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Comparison of Three Ventilation Rate Measurement Methods under Different Window Apertures in Winter and Spring

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The ventilation rate is an essential parameter for the continuous monitoring of the photosynthetic rate for greenhouse-cultivated plants via the CO_2 balance method. Diurnal changes in the ventilation rate (*G*) according to window aperture (*W*) and solar radiation level were therefore measured using the heat balance (HB) and water vapor balance (WVB) methods during winter and spring in a naturally ventilated greenhouse cultivating tomatoes. The results were indirectly compared with those of the tracer gas (TG) method. The *G* obtained through both methods increased with increasing *W*. However, when *W* increased rapidly, the increase in *G* was delayed when using the HB method compared to the WVB method. The *G* obtained via the WVB method performed similarly to the TG method at small values of *W*, and similarly to the HB method at moderate values of *W*. Furthermore, when measured using the HB method, the value in *G* was sensitive to the change in solar radiation level. Meanwhile, the *G* measured using the WVB method exhibited a stable response to the changes in *W* and could permit continuous real-time monitoring of greenhouse ventilation rates, which is necessary to estimate the photosynthetic rate for the plants in a greenhouse.

Keywords : CO_2 balance, photosynthetic rate, heat balance, water vapor balance, tracer gas

INTRODUCTION

Real-time photosynthetic rate monitoring is crucial for managing crop cultivation in greenhouses. Nederhoff and Vegter (1994) accordingly presented a canopy photosynthesis measurement method that enabled the accurate estimation of the greenhouse CO_2 balance. The photosynthesis of cultivated plants in a greenhouse is directly related to the ventilation rate, which also affects the air temperature and humidity. Takakura et al. (2017) proposed a method for directly estimating the canopy photosynthetic rate by introducing the ventilation rate, determined from the greenhouse environmental parameters, into the CO_2 balance equation. The ventilation is very complex as it is the result of the heat transfer processes of conduction, convection, and radiation occurring in a naturally ventilated greenhouse. Additionally, the ventilation rate has been found to be influenced by the presence of crops as well as the structure and design of the greenhouse, and has been observed to constantly fluctuate throughout the day (Mashonjowa et al., 2010). Therefore, it is necessary to continuously measure the ventilation rate in greenhouses used for cultivation.

Various ventilation rate measurement techniques have been studied extensively, such as the tracer gas (TG), heat balance (HB), and water vapor balance (WVB) methods. The TG and HB methods are the most widely adopted for greenhouse ventilation rate measurement (Fernandez and Bailey, 1992). In previous research, the TG method has exhibited highly accurate air exchange rate measurement under leakage conditions (i.e., with the window apertures closed) and with the smallest window apertures (Fernandez and Bailey, 1992; Nederhoff et al., 1985; Baptista et al., 1999; Muñoz et al., 1999). Other studies have shown that the HB method achieves high accuracy with larger window apertures (Fernandez and Bailey, 1992; Baptista et al., 2001). However, the WVB method was found to estimate the ventilation rate more accurately than the TG method with small window apertures (Boulard and Draoui, 1995) and has been applied in a greenhouse used to cultivate mature plants (Harmanto et al., 2006).

It is important to note that the TG method is not suitable for long-term, continuous ventilation rate measurement (Sherman, 1990) because it requires that a considerable amount of the TG be present in a greenhouse under cultivation, and SF_6, which is often used as a TG, is quite expensive. Meanwhile, the HB technique requires numerous variables to measure the ventilation rate even when it is possible to do so continuously (Baptista et al., 1999). There are also several challenges associated with the WVB method related to the i) direct measurement of the transpiration rate parameter using a lysimetric device (Kittas et al., 2002); ii) overestimation of the ventilation rate at night (Mashonjowa et al., 2010); and iii) evaluation of the error

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in the evapotranspiration rate, which increases when scaling up from a few plants to the entire canopy (Mashonjowa et al., 2010; Boulard and Draoui, 1995).

