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Continuous Measurement of Greenhouse Ventilation Rate in Summer and Autumn via Heat and Water Vapor Balance Methods

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Continuous monitoring of canopy photosynthetic rates in a naturally ventilated greenhouse requires a method of measuring ventilation rates that can record accurate short-term responses throughout the day. It is necessary to clarify the difference between the accuracy and operability of ventilation rate methods. This study evaluated the diurnal-change of ventilation rate measured by the heat balance (HB) and water vapor balance (WVB) methods in the summer and early autumn seasons and compared two methods with the tracer gas (TG) method as a reference. The ventilation rate was determined in a single-span type experimental greenhouse with mature-stage tomato crops under different ventilator configurations to assess the accuracy of the above two methods. The ventilation rates measured via the HB and WVB methods were slightly lower than that measured by the TG method in the greenhouse without crops. However, the ventilation rates obtained using both methods exhibited similar variation trends with time. It is difficult to maintain high concentrations of TG in a greenhouse with a large ventilation opening area. However, it was easy to continuously measure the ventilation rate even in such a greenhouse using the HB and WVB methods. Practically, the WVB system is simpler than the HB method, which utilizes numerous sensors.

Keywords : CO_2 balance, naturally ventilated greenhouse, photosynthetic rate, air exchange rate

INTRODUCTION

One of the methods of increasing tomato production and quality in a greenhouse is to manage the CO_2 concentration at or above the ambient level for supporting photosynthesis. CO_2 fertilization enables plants to assimilate CO_2 gas with high efficiency (Kuroyanagi et al., 2014) and increases fruit yield (Kimball and Mitchell, 1979; Yelle et al., 1990). Attention has also been focused on a method of applying CO_2 to a similar level as the outside air in the greenhouse during the daytime in summer or autumn when the windows are sufficiently opened for temperature control (Ohyama et al., 2005). Furthermore, the continuous measurement of the greenhouse ventilation rate throughout the year allows for the long-term direct monitoring of the canopy photosynthetic rate and CO_2 use efficiency using the CO_2 balance method (Nederhoff and Vegter, 1994).

The ventilation rate is a crucial parameter for heat and gas exchanges in a greenhouse. Ventilation regulates the air temperature and humidity in the greenhouse. Additionally, it influences CO_2 concentration, which affects the canopy photosynthetic rate. Various techniques have been used to measure and predict the ventilation rate, such as the tracer gas (TG) method (Boulard and Draoui, 1995; Papadakis et al., 1996; Baptista et al., 1999), heat balance (HB) method (Fernandez and Bailey, 1992; Demrati et al., 2001; Harmanto et al., 2006a), and water vapor balance (WVB) method (Boulard and Draoui, 1995; Harmanto et al., 2006a, 2006b). The TG method has been widely used in greenhouse experiments. The ventilation rate measurement by the TG method is highly reliable in leakage and low ventilation conditions for different types of greenhouse and ventilation configurations (Nederhoff et al., 1985; Baptista et al., 1999; Muñoz et al., 1999; Katsoulas et al., 2006). The TG method exhibits good agreement with an infrared gas analyzer (IRGA), as mentioned by Nederhoff et al. (1985), and with a theoretical model based on pressure difference (Baptista et al., 1999) and wind pressure model approaches (Muñoz et al., 1999).

However, in the summer season with the maximum ventilation opening area, the TG method experiences numerous disadvantages in large-scale greenhouses (Demrati et al., 2001). A large amount of CO_2 gas must be supplied to maintain the CO_2 concentration in a greenhouse higher than outside air for a large window aperture. Moreover, this method is expensive, and the long-term continuous measurement of the ventilation rate is extremely difficult under plant cultivation, where CO_2 gas is absorbed. Hence, it may not be possible to use this technique for the continuous monitoring of the ventilation rate in summer and autumn season when windows are fully

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opening during the daytime.

