects of shade nets on greenhouse air temperature were also evaluated. Finally, using the empirical model of the relationship between A_c and I , we evaluated the loss of A_c due to the greenhouse superstructures and shade nets.

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Materials and Methods

Greenhouse and experimental setup

All experiments were conducted in the Nankoku Field located at Monobe Campus, Kochi University (33°33'4"N, 133°40'37"E). Two identical, arch-roofed single-span greenhouses were used (Fig. 1). Each of the two greenhouses was 50 m long, 9 m wide, and 5.2 m high (at the center) and north-south oriented (i.e., the ridges of the greenhouses ran north-south). These two greenhouses were constructed side by side and were only 4.25 m away from each other. These greenhouses were enveloped with a diffuse ETFE film (F-CLEAN Diffused; AGC Green-Tech Co., Ltd., Tokyo, Japan). This covering material has high transmissivity for *PAR* with haze (i.e., a light-diffusing property) to improve canopy photosynthesis (hemispherical transmission = 0.81; Hemming et al., 2008). The covering material was less than 2 years old at the time of the experiment. The two greenhouses were equipped with movable shade nets (TEMPA 6562 D; Ludvig Svensson,

Kinna, Sweden) on the inside, ≈ 3 m above the ground. The shade nets are composed of aluminum and polyester strips (4 mm wide each) woven in a stripe pattern at a ratio of 5:3 (aluminum: polyester). According to the manufacturer's specifications, the transmissivities for direct and diffuse light are 35% and 32%, respectively. These shade nets can be extended/folded similarly to curtains with motors and can cover the entire ground area of each greenhouse. For ventilation and temperature control, each greenhouse was equipped with motor-operated top and side windows along the north-south direction; the top windows were 0.85 m wide and equipped on both sides of the roof ridge, and the side windows were 2.5 m high and equipped on the east and west sides of each greenhouse. During this study, the top and side windows were all fully open, and the window openings were covered with insect screens with the mesh size of 0.4 mm. The air inside each greenhouse was mixed using four 36-cm diameter electric fans (AB363NA; Fulta Electric Machinery Co., Ltd, Aichi, Japan)

installed at the beams. These fans were switched on and off at 10-min intervals.

Plant materials and cultivation conditions

Paprika and tomato canopies were cultivated hydroponically in each of the two greenhouses. In one greenhouse (Greenhouse 1), tomato plants (*S. lycopersicum* L., variety 'Momotaro Peace') were cultivated using the nutrient film technique (NFT) with a planting density of 1.9 plants/m² (180 cm between rows and 20 cm between plants within a row). These tomato plants were seeded on 28 July 2020, and transplanted to NFT panels on 6 Aug. 2020. The plants were pruned to a single shoot and led with support strings tied to one of two parallel wires 2.0 m above the ground. Once the plants reached the wire height, the plants were leaned forward and lowered by ≈ 50 cm by releasing the support strings from the wires. These actions of leaning and lowering move plants forward along the wire. Once a plant reached the edge of the row, the plant

Fig. 1. Experimental greenhouses. (A) Plan view of the two experimental greenhouses. (B) Frontal view of one of the greenhouses. The arrows over the shade nets indicate that these shade nets can be extended (closed) or folded (opened). The dotted lines at the side and top windows represent insect screens with a mesh size of 0.4 mm, whereas the broken lines at the side windows represent a windscreen with a mesh size of 6 mm. All lengths in the figures are in meters. (C) Photograph of the experimental greenhouses taken from the northwest side.

was turned back using the other wire. The leaves were pruned once all the fruits on the nearest upper truss were harvested. The tomato plants were supplied with the OAT SA nutrient solution (OAT Agrio Co., Ltd., Tokyo, Japan) with an electrical conductivity (EC) of $2.2 \text{ dS}\cdot\text{m}^{-1}$. The nutrient supply was switched on and off every 5 min to provide the plant roots with sufficient oxygen.