The authors have conducted research into the measurement of the ventilation rate, which is among the essential parameters for the direct and continuous prediction of the photosynthetic rate for greenhouse-cultivated plants, using the CO_2 balance method in a naturally ventilated greenhouse. As the protected cultivation of tomato plants occurs from early autumn to early summer of the following year in Japan, the area of opened greenhouse windows must be constantly adjusted depending on the changing climatic conditions to maintain an acceptable interior environment. However, no comparison of ventilation rate measurement methods in different seasons has been reported to date. Therefore, in this study, the diurnal change in the ventilation rate was continuously measured using the HB and WVB methods in a naturally ventilated greenhouse used to cultivate tomato plants during the winter and spring. The validity of the results was then evaluated by indirectly comparing the measured ventilation rates with those obtained using the CO_2 TG method as a reference.

MATERIALS AND METHODS

Greenhouse experiment setup

The experiments were performed in the spring (April 20–22, 2019) and winter (December 12–19, 2019) in a single-span greenhouse at a research field site of the Faculty of Applied Biological Science, Gifu University, Japan. The greenhouse was composed of glass (glasshouse) and had dimensions of 3.2 m×5.0 m×2.8 m covered by a supported roof. Ventilation was provided by double flap side vents that were covered by a screen-net material with a pore size of 0.4 mm and a porosity of 52.2%. The experiments were conducted with two upper side vents and the roof vents (SV2-RV1) open in the spring and only the roof vents (SV0-RV1) open in the winter, as shown in Fig. 1. The window aperture (*W*) is presented in this paper as a percentage calculated based on the ratio of the total ventilation area to the greenhouse floor area as follows:

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

The window aperture area was automatically controlled as required to maintain the inside air temperature at 20℃ and 25℃ in winter and spring, respectively, using five opening angles (S0, S1, S2, S3, and S4) (Table 1). The *W* values for S0, S1, S2, S3, and S4 were 0, 3, 7, 12, and 16%, respectively, under the SV2-RV1 ventilation treatment and 0, 2, 4, 6, 13%, respectively, under the SV0-RV1 ventilation treatment.

The greenhouse contained mature fruiting tomato crops (*Solanum lycopersicum* L., variety "Momotaro"), cultivated in 14 modified Wagner pots with a volume of 10 L (one plant per pot), filled with light sandstone (diameter 1–5 mm) and covered with plastic mulch. The plants were supplied with a hydroponic nutrient solution (EC = 1 dS

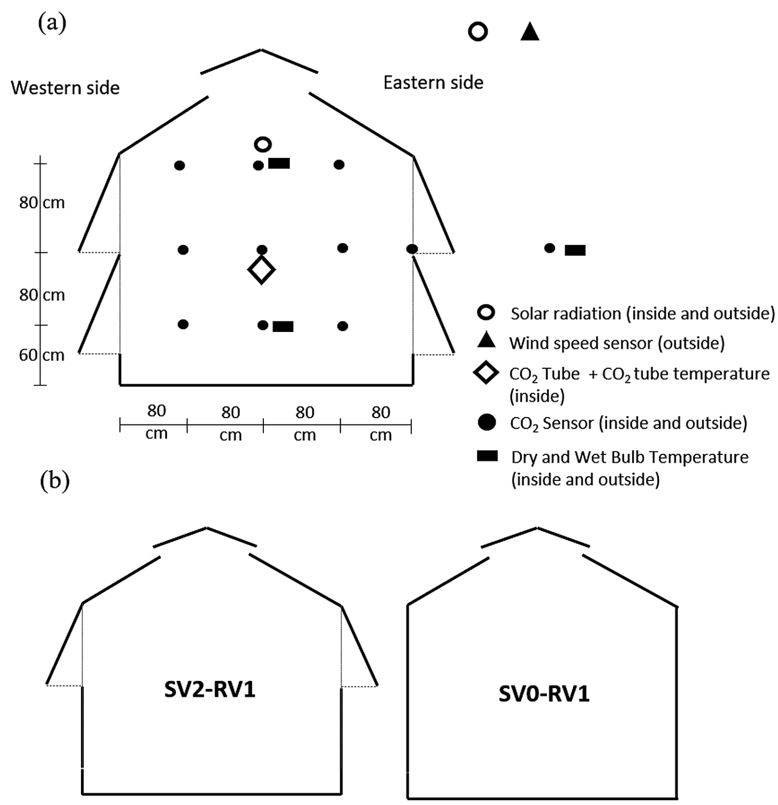

Fig. 1 Schematic diagrams of cross-sections, ventilators, and locations of instrumentation in the experimental greenhouse. (a) Locations of sensors for dry and wet bulb temperatures, CO_2, solar radiation (inside and outside), and outside wind speed. (b) Window aperture treatments: upper side and roof vents used in spring (SV2-RV1) and roof vents used in winter (SV0-RV1).