There are two alternative methods of predicting the ventilation rate, i.e., the HB (Fernandez and Bailey, 1992; Katsoulas et al., 2006; Yasutake et al., 2017) and WVB techniques (Boulard and Draoui, 1995; Kittas et al., 2002; Mashonjowa et al., 2010). The ventilation rates predicted using the heat balance model showed good agreement with measured values using the TG method for large ventilation opening areas (Fernandez and Bailey, 1992; Baptista et al., 2001). However, there is a problem when the ventilation opening area is small (Yasutake et al., 2017). On the contrary, the WVB method provides better accuracy in estimating the ventilation rate for mature plants under small ventilation opening areas (Boulard and Draoui, 1995; Harmanto et al., 2006b). Most of the authors performed at low ventilation (i.e., with 10% of window aperture or below 20 h^{-1} of the air exchange rate) for the multi-span greenhouse (Boulard and Draoui, 1995; Kittas et al., 2002; Mashonjowa et al., 2010). Harmanto et al. (2006b) calculated the ventilation rate using the WVB method under various screen mesh size on the wall of the greenhouse with three times measurement of water vapor from the crops every day. However, few studies have investigated the ventilation rate performance using the WVB method at moderate and maximum window openings, especially in a single-span type greenhouse. Therefore, the accuracy of estimating the ventilation rate using the WVB method for large ventilation opening areas must be examined in detail. As described above, the accuracy of the ventilation rate measurement of the naturally ventilated greenhouse by the HB and WVB method has not been sufficiently verified by the influence of the window opening area. However, both methods are more suitable than the TG method for long-term continuous measurement of the ventilation rate of a cultivated greenhouse with large opening windows.

The purpose of this research is to clarify the validity of the HB method and the WVB method as the measuring method of the ventilation rate, which is required for continuous monitoring of the canopy photosynthetic rate in a naturally ventilated greenhouse during the cultivation period. First, we measured the ventilation rate via the TG method using CO_2 as a standard reference at various window apertures with no crop cultivation. Next, we evaluated the diurnal change of ventilation rate measured by the HB method and WVB method under the greenhouse mentioned above with cultivating plants and compared it with the value of the TG method.

MATERIALS AND METHODS

Greenhouse experiment set up

An experiment was performed in a single-span greenhouse at a research field site of the Faculty of Applied Biological Sciences, Gifu University, Japan. The greenhouse was fabricated from glass (glasshouse) with dimensions of 3.25 m in width×5.00 m in length×2.80 m in height. It had a supported roof and double-flap side vents, which were covered with screen-net materials (pore size of 0.4 mm and porosity of 52.2%). The experiment was performed for different values of the ventilation opening area, which was expressed in terms of the *W* value in percentage. The *W* value was calculated based on the ratio of the total ventilation opening area to the greenhouse floor area (Eq. 1). In this experiment, the *W* value was obtained under moderate and maximum ventilation as 16%, 20%, 24%, and 40% in the summer and early autumn seasons. The ventilation rate was measured under constant of the *W* value on the day experiment.

$$W = \frac{\textit{Total window opening area}\ (\mathrm{m}^2)}{\textit{Greenhouse floor area}\ (\mathrm{m}^2)} \times 100\ (\%) \quad (1)$$

The greenhouse was occupied by mature fruiting tomato crops (*Solanum lycopersicum* L.,variety 'Momotaro'), which were cultivated on 14 modified Wagner pots with a volume of 10 L (one plant per pot). The pots were filled with light sandstones (diameters ranging from 1 to 5 mm) and supplied with hydroponic nutrient solutions (electrical conductivity, EC = 1 dS m^{-1}, and pH = 5.5–6.5) in the lower part of the pot system with a maximum water level of 10 cm (capillary irrigation system). The growing medium in the pot system was covered with plastic mulch. During the measurement periods in summer 2018 and early autumn 2019, the average height of tomato plants was approximately 1.6 m, and the leaf area index of the crop was approximately 3.8 m^2 m^{-2}. The plants were placed 0.45 m apart in double rows, with an inter-row distance of 0.80 m.

The following climatic data were recorded: air temperature inside and outside (dry and wet bulb temperatures) the greenhouse, solar radiation inside and outside the greenhouse, and wind velocity outside the greenhouse. Figure 1a shows the location of instrumentation sensors in the greenhouse. Air temperature (dry and wet bulb temperatures) was measured by two aspirated psychrometers using T-type thermocouple (copper/constantan) sensors. The psychrometers were set up at heights of 0.5 m and 2.0 m above the floor at the center of the greenhouse. The aforementioned data were recorded in a data logger (CR1000, Campbell Scientific, Inc., USA) every minute. Then, the ventilation rate was calculated based on the average data for 15 minutes over a long period (from 8:00 AM to 4:00 PM).

Determination of the ventilation rate

The air exchange rate, or ventilation rate, in the naturally ventilated greenhouse was estimated using two approaches, namely, the WVB and HB methods.