In the other greenhouse (Greenhouse 2), paprika plants (*C. annuum* L., variety 'Fairway') were cultivated on rockwool cubes with a planting density of 1.3 plants/m^2 (180 cm between rows and 30 cm between plants within a row). These paprika plants were seeded on 21 Aug. 2020, and transplanted onto the rockwool cubes on 10 Sept. 2020. The plants were pruned to two shoots, which were led with support strings tied to two parallel wires 2.0 m above the ground. Similar to the tomato canopy, a nutrient solution was prepared following the OAT SA prescription with an EC of $1.8 \text{ dS}\cdot\text{m}^{-1}$. This nutrient solution was supplied to the paprika plants intermittently every hour during the daytime and every 2 hours during the nighttime. Both the tomato and paprika cultivations ended on 8 July 2021.

Measurements

Canopy photosynthesis. The A_c of paprika and tomato canopies was measured to construct a model of canopy-scale photosynthetic responses to I . The measurements were performed according to the open-chamber method, which was modified from the method described by Nomura et al. (2020) (Fig. 2). Four open chambers, each being 1.2 m long, 1.2 m wide, and 2.4 m high, were

constructed; two chambers were used for the paprika canopy, and the other two chambers were used for the tomato canopy. Four individual paprika plants were enclosed per chamber, and seven individual tomato plants were enclosed per chamber. Each chamber was covered with F-CLEAN Clear (AGC Green-Tech Co., Ltd.). The measurements continued for 18 d, from 19 June to 6 July 2021. The leaf area index (LAI) of paprika and tomato canopies was estimated with an LAI-2200C (LI-COR Biosciences, Lincoln, NE) on 14 June 2021. The LAI values were 1.73 and 1.56 for the paprika and tomato canopies, respectively. I at the top of the canopies was measured with a PPFD sensor (PAR-02; PREDE, Tokyo, Japan) installed inside each chamber during the chamber applications. Ambient air was continuously introduced into each chamber with a blower (San Ace 9CRA0912P0G001; Sanyo Denki, Tokyo, Japan), and A_c ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ based on ground area) was calculated according to the difference in CO_2 concentrations (C_a) at the chamber inlet and outlet ($C_{a,\text{in}}$ and $C_{a,\text{out}}$, respectively) multiplied by the airflow rate (Q ; $\text{mol}\cdot\text{s}^{-1}$):

$$A_c = Q(C_{a,\text{in}} - C_{a,\text{out}})/S, \quad [1]$$

where S is the ground area. S was calculated as the plant row interval (1.8 m) multiplied by the chamber length (1.2 m) to include the aisle width in the calculation of S (i.e., $S = 2.16 \text{ m}^2$). Q was set to $45 \text{ m}^3\cdot\text{h}^{-1}$, which corresponded to $\approx 5 \text{ min}$ for the chamber air to be replaced entirely. In each greenhouse, $C_{a,\text{in}}$ and $C_{a,\text{out}}$ values, along with the water vapor concentrations at the inlet and outlet of

each chamber ($W_{a,\text{in}}$ and $W_{a,\text{out}}$), were measured with an infrared gas analyzer (LI850, LI-COR Biosciences), whose internal pump brought in the air at the two chambers' inlets and outlets sequentially at 1-min intervals. The air temperature (T_a) was also measured at the inlet and outlet of each chamber using T-type thermocouples. The atmospheric vapor pressure deficit (VPD) was computed based on the W_a and T_a values.

PPFD and other environmental elements. I was measured outside and inside greenhouses and under shade nets to evaluate radiation losses due to both the greenhouse superstructures and shade nets. A PPFD sensor (PAR-02) was installed in the northwestern part of each of the two greenhouses on top of a horizontal beam $\approx 2.5 \text{ m}$ above the ground (see Fig. 1A and B). This position was chosen to avoid shade created by the folded shade nets during periods of nonuse. The analog outputs from each PPFD sensor were recorded every 30 seconds using a datalogger (LR8431; Hioki E.E. Corporation, Nagano, Japan) and later averaged over 30 min. Another PPFD sensor (PAR-02) was installed in the middle of an open field, $\approx 100 \text{ m}$ away from the greenhouses. The analog outputs from this outside sensor were recorded every 2 min using a datalogger (MCR-4V; T&D, Nagano, Japan) and later averaged over 30 min. The measurements were conducted for 10 d in 2021: 17, 18, 22, 23, 24, 25, and 31 July, and 1, 7, and 8 Aug. During the experiment, one greenhouse was shaded with the shade net, while the other was unshaded, and the shaded and unshaded greenhouses were switched each day to