Table 1 Performances of the evaluated ventilation rate measurement methods under different window apertures in spring and winter.

Ventilation step	W (%)	n data	Climate condition* Q_{Rn} W m^{-2}	v m s^{-1}	ΔT °C	VPD kPa	Ventilation rate (m^3 m^{-2} min^{-1})** WVB	HB	Air exchange rate (h^{-1})** WVB	HB
SV2-RV1	Spring (April 20–22, 2019)									
S0	0	13	29	0.4	3.1	0.2	0.173±0.009	−0.112±0.036	4.6±0.2	−3.0±1.0
S1	3	5	62	0.4	4.6	0.4	0.260±0.031	0.094±0.125	6.9±0.8	3.3±2.5
S2	7	3	85	0.6	2.2	2.4	0.777±0.036	0.232±0.034	20.7±1.0	6.2±0.9
S3	12	12	186	1.5	3.9	0.5	0.582±0.036	0.439±0.078	15.5±1.0	11.7±2.1
S4	16	27	353	1.0	2.2	3.5	0.810±0.017	0.819±0.059	21.6±0.4	21.8±1.6
SV0-RV1	Winter (December 12–19, 2019)									
S0	0	81	52	0.1	5.6	0.2	0.167±0.010	0.031±0.015	4.5±0.3	0.8±0.4
S1	2	7	110	0.3	7.4	0.1	0.177±0.009	0.073±0.058	4.7±0.2	2.0±1.5
S2	4	22	138	0.5	8.3	0.2	0.230±0.029	0.126±0.031	6.1±0.8	3.4±0.8
S3	6	25	194	0.7	8.8	0.3	0.235±0.031	0.229±0.038	6.3±0.8	6.1±1.0
S4	13	5	281	0.3	7.7	1.3	0.949±0.065	0.899±0.158	25.3±1.7	24.0±4.2

*Means of climate data conditions for n data points. W: window aperture, Q_{Rn}: inside net radiation, v: outside wind speed, ΔT: temperature difference between inside and outside, and VPD: vapor pressure deficit.

**The means and standard errors are shown for the ventilation and air exchange rate values.

m^{-1} and pH 5.5–6.5) in the lower part of the pot system using capillary irrigation to maintain a maximum water level of 10 cm. The plants were fertilized with a complete nutrient solution—Stock A (10% N, 8% P_2O_5, 27% K_2O, 4% MgO, 0.10% MnO, 0.10% B_2O_3, 0.18% Fe, 0.002% Cu, 0.006% Zn, and 0.002% Mo) and Stock B (11% N and 16.4% Ca)—after being transplanted to the production system. During the measurement periods in the spring and winter, the cultivated tomato plants were maintained with an average height of about 1.6 m, and the leaf area index (LAI) of the crop was about 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 during the experiments: the air temperatures both inside and outside the greenhouse (dry and wet bulb temperatures), the solar radiation both above the crops in a greenhouse and exterior height of 2 m, and the exterior wind velocity. The air temperatures (dry and wet bulb) were measured by two aspirated psychrometers using T-type thermocouple (copper/constantan) sensors. The two psychrometers were set up at heights of 0.5 m and 2.0 m above the floor in the center of the greenhouse and one psychrometer at height of 1.0 m in the outside. To measure the solar radiation, two pyranometers (Model MS-602, EKO Instruments, Japan) were placed inside and outside the greenhouse at 1.8 m and 3.5 m above the ground, respectively. All the above measurements were recorded by a data logger (CR1000, Campbell Scientific, Inc., USA) in 1 minutes intervals for an extended time during daylight (from 8:00 to 16:00).