Only the water vapor that originated from the crop transpiration in the growth process was considered, and the evaporation from the pot medium and greenhouse floor were neglected because they were covered with plastic mulch. The assumption had been made that water vapor transpired from each plant was uniform for all points in the greenhouse, and the amount of water to be evaporated should be equivalent to the amount of water vapor removed by ventilation. Thus, a steady-state condition was assumed in the greenhouse because the changes in the amount of water vapor in a short period of time were small. The crop transpiration rate was directly measured by

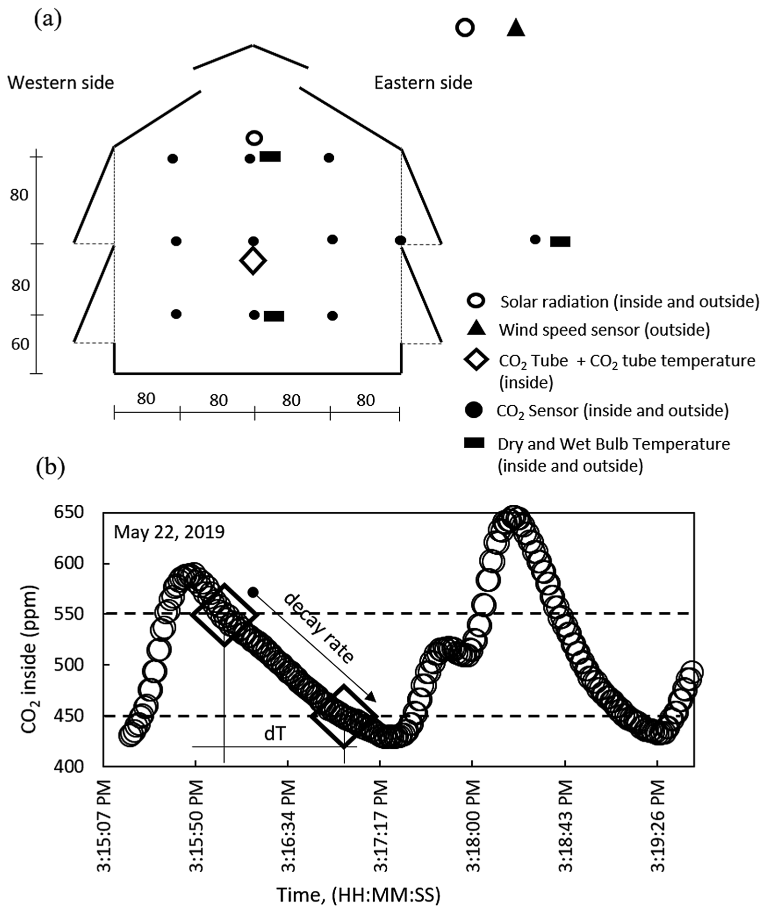

Fig. 1 Schematic of cross-sectional views, ventilator, and locations of instrumentation in the experimental greenhouse. (a) Location of all sensors: dry and wet bulb temperatures (inside and outside), CO_2 (inside and outside), CO_2 tube temperature, solar radiation (inside and outside), and wind speed (outside). All dimensions are in cm. (b) Ventilation rates measured using the tracer gas technique. The decay rate method is used with CO_2 concentration maintained between 450–550 ppm without crops. dT: time length of decay rate.

employing two stem heat balance sensors (Model SGA13-WS, Dynamax Inc., USA). Then, the average estimated evapotranspiration was converted to a unit land area basis by multiplying it with the number of plants and adding a plant coverage factor to the total greenhouse floor area (Eq. 2). The plant coverage factor was measured from the real horizontal projection of the canopy, as performed by Gerson et al. (2001). The following equation was used to calculate the ventilation rate using the WVB method:

$$G_{\mathrm{WVB}} = \frac{nE}{A_{\mathrm{f}}F_{\mathrm{ca}}[AH_{\mathrm{in}}-AH_{\mathrm{out}}]\times 60} \quad (2)$$

where G_{WVB} is the measured ventilation rate per unit floor area of the greenhouse over a period [$\mathrm{m^3\ m^{-2}\ min^{-1}}$]; n is the total number of plants; E is the measured transpiration per plant [$\mathrm{g\ h^{-1}}$]; A_{f} is the greenhouse floor area [$\mathrm{m^2}$]; F_{ca} is the ratio of the total plant coverage area to the greenhouse floor area; and $AH_{\mathrm{in}}-AH_{\mathrm{out}}$ [$\mathrm{g\ m^{-3}}$] is difference between the absolute humidity inside and outside the greenhouse over a period.