Fig. 2. Schematic view of the open-chamber system for measuring the net photosynthetic rates (A_c) of a crop canopy. A_c was estimated by multiplying the airflow rate with the difference in the CO_2 concentrations between inlet and outlet air. The inlet and outlet air was sampled sequentially through switchable air sampling paths, and the CO_2 concentrations were measured with an infrared gas analyzer. The infrared gas analyzer was connected to two chambers such that the A_c measurements were duplicated (only one chamber is shown in the figure).

prevent any biases associated with differences in the two greenhouses. This operation of the shade nets was performed after sunset. Linear regression coefficients relating I_{out} and I_{in} as well as I_{out} and I_{sh} were derived based on the I values obtained outside (I_{out}) and inside the greenhouses (I_{in}) and under the shade nets in the greenhouses (I_{sh}). In addition, each of the greenhouses was equipped with a set of environmental sensors (i.e., a pair of thermistors measuring dry- and wet-bulb temperatures and a CO₂ sensor; EyeFARM-box EB-500, Nippo, Saitama, Japan) in the center of the greenhouse.

Calculations

Canopy photosynthesis model. Based on the A_c and I measurements using the open chambers, light-photosynthetic response curves (A_c - I curves) at the canopy scale were obtained by fitting a nonrectangular hyperbola [Eq. (2)], which has been used to express light-photosynthetic response curves at the single-leaf scale (e.g., Hikosaka et al., 2016; Thornley, 2002) as

$$A_c = \frac{\phi I + A_{\text{max}} - \sqrt{(\phi I + A_{\text{max}})^2 - 4\phi I A_{\text{max}} \theta}}{2\theta} - R, \quad [2]$$

where A_{max} is the light-saturated canopy photosynthetic rate, ϕ is the initial slope of the A_c - I curve, θ is a convexity term, and R is the respiration rate in light. The values of A_{max} , ϕ , θ , and R were obtained by fitting Eq. [2] to the A_c - I relationships measured using the chamber system. This fitting was performed by minimizing the sum of squared errors between the measured and predicted A_c values using the Python lmfit package (version 1.0.1; Newville et al., 2014) based on the Levenberg-Marquardt method.

It should be noted that the use of the regression model [Eq. (2)] is not intended for constructing a predictive canopy photosynthesis model for use in other situations; we used the regression model to provide estimates of A_c based on our specific observations of A_c - I relationships. Thus, model parameters obtained through curve fitting will not be applicable to other cases if environmental conditions (e.g., temperature, humidity, and CO₂ concentration) and the canopy structure (e.g., LAI) are widely different.

Simulation of canopy photosynthesis. The effects of shade nets on A_c were evaluated quantitatively using Eq. [2] with a set of parameters obtained from the curve fittings. Daytime responses of A_c to I_{out} , I_{in} , and I_{sh} were simulated based on I_{out} values in typical sunny and cloudy days in the summer in Japan (i.e., I_{out} measured on 18 and 31 July 2021). In this simulation, I_{in} and I_{sh} were predicted based on the linear relationships between I_{out} and I_{in} and between I_{out} and I_{sh} , respectively.

Results and Discussion

Canopy photosynthetic rates

Figure 3 shows the changes in the A_c of the paprika canopy, along with the environmental

Fig. 3. Changes in the (A) photosynthetic photon flux density (PPFD; I), (B) CO₂ concentration (C_a), (C) air temperature (T_a), and (D) vapor pressure deficit (VPD) inside the chambers, and (E) canopy photosynthetic rate (A_c) of the paprika canopy. Measurements were duplicated using two open chambers.

elements measured inside the two chambers. During the daytime, I , T_a , and VPD increased, whereas C_a decreased due to photosynthetic CO₂ uptake by the canopy inside the greenhouse. The daytime averages of I , C_a , T_a , and VPD in one of the two chambers (Chamber 1

in Fig. 3) were 273 ± 269 ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), 437 ± 54 ($\mu\text{mol}\cdot\text{mol}^{-1}$), 35 ± 5 ($^{\circ}\text{C}$), and 2.08 ± 1.0 (kPa), respectively (the values after the plus-minus signs represent the standard deviations). As shown in Fig. 3, there were no considerable differences between the environments

Fig. 4. Changes in the (A) photosynthetic photon flux density (PPFD; I), (B) CO₂ concentration (C_a), (C) air temperature (T_a), and (D) vapor pressure deficit (VPD) inside the chambers, and (E) canopy photosynthetic rate (A_c) of the tomato canopy. Measurements were duplicated using two open chambers.