TG method

Though it is possible to calculate a corrected G value according to the presence of plants in ventilation measurements conducted using the TG method if the amount of CO_2 absorbed by plant photosynthesis is known, this approach is not recommended for practical use (Nederhoff et al., 1985). Indeed, Nederhoff et al. (1985) reported that when applied with CO_2, the TG method can be best used to determine the ventilation characteristics of greenhouse when it is free of plants. The ventilation and leakage rates were therefore measured by injecting a TG into the empty greenhouse and then measuring the decay rate of its concentration (the dynamic TG method). The TG CO_2 was supplied from a tank by a 2-m long diffusion tube run at a height of 0.8 m (approximately the mid-height of the plants present during the HB and WVB tests). Ten CO_2 sensors (Model K30, Senseair, Sweden) were placed inside the greenhouse and one sensor was placed outside the greenhouse (Fig. 1) to measure the CO_2 concentration level every 1 second. The TG experiment was performed continuously in the greenhouse without crops on from April 27 to May 22, 2019, with no ventilation and with two small window aperture areas ($W = 0\%$, 4%, and 12%). Data were collected every 1 second, and the decay rate was averaged in 15 minutes intervals. The method applied for ventilation rate measurement using the CO_2 TG was based on the technique proposed by Nederhoff et al. (1985) with a modified CO_2 concentration. In this experiment, CO_2 gas was injected into the greenhouse until a concentration of 550 μmol mol^{-1} was reached, at which point the supply was stopped. As a result of exchange with the outside air, the CO_2 concentration in the greenhouse can be expected to decrease at a rate proportional to the difference between the interior and exterior CO_2 concentrations, assuming the ventilation rate is constant over time. Once the CO_2 level decreased to below 450 μmol mol^{-1}, CO_2 was again injected to a concentration of 550 μmol mol^{-1} and additional measurements collected. The ventilation rate obtained using the TG technique (G_{TG}) can be determined using the following equations:

$$N_{TG} = \frac{3600}{t_1} \ln\left[\frac{C_{in}(t_0) - C_{out}}{C_{in}(t_1) - C_{out}}\right] \quad (2)$$

$$G_{TG} = \frac{1}{60}\frac{N_{TG} V_g}{A_f}, \quad (3)$$

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 $t = t_1$, V_g is the greenhouse volume (m^3), and A_f is the greenhouse floor area (m^2). A factor of 3,600 is present in Eq. 2 because the greenhouse air exchange rate (N_{TG}) expresses the number of greenhouse volume exchanges per hour (in units of h^{-1}), whereas t is measured in seconds. The value of N_{TG} can be converted into the TG ventilation rate, G_{TG} ($m^3\ m^{-2}\ min^{-1}$) using Eq. 3. The resulting values were used as references for comparison with the ventilation rates measured using the HB and WVB methods in the greenhouse under cultivation as described below.

HB method

Ventilation removes heat from a greenhouse to prevent excessively high temperatures. The HB method assumes steady-state conditions and uses the principle of energy conservation, i.e., the heat losses from inside the greenhouse are equal to the heat gains outside the greenhouse. When no heating is used, the heat removed by leakage (i.e., the heat loss occurring when the vents are closed) and by ventilation (Q_v) is equal to the solar radiation collected in the greenhouse (Q_{Rn}) minus the thermal loss through the cover (Q_c) minus the stored heat in the soil (Q_s). The value of Q_s was measured every 1 minutes by a soil heat flux sensor placed 10 mm below the ground surface. Mathematically, the equation for the static HB of a naturally ventilated greenhouse has the following general form:

$$Q_v = Q_{Rn} - Q_s - Q_c \tag{4}$$

$$Q_c = k(T_{in} - T_{out})\frac{A_c}{A_f} \tag{5}$$

$$G_{HB} = \frac{Q_V}{[c_p \cdot \rho_a \cdot (T_{in} - T_{out}) + L_v \cdot (AH_{in} - AH_{out})]} \times 60 \tag{6}$$

where G_{HB} is the measured ventilation rate per unit floor area over a period of time ($m^3\ m^{-2}\ min^{-1}$), Q_{Rn} is the average incoming net solar radiation inside the greenhouse during the day ($W\ m^{-2}$), Q_s is the soil heat flux ($W\ m^{-2}$), Q_c is the heat transfer through the greenhouse cover, Q_v is the heat removed via ventilation ($W\ m^{-2}$), k is the heat transmittance coefficient of the greenhouse cover ($W\ m^{-2}\ K^{-1}$), 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), L_v is the latent heat of vaporization ($J\ kg^{-1}$), and $AH_{in} - AH_{out}$ is the difference between the absolute humidity inside and outside the greenhouse ($kg\ m^{-3}$). A factor of 60 has been included in Eq. 6 to convert the units of time from seconds into minutes.