In the HB method, it is considered that ventilation removes energy from a greenhouse and prevents excessively high temperatures. The HB method assumes a steady-state condition and uses the principle of energy conservation, i.e., heat gains are equal to heat losses inside and outside a greenhouse. No heating is used, and the energy removed by leakage (under the closed vents condition) and ventilation (Q_{v}) is equal to the net solar radiation collected in the greenhouse (Q_{Rn}) minus the energy stored in soil (Q_{s}), and the thermal losses through the cover (Q_{c}). The energy stored in soil was measured every minute by a soil heat flux sensor that was placed 10 mm below the ground surface. The equations for the static energy balance of a naturally ventilated greenhouse have the following general form:

$$Q_{\mathrm{v}} = Q_{\mathrm{Rn}} - Q_{\mathrm{s}} - Q_{\mathrm{c}} \quad (3)$$

$$Q_{\mathrm{Rn}} = (1-\alpha)\tau R_{\mathrm{so}} - \sigma T_{\mathrm{in}}^{4}(\varepsilon_{\mathrm{a}} - \varepsilon_{\mathrm{c}}) \quad (4)$$

$$Q_{\mathrm{c}} = k(T_{\mathrm{in}} - T_{\mathrm{out}})\frac{A_{\mathrm{c}}}{A_{\mathrm{f}}} \quad (5)$$

$$G_{\mathrm{HB}} = \frac{Q_{\mathrm{V}}}{[c_{\mathrm{p}}\cdot\rho_{\mathrm{a}}\cdot(T_{\mathrm{in}}-T_{\mathrm{out}})+L_{\mathrm{v}}\cdot(AH_{\mathrm{in}}-AH_{\mathrm{out}})]}\times 60 \quad (6)$$

where G_{HB} is the measured ventilation rate per unit floor area over a period [$\mathrm{m^3\ m^{-2}\ min^{-1}}$]. Q_{Rn} is the average incoming net solar radiation inside the greenhouse during the day [W m^{-2}]. It is calculated based on the total solar radiation (R_{so}) outside the greenhouse, with α as the ground surface albedo. τ is the coefficient of solar radiation transmittance of the glazing material (dimensionless), σ is the Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), and ε_a and ε_c are atmospheric air emissivity and crop emissivity, respectively. ε_a was computed using the model developed by Idso (1981), and ε_c for tomato crop was used as Pieters and Deltour (1997). Q_s is the soil heat flux [W m^{-2}]; Q_c is the heat transfer through the greenhouse cover; and Q_v is the heat removed via ventilation [W m^{-2}]. k is the heat transmittance coefficient of the greenhouse cover [W m^{-2} K^{-1}]; in this experiment, the value of k was 6.0 W m^{-2} K^{-1} for single glass. A_c is the covered area of the greenhouse [m^2]; c_p is the specific heat capacity of air [J kg^{-1} K^{-1}]; ρ_a is the specific mass of air [kg m^{-3}]; T_{in}–T_{out} is the difference between the air temperature inside and outside the greenhouse [K]; and L_v is the latent heat of vaporization [J kg^{-1}]. The value of 60 is introduced as a factor to convert the unit of time from seconds to minutes.

Prediction of ventilation rate

Table 1 shows the periods and window apertures for which the ventilation rate was measured in the summer and early autumn seasons using the WVB and HB methods. Furthermore, the ventilation rate was measured via the TG technique in the same greenhouse without crops in April and May 2019. An equation was made from the window aperture and the ventilation rate with simple linear regression, and then, the predicted ventilation rates were compared and validated using it.

The ventilation rate was obtained using the WVB and HB method every minute and then averaged over an interval of 15 minutes. The ventilation rate was measured using the TG technique every second and then averaged over an interval of 15 minutes. The ventilation rate measurement using the TG method with CO_2 gas was conducted based on the method proposed by Nederhoff et al. (1985); however, the CO_2 concentration was modified. In the experiment, nine CO_2 sensors (Model K30, Senseair Co., Sweden) were installed inside the greenhouse, one on the side vents, and one outside the greenhouse (Fig. 1a). CO_2 gas was injected into the greenhouse until a concentration of 550 ppm was reached, and then, the supply was stopped. As a result of an exchange with outside air, the CO_2 concentration in the greenhouse decreased with a rate proportional to the difference between the CO_2 concentration inside and outside the greenhouse. When the CO_2 concentration decreased to 450 ppm, CO_2 was injected again to increase the concentration to 550 ppm (Fig. 1b). The ventilation rate obtained using the TG technique (G_{TG}) is given by the following equations:

$$N_{TG} = \frac{3600}{t_1} \ln\left[\frac{C_{in}(t_0) - C_{out}}{C_{in}(t_1) - C_{out}}\right] \qquad (7)$$