Fig. 5. Relationships between the canopy photosynthetic rate (A_c) and photosynthetic photon flux density (PPFD; I) measured for (A) paprika and (B) tomato canopies. For each fruit vegetable, measurements were duplicated in two different canopies using two open chambers (the circles and triangles indicate the different canopies). The curves (solid lines) were obtained by fitting Eq. [2] to the observations. The measurements were conducted from 19 June to 6 July 2021.

in the duplicated chambers. As a result of these diurnal changes in the environmental conditions, A_c changed dynamically during the daytime. The tomato canopy inside the chambers had environmental conditions similar to those of the paprika canopy (Fig. 4); the daytime averages of I , C_a , T_a , and VPD in one of the chambers (Chamber 1 in Fig. 4) were 316 ± 307 ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), 428 ± 27 ($\mu\text{mol}\cdot\text{mol}^{-1}$), 35 ± 5 ($^{\circ}\text{C}$), and 2.3 ± 1.1 (kPa), respectively.

Figure 5 shows the A_c - I curves for the paprika and tomato canopies. The A_c - I curves for both species showed the typical shape of photosynthetic nonlinear rectangular hyperbolae represented by Eq. [2]. The duplicate measurements in each canopy provided almost identical results (i.e., in Fig. 5A and B, the circle and triangle markers indistinguishably overlap), suggesting homogeneity in the paprika and tomato canopies. A_c increased almost linearly with I up to $I = 450$ $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and then showed signs of light saturation. This response of A_c to I can be explained by two distinct limiting processes, namely, the regeneration and carboxylation of ribulose-1,5-bisphosphate (RuBP) (Farquhar et al., 1980). The linear increase in A_c in the low I region indicates that the

photosynthetic process was limited by RuBP regeneration, which ultimately depends on incoming I . In contrast, the apparent saturation of A_c in the high- I region indicates that the photosynthetic process was limited by RuBP carboxylation, which depends mainly on the CO_2 concentration. During the experiment, the average daytime $C_{a,\text{in}}$ value was ≈ 430 $\mu\text{mol}\cdot\text{mol}^{-1}$, which is within the normal CO_2 concentration range observed in a greenhouse. If the CO_2 concentration was artificially elevated, the saturating I would have been higher than 450 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ because a higher CO_2 concentration alleviates the CO_2 limitation of A_c that occurs under high I conditions (Stitt, 1991). However, it should be noted that A_c continued to increase slightly even over $I = 450$ $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. This slight increase in A_c can be attributed to the lower leaves in the canopy, which are not light saturated due to the shading of the upper leaves (Nomura et al., 2021b). With an increase in I at the top of the canopy, these lower leaves could have received stronger I and increased the A_c .

During the experiment, the average daytime temperature inside the chambers was ≈ 35 $^{\circ}\text{C}$ and sometimes exceeded 40 $^{\circ}\text{C}$, with

a maximum of ≈ 45 $^{\circ}\text{C}$ (see Figs. 3 and 4). Such high temperatures, however, did not cause any explicit A_c drops, which occur at the molecular and single-leaf scales (Mathur et al., 2014; Medlyn et al., 2002; Wise et al., 2004).

Table 1 summarizes the parameter values of the nonrectangular hyperbola [Eq. (2)] obtained by least-square fitting to the measured A_c - I curves for the paprika and tomato canopies shown in Fig. 5. The estimated standard errors of the model parameters were small compared with the best-fit parameters (the standard error/best-fit parameter was less than 3.2%), indicating that the model parameters were identified well. The optimized parameters slightly differed between the two species, which can be attributed to differences in 1) the photosynthetic properties of individual leaves in each canopy [e.g., different leaf-scale parameters such as V_{cmax} and J_{max} (Farquhar et al., 1980; von Caemmerer, 2000)]; 2) the distributions of photosynthetic properties within each canopy (Hirose and Werger, 1987); and 3) canopy structure, including the LAI, leaf angle distribution, and leaf clumping (Chen et al., 2012; Lawlor, 1995; Wang et al., 2007).