Clearly, due to the importance of Q_{Rn} in the calculation of G_{HB} in Eqs. 4–6, the accuracy of the HB method will depend on the location of the solar radiation sensor in the greenhouse; the effects of shadow upon the direct radiation sensor cannot be neglected if the results of the HB method rely upon data collected by this sensor. Akutsu et al. (2015) noted that the use of double sensors or a diffused covering material would help solve this problem. However, it was not easy to evaluate the difference between double sensors because of the constraints on the method used to match their outputs and select their values. Takakura (2008) proposed a plant solar meter with a spherical sensor that can measure the solar radiation at the top of the canopy to minimize this problem when using the HB method and enable more effective greenhouse environmental control. Therefore, the measurements in this experiment were performed with one radiation sensor above the canopy.

WVB method

Water vapor was considered to originate only from crop transpiration during the growth process. The evaporation from the substrate media and greenhouse floor was neglected as these surfaces were covered by plastic mulch. The interior of the greenhouse was thus assumed to be in uniformly humid and steady-state conditions. The crop evapotranspiration rate was directly measured for two plants by weighing devices (Model SW-15KS, A&D Company, Japan) with an accuracy of 2 g. The average measured evapotranspiration rate was then scaled up to cover all plants by assuming that the evapotranspiration was uniform, and adding a plant coverage factor to the total greenhouse floor area in the following equation used to calculate the ventilation rate:

$$G_{WVB} = \frac{n\ ET}{A_f F_{ca}[AH_{in} - AH_{out}] \times 60}, \tag{7}$$

where G_{WVB} is the measured ventilation rate per unit surface area of the greenhouse floor over a period of time ($m^3\ m^{-2}\ min^{-1}$), n is total number of plants, ET is the average measured evapotranspiration rate ($g\ h^{-1}$), A_f is the greenhouse floor surface area (m^2), F_{ca} is the plant coverage factor, defined as the ratio of the plant coverage area to the greenhouse floor area and measured based on the real horizontal projection of the canopy (de Medeiros et al., 2001), and $AH_{in} - AH_{out}$ ($g\ m^{-3}$) is the absolute difference between the humidity inside and outside the greenhouse during the measurement period.

Analysis and comparison of methods

The ventilation rate was measured using the WVB and HB methods in a naturally ventilated greenhouse cultivating a fully grown tomato crop. The measurements were recorded every 1 minute and averaged in 15 minutes intervals because of the time lag associated with the direct estimation of the evapotranspiration rate in the WVB method. All measurements were performed on the same day, and the window aperture configuration ranged between closed (0%) and moderately open (16%). During ventilation rate measurements using both methods, CO_2 gas was supplied to maintain an inside CO_2 concentration of around 400 μmol mol^{-1} via the diffusion tube in center of the greenhouse in spring and between 450 μmol mol^{-1} and 550 μmol mol^{-1} in winter. All ventilation rates measured using these two methods were indirectly compared with the results of the TG method applied with no crops present in the greenhouse.

RESULTS AND DISCUSSION

The effects of different W values on the ventilation rate were first measured using the TG method (G_{TG}) in a naturally ventilated greenhouse without crops. Figure 2 shows the time series corresponding to $W = 0\%$ (closed apertures), 4% (small apertures), and 12% (moderate apertures) during the daytime on the measurement days (April 27 and May 2, 2019). The ventilation rate determined by the TG method was considered be accurate as the CO_2 control system was able to maintain the gas concentration at the predetermined level. The measured value of G_{TG} was observed to increase as W increased from 0% to 12%. The average G_{TG} values when W=0%, 4%, and 12% were 0.059, 0.254, and 1.955 $m^3\ m^{-2}\ min^{-1}$, respectively. The increase in ΔT increased the ventilation rate under leakage conditions, indicating that the air temperature had a greater effect on the gas flow in the greenhouse because the gas volume expands with increasing temperature. However, with a small window aperture ($W = 4\%$), G_{TG} leveled off at 0.153–0.350 $m^3\ m^{-2}\ min^{-1}$ even though ΔT decreased linearly with decreasing solar radiation. Generally, the ventilation rate is expressed as the product of the window aperture area, the outside wind speed, and the square root of the wind pressure coefficient. The wind pressure coefficient of a flap type window, such as that present in the subject greenhouse, depends on the angle of its opening (Boulard and Baile, 1995); the measurement of ventilation rate with the TG method in the subject greenhouse correctly showed this relationship. Figures 2b and 2c show a proportional increase in the average of G_{TG} with a window aperture from 0.254 $m^3\ m^{-2}\ min^{-1}$ ($W = 4\%$) to 1.955 $m^3\ m^{-2}\ min^{-1}$ ($W = 12\%$) for an average wind speed outside the greenhouse of 0.3 and 0.9 $m\ s^{-1}$, respectively.