$$G_{TG} = \frac{1}{60}\,\frac{N_{TG} V_g}{A_f} \qquad (8)$$

where $C_{in}(t_0)$ is the initial CO_2 concentration at $t = 0$, $C_{in}(t_1)$ is the CO_2 concentration measured at $t = t_1$, and V_g is the greenhouse volume (m^3). The value of 3,600 is introduced as a factor because the greenhouse air exchange rate (N_{TG}) is expressed as times per hour of greenhouse volume exchange (expressed in h^{-1}) and t is in seconds. The greenhouse air exchange rate per hour (N_{TG}) can be converted to the ventilation rate, G_{TG} (m^3 m^{-2} min^{-1}), using Eq. 8.

Table 1 Ventilation rates observed in different seasons.

Season	Date of experiments	W (%)
Summer	July 10–11, 2018	16%
	July 19–20, 2018	20%
	July 22–23, 2018	24%
Autumn	September 16, 17, 19, and 25, 2019	40%

RESULTS AND DISCUSSION

Figure 2 shows the relationship between G_{TG} and W in the greenhouse without crops, and the linear regression equation with W as an independent variable is as follows:

$$G_{TG} = 0.132\times W + G_0 \qquad (9)$$

with a coefficient of determination $R^2 = 0.83$ (P-value = 2.2×10^{-16}).

The G_{TG} at leakage condition, G_0 ($W = 0\%$) was 0.052 m^3 m^{-2} min^{-1} (N_{TG}: 1.3 h^{-1}). The maximum of N_{TG} was 140 h^{-1} when W was 40%. Simultaneously, the range of variation in the measured ventilation rate also increased with W. This was probably because the effect of outside wind on the ventilation rate became stronger as the window aperture increased. During the experimental period, the average wind speed outside the greenhouse was 0.9 m s^{-1} (0–3.1 m s^{-1}), and the average CO_2 concentrations inside and outside the greenhouse were 514 and 393 ppm, respectively (Table 2). Equation (9) and Fig. 2 could be used as a reference for validating the ventilation rate predicted using the HB and WVB methods.

Figure 3 illustrates the ventilation rate (G) for differ-

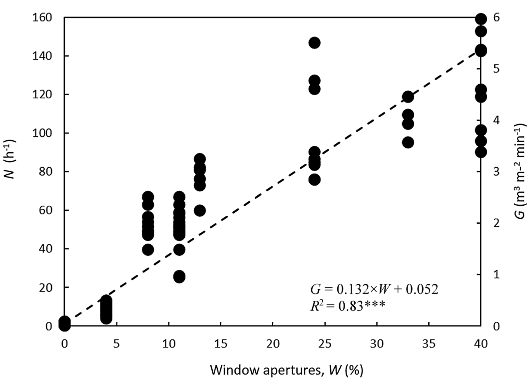

Fig. 2 Ventilation rates measured using tracer gas technique without crops on several days (April 27 and May 2, 5, 8, and 22, 2019). Data are averaged every 15 minutes. 4–18 data measurements (N) are obtained for each window aperture (total of 84 observations). ***$P = 2.2\times10^{-16} < 0.01$.

Table 2 Climatic conditions during observation of ventilation rate using tracer gas (no crops)[a].

W	Q_{Rn}	v	$(T_{in}-T_{out})$	VPD	CO_{2in}	CO_{2out}
%	W m^{-2}	m s^{-1}	℃	kPa	ppm	ppm
0	112–625[b] 338[c]	0.4–2.6 1.4	7.8–12.8 10.3	0.3–2.9 1.3	465–668 556	373–409 389
4	23–800 291	0.2–1.1 0.5	3.1–11.8 8.6	0.3–4.3 2.2	496–566 519	379–409 393
8	136–636 362	0.6–1.3 0.9	4.3–5.8 5.1	0.4–0.6 0.5	497–514 503	378–380 379
11	136–815 385	0.1–2.7 1.0	4.2–7.6 5.6	0.2–2.4 0.6	492–517 504	378–405 382
13	184–569 470	0.4–0.9 0.7	2.8–3.8 3.2	0.3–0.4 0.3	503–519 512	380–384 383
24	527–805 666	0.8–1.0 0.9	2.5–2.8 2.7	1.7–1.9 1.8	520–523 521	409–412 411
33	127–488 240	0–0.8 0.4	3.7–5.4 4.7	1.6–1.8 1.7	491–515 499	407–413 410
40	249–815 548	0.3–3.1 1.4	1.7–6.8 3.7	0.2–2.3 1.2	475–513 497	382–412 397
Average	413	0.9	5.5	1.2	514	393