Effects of the greenhouse superstructures and shade nets on incoming PPFD

Figure 6 shows daily changes in I_{out} , I_{in} , and I_{sh} . I_{out} underwent diurnal changes caused by the movement of the sun and clouds. The first 2 d of the experimental period (17 and 18 July) were cloudy and rainy, but the other days were largely sunny. I_{out} reached a maximum value of 2400 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ around noon on 7 Aug.

In comparison with I_{out} , I_{in} was much smaller. This reduction in I_{in} was partly due to the reflection and absorption of the incoming PAR by the cover material. In addition, I_{in} was reduced because of interceptions by the greenhouse structural elements (e.g., the ridges, trusses, and folded shade nets), which prevented some of the PAR transmitted by the cover from reaching the PPFD sensor (Matsuda et al., 2020). Because the cover material has a diffusing property that scatters photon flux in various directions, any greenhouse structures above the PPFD sensor could have reduced I_{in} , even if these structures did not occur along the straight line between the sun and the PPFD sensor. I_{in} showed a strong linear relationship ($R^2 = 0.95$) with I_{out} (Fig. 7). This strong linear relationship also may be attributed to the diffusing property of the cover material, which caused the incoming photon flux to be largely uniform. The regression coefficient (i.e., slope) between I_{in} and I_{out} was 0.61, indicating that I was reduced by almost 40% due to the greenhouse cover and structures. This $I_{\text{in}}/I_{\text{out}}$ value (0.61) is substantially lower than a laboratory-measured transmissivity value of 0.81 (hemispherical transmission; Hemming et al., 2008). These results indicate that a considerable amount of incoming PAR was

Table 1. Parameter values of the nonrectangular hyperbola [Eq. (2)] obtained by least-square fitting to the measured A_c - I curves for the paprika and tomato canopies (Fig. 5). The estimates of the standard errors of the parameters are also shown after the plus-minus signs.

Parameter	Paprika	Tomato
A_{max} ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	19.4 ± 0.26	21.8 ± 0.30
θ (—)	0.91 ± 0.013	0.86 ± 0.018
Φ (—)	0.048 ± 0.001	0.051 ± 0.001
R ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	1.56 ± 0.050	1.73 ± 0.048

Fig. 6. Daily changes in the photosynthetic photon flux density (PPFD; I) measured outside (I_{out} ; solid line) and inside the greenhouses (I_{in} ; broken line) and under the shade nets in the greenhouses (I_{sh} ; dotted line). The measurements were conducted during four periods between 17 July and 8 Aug. 2021; these periods are separated in the figure by the solid vertical lines. The gray-shaded regions indicate nighttime. Thirty-minute averages are shown.

Fig. 7. Relationships between the photosynthetic photon flux density (PPFD; I) measured outside the greenhouses (I_{out}), inside both greenhouses (I_{in}) and under the shade nets in the greenhouses (I_{sh}). These relationships were obtained based on the 30-min average values. The regression lines were drawn with forced zero intercepts. A 1:1 line is displayed for reference.

blocked by the greenhouse superstructures. In addition, it is possible that the transmission of the cover material was reduced by tiny particles (e.g., dust) attached to the cover material. The value of 0.61 was consistent with that found in a previous study (Giacomelli and Roberts, 1993) reporting the average daily transmission of PAR measured inside greenhouses with four different covering materials (i.e., single-layer glass, acrylic, double-layer glass, and double-layer polyethylene, whose transmissions were 0.56, 0.55, 0.56, and 0.45, respectively, near the plant canopy).

The shade nets further reduced the incoming I ; I_{sh} was only 19% of I_{out} (Fig. 7) and had a strong linear relationship with I_{out} ($R^2 = 0.96$). This strong linear relationship can be used to predict the amount of I_{sh} based on I_{out} in this specific setting. I_{sh} was also linearly correlated with I_{in} ; I_{sh} was only 31% of I_{in} (not shown in the figures). This value was consistent with the manufacturer's specifications, in which the transmissivities for direct light and diffuse light were 35% and 32%, respectively.