Figure 3 shows time series of the ventilation rates (G) obtained in winter on December 14 (Fig. 3a) and in spring on April 22, 2019 (Fig. 3b) using the HB and WVB

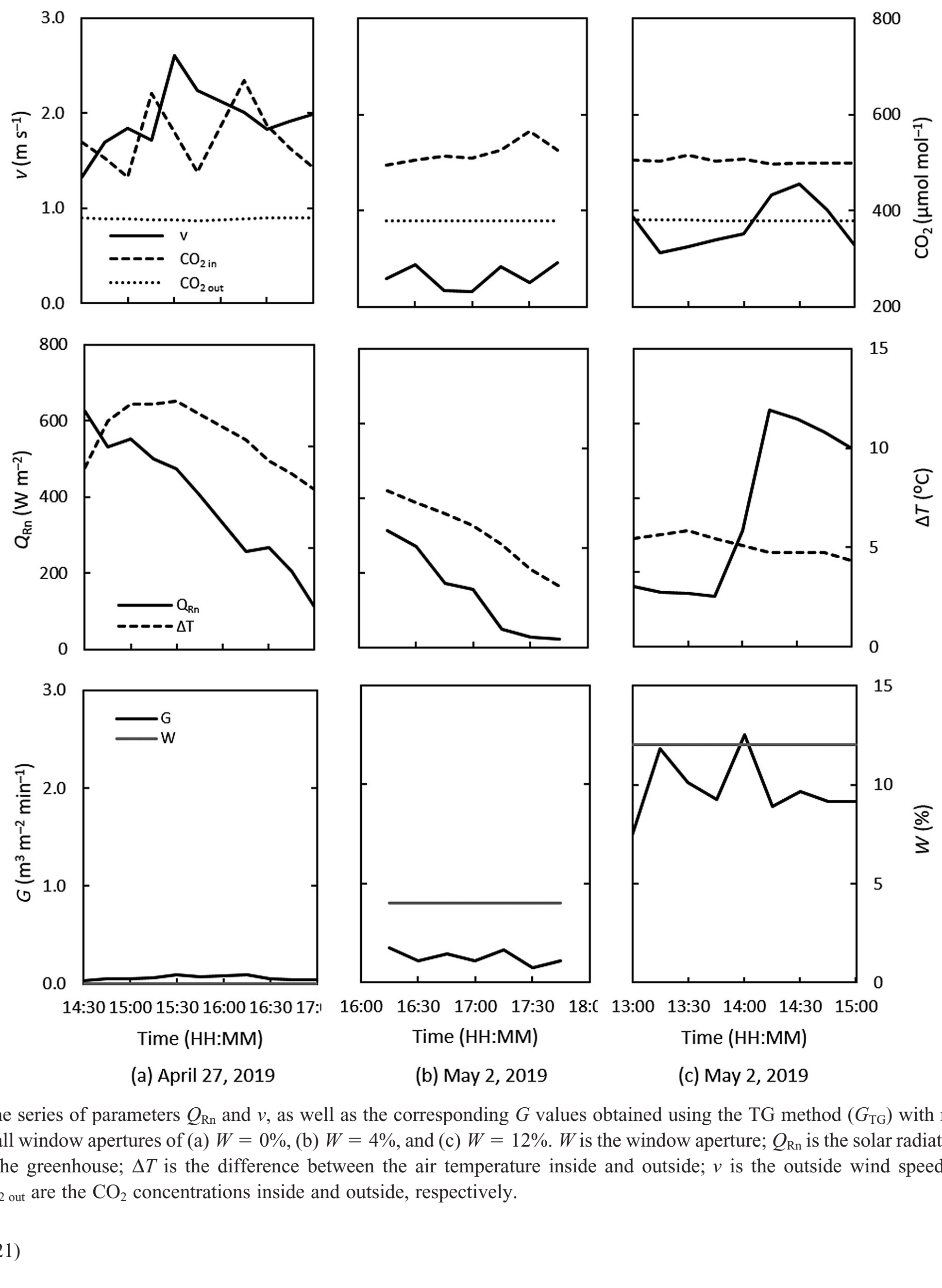

Fig. 2 Time series of parameters Q_{Rn} and v, as well as the corresponding G values obtained using the TG method (G_{TG}) with no crops and small window apertures of (a) $W = 0\%$, (b) $W = 4\%$, and (c) $W = 12\%$. W is the window aperture; Q_{Rn} is the solar radiation absorbed in the greenhouse; ΔT is the difference between the air temperature inside and outside; v is the outside wind speed; $CO_{2\ in}$ and $CO_{2\ out}$ are the CO_2 concentrations inside and outside, respectively.