W: window aperture, Q_{Rn}: solar radiation inside greenhouse, v: wind speed outside greenhouse, $(T_{in}-T_{out})$: difference temperature between inside and outside greenhouse, VPD: vapor pressure deficit, CO_{2in} and CO_{2out}: CO_2 concentration in inside and outside, respectively.
a) Climatic conditions during observation on April 27 and May 2, 6, 8, and 22, 2019.
b) Data range from minimum to maximum.
c) Average data for each window aperture.

ent W. The vents were moderately opened at $W = 24\%$ (Fig. 3a) and fully opened at $W = 40\%$ (Fig. 3b). The value of G at $W = 40\%$ was larger than at $W = 24\%$. Even if the window aperture was constant throughout the day, the ventilation rate fluctuated owing to the climate conditions outside the greenhouse. The difference of the enthalpy (Δh) between inside and outside the greenhouse indicates the total heat (sensible and latent heat) energy difference per kg of dry air. Fig. 3 showed that Δh increased with increasing temperature (as shown in temperature difference, ΔT). At the moderate level of W, ΔT and Δh were higher than the larger level of window aperture. Also, Δh was lower in the afternoon than that in the morning. It might be owing to the increase in the ventilation rate depending on the wind speed outside the greenhouse in the afternoon (above 1 m s^{-1}).

The G_{HB} and G_{WVB} methods showed similar variation trends with time, and the ventilation rate changed considerably with the wind speed outside the greenhouse. The change in the ventilation rate for the large ventilation opening area (September 16, 2019) was higher than that for the moderate ventilation opening area (July 22, 2018), even with the same amount of absorbed solar radiation. A high ventilation rate reduced ΔT and Δh to a larger extent compared with a low ventilation rate. Increased solar radiation affects the climate condition in a naturally ventilated greenhouses. Thus, ventilation systems are a crucial part of maintaining the optimal environment for crop cultivation. In summer, it is better to open vents to the maximum level because the ΔT increases to above 4℃ (at $W = 24\%$), as shown in Fig. 3a. Therefore, it is better to keep a high ventilation rate in the summer and should be measured continuously at short intervals to consider the effect of external climate conditions.

The maximum ventilation rate at $W = 24\%$ was approximately 3.6 m^3 m^{-2} min^{-1} and 3.2 m^3 m^{-2} min^{-1} at midday (between 12:00 and 14:00) under a high solar radiation of almost 500 W m^{-2}. In contrast, at $W = 40\%$, the ventilation rate was the maximum at 5.4 m^3 m^{-2} min^{-1} and 4.9 m^3 m^{-2} min^{-1} for the HB and WVB methods, respectively. At moderate and maximum ventilator openings, the average G value obtained using the WVB was slightly lower than the HB method. Furthermore, the G value via the TG method was higher than the HB and the WVB at the maximum level of W (Fig. 4). Yasutake et al. (2017) reported the maximum value of air exchange rate (N) by the CO_2 balance method between 5–7 h^{-1} at 20% of W in the midday, whereas the gas method was slightly higher than the heat balance method. They noticed a small value of N due to a different size of greenhouse (a single-span greenhouse, 150 m^2 of floor area, without crops condition). In this paper, a slightly lower value of G_{HB} and G_{WVB} was because of gas diffusion resistance owing to the tomato plant canopy in the greenhouse during the measurement. However, the average ventilation rates obtained via both measurement methods were equivalent for each ventilation opening area. In addition, the ventilation rate increased gradually as the window aperture increased from 16% to 40% (Fig. 5).

The aforementioned results confirmed that the HB method provided accurately predicted the ventilation rate not only for the maximum window aperture, as mentioned by Fernandez and Bailey (1992), but also for the moderate window aperture (approximately 16–24%), as presented in