Effects of the shade nets on the greenhouse temperature

Figure 8A shows the daily changes in the temperature (T) measured outside the greenhouses (T_{out}) and inside the greenhouses without (T_{in}) and with the shade nets (T_{sh}). A clear diurnal pattern in T was found; upon sunrise, T_{out} , T_{in} , and T_{sh} began to steeply increase from $\approx 23^\circ\text{C}$ to more than 30°C during the midday hours (i.e., between 1000 and 1500 hr) and then gradually decreased until the next sunrise. Throughout the experimental period, T showed an overall increasing trend.

Figure 8B shows the differences in T inside and outside the greenhouses. Both $T_{in} - T_{out}$ and $T_{sh} - T_{out}$ were positive during the daytime, indicating that the air inside the greenhouses was warmer than the outside air.

Fig. 8. (A) Daily changes in temperature (T) measured outside (T_{out} ; solid line) and inside the greenhouses (T_{in} ; broken line) and under the shade nets in the greenhouses (T_{sh} ; dotted line). (B) Increases in T inside the greenhouses in comparison with the outside T (i.e., $T_{in} - T_{out}$ and $T_{sh} - T_{out}$ for greenhouses with the shade nets and without the shade nets, respectively). (C) Differences in T with and without the shade nets ($T_{in} - T_{sh}$). The measurements were performed during four periods between 17 July and 8 Aug. 2021; these periods are separated in the figure by the solid vertical lines. The gray-shaded regions indicate nighttime.

During the midday hours, the average difference in T outside and inside the greenhouses without shade nets ($T_{in} - T_{out}$) was 2.0°C , with a maximum value of 3.5°C . With the application of shade nets, the midday average difference in T ($T_{sh} - T_{out}$) was reduced to 1.0°C , with a maximum value of 2.6°C , indicating an air-cooling effect of the shade nets.

Figure 8C shows the differences in T inside the greenhouses with and without shade nets (i.e., $T_{in} - T_{sh}$). During the midday hours, $T_{in} - T_{sh}$ was almost always positive, with an average value of 0.98°C , indicating that the greenhouse air without shade nets was nearly 1°C higher than that when shade nets were present. This temperature reduction by the shade nets was caused by the improvement of greenhouse heat balance due to the reduction in incoming solar radiation, as indicated in Fig. 7, which shows that incoming solar radiation energy can be reduced by 81% when the shade nets are used (assuming that I is proportional to the energy flux density in $\text{W}\cdot\text{m}^{-2}$).

Because incoming solar radiation is the dominant heat source warming the greenhouse air during the summer (Kittas et al., 2005), such a considerable reduction in radiation by shade nets can contribute to a reduction in T . In addition, such a reduction in solar radiation by the shade nets would cause a reduction in the apparent T (i.e., the temperature equivalent perceived by humans) experienced by workers inside the greenhouse. In contrast to the positive daytime $T_{in} - T_{sh}$, the nighttime $T_{in} - T_{sh}$ was negative (i.e., the air temperature was higher when the shade nets were present than when they were absent), indicating that the shade nets trap longwave radiation from the ground below. This warming effect of shade nets can help maintain a higher nighttime T in the winter (Ahemd et al., 2016).

Effects of greenhouse superstructures and shade nets on canopy photosynthesis

Using Eq. [2] and the parameters obtained from the least-square curve fitting, we estimated

Table 2. Effects of the greenhouse superstructures and shade nets on the photosynthetic photon flux density (PPFD; I) and canopy photosynthetic rates (A_c) simulated using Eq. [2] and parameters for the paprika and tomato canopies on a sunny day. Cumulative values of I and A_c during the daytime are shown in $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ (middle columns), and these values were compared as proportions (right columns). I values measured outside on 31 July 2021 were used as the inputs.

	Simulated value ($\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)			Proportion		
	Outside	Inside	Shaded	Inside/outside	Shaded/outside	Shaded/inside
I	58.3	35.6	11.1	0.61	0.19	0.31
A_c (paprika)	0.728	0.666	0.376	0.91	0.52	0.57
A_c (tomato)	0.790	0.710	0.379	0.90	0.48	0.53

Table 3. Effects of the greenhouse superstructures and shade nets on I and A_c simulated for a cloudy day. I values measured outside on 18 July 2021 were used as the inputs. The other simulation conditions were the same as those for Table 2.