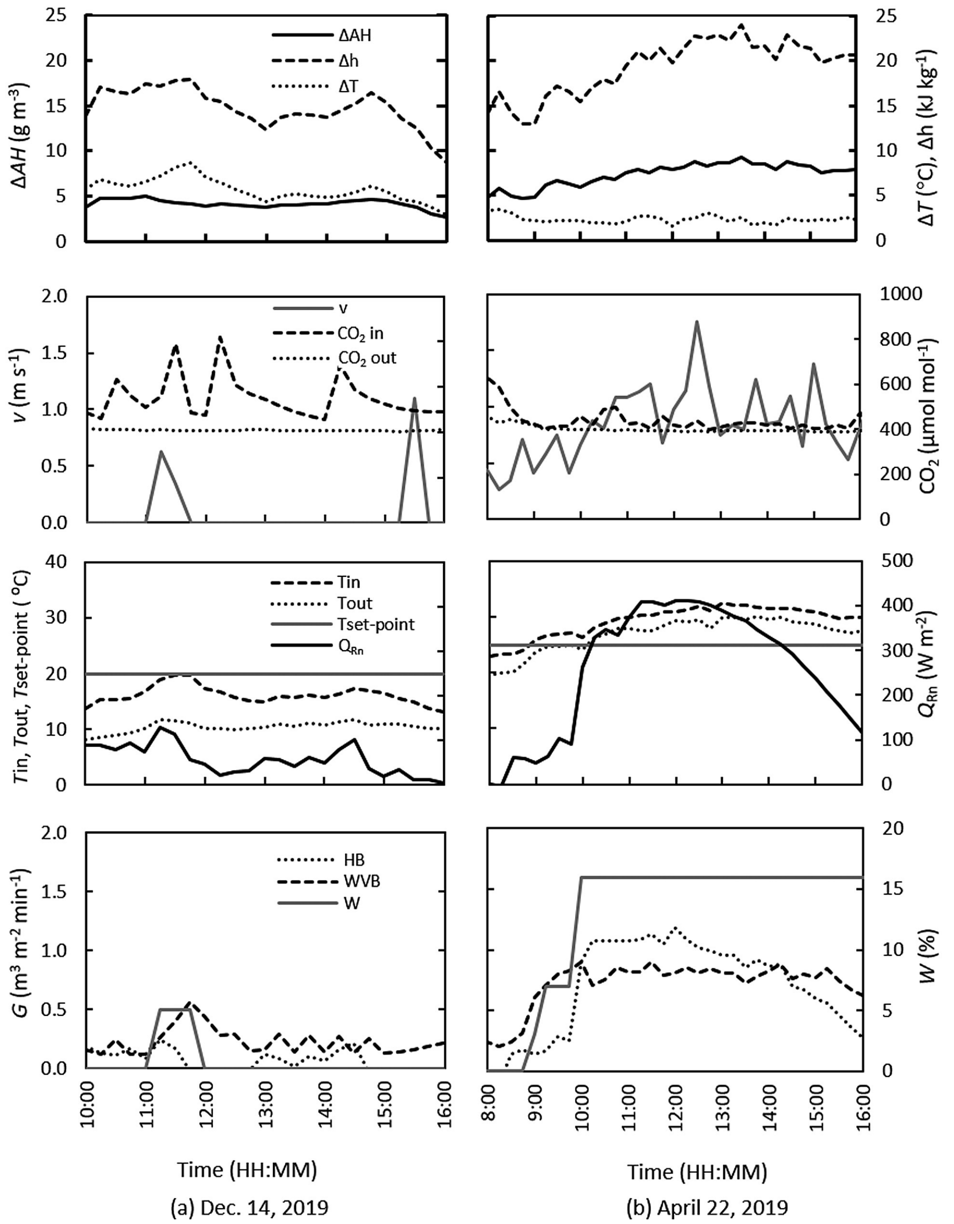

Fig. 3 Time series of parameters and corresponding G values obtained using the HB (G_{HB}) and WVB methods (G_{WVB}) at different W in (a) winter and (b) spring. Q_{Rn} is the solar radiation absorbed in the greenhouse; T_{in}, T_{out}, and $T_{set\text{-}point}$ are the inside air temperature, outside air temperature, and set point of temperature for ventilation, respectively; v is the outside wind speed; $CO_{2\ in}$ and $CO_{2\ out}$ are the CO_2 concentrations inside and outside, respectively; ΔAH is the difference between the absolute humidity inside and outside; Δh is the difference between the enthalpy inside and outside; ΔT is the difference between the air temperature inside and outside. Note that tomato plants were cultivated by substrate culture in the greenhouse.

methods. During the daytime on December 14 and April 22, 2019, the solar radiation inside the greenhouse was less than 100 W m^{-2} and 400 W m^{-2}, respectively. Since the ventilation temperature was set at 20℃, the windows were hardly opened during the low solar radiation period (December 14, 2019). With the windows closed, the values of G measured using the two methods were relatively small. With the windows opened slightly from 11:00 to 12:00 ($W = 5\%$), the values of G_{WVB} increased slightly (0.5–0.7 m^3 m^{-2} min^{-1}), while those of G_{HB} remained small (0–0.2 m^3 m^{-2} min^{-1}). Under such low W conditions, the value of G_{WVB} was similar to that of G_{TG} shown in Fig. 2b even though the tests were not conducted on the same date. However the environmental conditions during measurement were almost similar; for example, the inside net radiation (Q_{Rn}) ranged 50–200 W m^{-2}, temperature difference (ΔT) was 5–8℃, and air velocity (v) was less than 0.5 m s^{-1}.