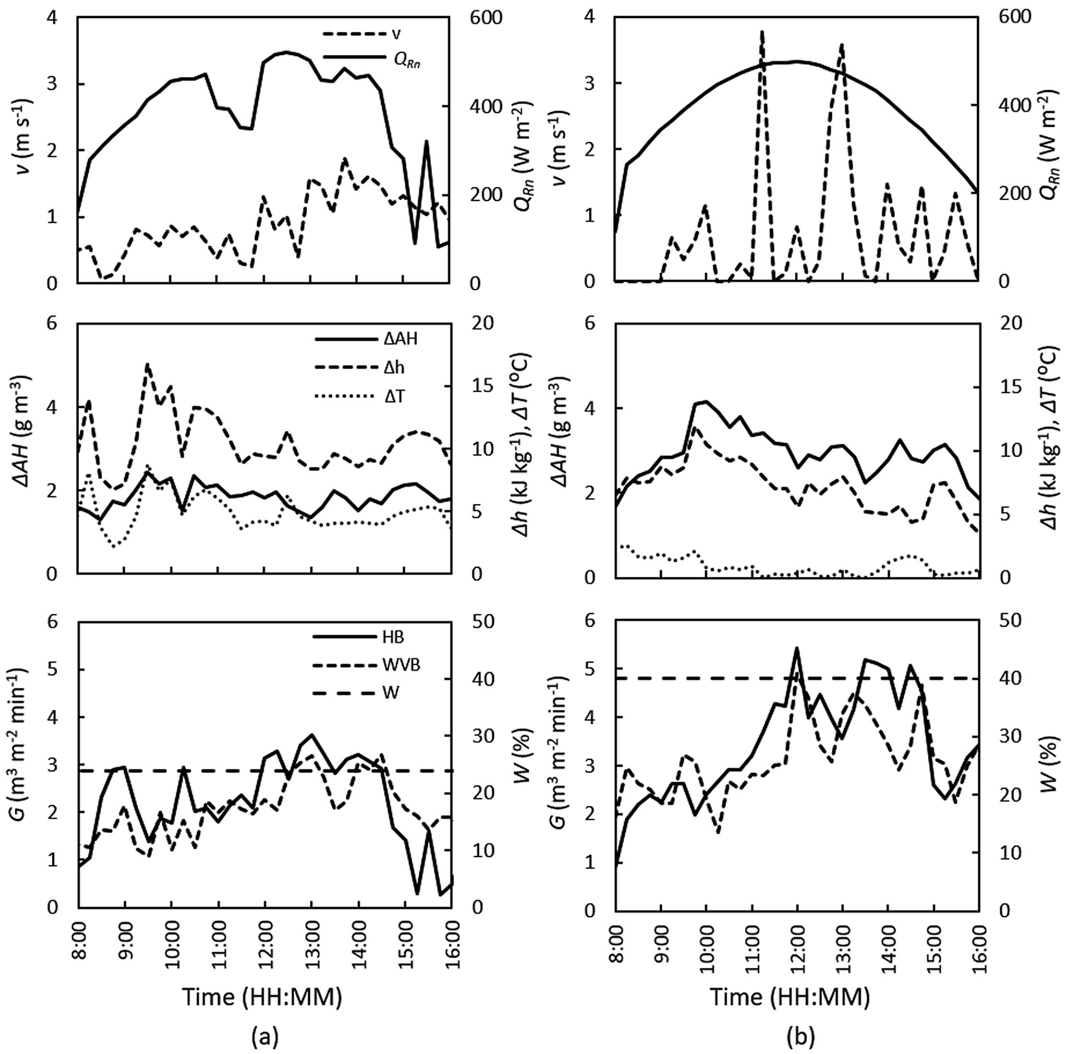

Fig. 3 Time series of the ventilation rate (G) obtained using the HB and WVB methods at different window apertures (W). (a) Moderate and (b) large apertures. v: outside wind speed, Q_{Rn}: solar radiation absorbed in the greenhouse, ΔAH: difference of absolute humidity between inside and outside, Δh: difference of enthalpy inside and outside, and ΔT: temperature difference inside and outside greenhouse. The measurements for the moderate and large window apertures were performed on July 22, 2018 and September 16, 2019, respectively. Tomato plants were cultivated by substrate culture in the greenhouse.

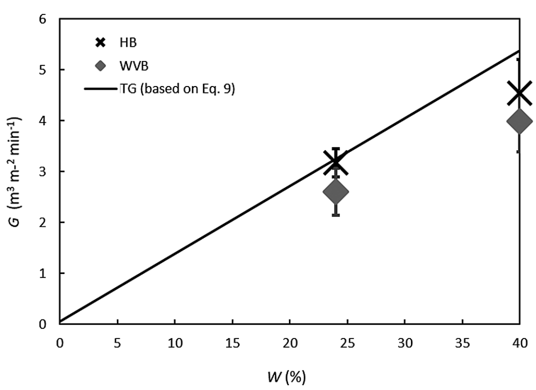

Fig. 4 The average ventilation rate (G) at midday (between 12:00 and 14:00) measured using the HB method (×) and WVB method (◆) under window aperture (W) 24% and 40%. The data are presented as means with standard deviations. The line graph showed the ventilation rate using the TG method without crop condition.