	Simulated value ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)			Proportion		
	Outside	Inside	Shaded	Inside/outside	Shaded/outside	Shaded/inside
I	16.5	10.0	3.1	0.61	0.19	0.31
A_c (paprika)	0.485	0.334	0.065	0.69	0.13	0.20
A_c (tomato)	0.499	0.337	0.063	0.68	0.13	0.19

to what extent A_c would be reduced due to the greenhouse superstructures and shade nets on typical sunny and cloudy summer days (Tables 2 and 3, respectively). As shown in Fig. 9 (i.e., a simulation on the sunny day), the effects of the greenhouse superstructures and shade nets on I were remarkable; only 61% and 19% of I_{out} was measured below the greenhouse superstructures and shade nets, respectively (Table 2). However, as shown in Fig. 9B for the paprika canopy, the simulated effects of the greenhouse superstructures and shade nets on A_c were much milder on a sunny summer day (31 July 2021); A_c in the greenhouse ($A_{c,\text{in}}$) and under the shade nets ($A_{c,\text{sh}}$) corresponded to 91% and 52% of the outside A_c ($A_{c,\text{out}}$), respectively (for the tomato canopy, $A_{c,\text{in}}$ and $A_{c,\text{sh}}$ corresponded to 90% and 48% of $A_{c,\text{out}}$; see Table 2). These results were attributed to the saturating A_c - I responses (Fig. 5), in which A_c was saturating over $I = 450 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. In comparison with this threshold value, I_{out} is almost always excessive on a typical sunny summer day in Japan except in the very early morning and evening. Because of this saturating nature of photosynthesis, the 39% reduction in I by the greenhouse superstructures caused only an $\approx 9\%$ reduction in A_c . However, the reduction in A_c caused by the shade nets was not

marginal; for the paprika and tomato canopies, $A_{c,\text{sh}}$ was only $\approx 57\%$ and 53% of $A_{c,\text{in}}$, respectively (Table 2).

Compared with the high I conditions simulated in Fig. 9 and Table 2, the loss of A_c due to greenhouse superstructures and shade nets is more serious under low I conditions. $A_{c,\text{in}}/A_{c,\text{out}}$ simulated on a cloudy day (18 July 2021, see Fig. 6) was only 69% for the paprika canopy (Table 3). This value was much lower than that for the sunny day (i.e., 91%). The lower value of $A_{c,\text{in}}/A_{c,\text{out}}$ on a cloudy day (i.e., low I) is not surprising, as A_c is sensitive to I under low I conditions (i.e., A_c responds to I linearly under low I conditions; see Fig. 5). Thus, the negative effect of greenhouse superstructures on A_c would be more considerable in winter, where I tends to be much lower than that in summer (Marcelis et al., 2006). The application of the shade nets can further reduce A_c ; on the cloudy day, $A_{c,\text{sh}}/A_{c,\text{out}}$ was simulated to be only 13% for both the paprika and tomato canopies (Table 3).

A good strategy for using shade nets is to use them only during the high I period (Klärning and Krumbein, 2013). For example, if the usage of the shade nets was limited to 0800 until 1600 HR, $A_{c,\text{sh}}$ could reach 76% and 71% of $A_{c,\text{in}}$ for the paprika and tomato canopies on a sunny day (data not shown). Such a limitation of shade net usage needs to be considered together with the working environment of human workers, because working in a hot greenhouse environment is a demanding and often dangerous task. To optimize the use of shade nets, future research should involve a more sophisticated analysis integrating detailed models that can estimate the temperature effects on A_c (e.g., Nomura et al., 2021a) and physics-based greenhouse climate models (Sethi et al., 2013) that can simulate the dynamic change in temperature in the presence and absence of shade nets.

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Fig. 9. Simulation of typical diurnal responses of canopy photosynthetic rates (A_c) to photosynthetic photon flux density (PPFD; I). I inside a greenhouse and under a shade net was estimated from outside I measured on 31 July 2021, using the linear regression equations shown in Fig. 7. With these I values as the inputs, A_c was estimated using Eq. [2] with the parameters obtained for the paprika canopy (Table 1).

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