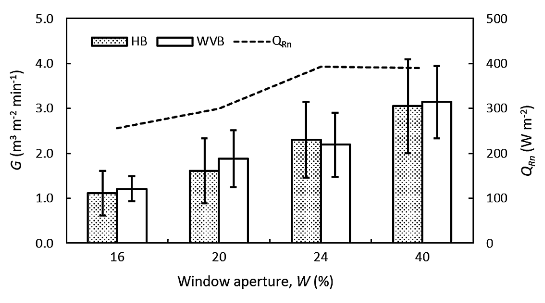

Fig. 5 Average ventilation rate (G) measured using the HB method (shaded bars) and WVB method (white bars) for W = 16–40%. The data are presented as means with standard deviations. The dashed line shows the average of the net radiation inside the greenhouse (Q_{Rn}).

Fig. 5. The HB method gave better results for moderate and higher ventilator openings under high radiation conditions. In the experiment, the average absorbed solar radiation during the observation was above 200 W m^{-2}.

The ventilation rate obtained using the WVB method exhibited good correlation and agreement with that obtained using the HB method, with the Pearson correla-

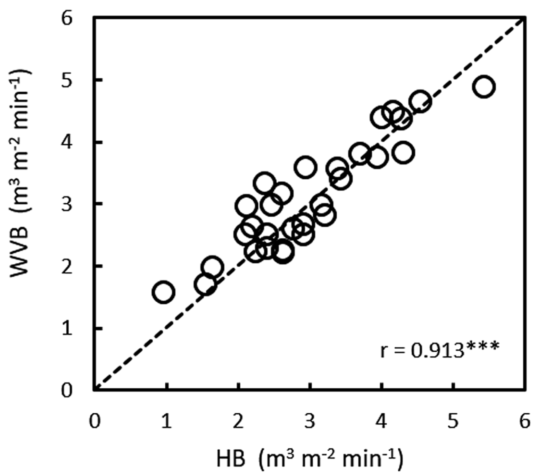

Fig. 6 Relationship between the ventilation rates obtained using the HB and WVB methods. Each value represents the mean of the values calculated every 15 minutes in the naturally ventilated greenhouse on September 16, 19, and 25, 2019, for a window aperture of 40%. The dashed line indicates the targeted line, and the corresponding value of the Pearson correlation coefficients (r) is presented in the figure (***$P = 2.13\times10^{-12}<0.01$).

tion coefficient (r)= 0.913, as presented in Fig. 6 (ventilation rate in a range of 1–5 m^3 m^{-2} min^{-1}). The results performed the ability of the WVB method that can predict the ventilation rate not only under a small ventilation opening area (Boulard and Draoui, 1995) but also until a high level of the window aperture. The cultivation period of greenhouse tomato production is long, ranging from early autumn to early summer of the following year in Japan. The ventilation opening area changes depending on the season owing to air temperature control. Therefore, the WVB method is suitable for the long-term continuous measurement of the ventilation rate under different window apertures.

The TG method is extremely reliable for measuring ventilation rates for various ventilation opening areas. However, when for a large ventilation opening area, a considerable amount of TG is required to maintain high and uniform concentration in a greenhouse. Furthermore, it is difficult to maintain a uniform CO_2 concentration in the greenhouse because the outdoor airflow affects the CO_2 concentration distribution in the greenhouse. One of the solutions to this problem is to set numerous measurement points of CO_2 concentration in the greenhouse (Romanini et al., 2012). However, sophisticated technology with large memory is required because data must be recorded at short intervals (every second). Furthermore, a large number of sensors is necessary for achieving good accuracy. Practically, it is quite difficult to implement the TG method for continuously monitoring the ventilation rate because of the above reasons and high cost. The results obtained in this study show that the HB and WVB methods can be used for monitoring the ventilation rate for moderate and large ventilation opening areas.

In conclusion, the ventilation rate was measured using the HB and WVB methods for moderate and maximum window apertures in a naturally ventilated greenhouse. The measured ventilation rate was compared with the ventilation rate obtained using the TG technique as a reference. The ventilation rates measured by the HB and WVB methods exhibited similar variation trends with time. Furthermore, the WVB method was simpler than the HB method because the WVB method had fewer measurement parameters. Overall, the WVB method was demonstrated to be a potentially useful tool for the continuous measurement of the ventilation rate.

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