On April 22, 2019, when the set temperature was 25 ℃, G_{WVB} showed a quick response to the rapid change in W from 9:00 to 10:00, but G_{HB} increased after a delay of about 40 minutes (Fig. 3b). Thereafter, the G values for both methods leveled off between 0.7 m^3 m^{-2} min^{-1} and 1.0 m^3 m^{-2} min^{-1} when W remained constant at 16%. When these results are compared with those obtained by the TG method (Fig. 2c), it can be seen that the value of G_{TG} is twice that of G_{HB} and G_{WVB} at W values greater than 10%. Even though the two evaluated methods were conducted on different days than the TG method, the experiments conducted in the same season (spring) under the same greenhouse environmental conditions showed a similar Q_{Rn}, ΔT, and v, indicating that the comparison is valid. The smaller G_{HB} and G_{WVB} values observed are likely the result of the drag effect of the plants. Indeed, Kacira et al. (2004) found that the greenhouse ventilation rate without plants was more than twice (1.54–3.16 $m^3\ m^{-2}\ min^{-1}$) that for a plant canopy zone (0.69–1.50 $m^3\ m^{-2}\ min^{-1}$) when the outside wind speed ranged from 0.5 to 1.0 $m\ s^{-1}$ in a two-span type greenhouse with butterfly side vents and roof vents. The results of the present experiment agree with the results of this previous study, despite the different type of greenhouse, as the side vent types were similar in both studies. Moreover, the air flow without the presence of plants has been observed to travel along the floor of the greenhouse and depart from the leeward side opening faster (Kacira et al., 2004), and the amount of CO_2 lost by ventilation has been noted to be much greater than that taken up by the plants (Nederhoff et al., 1985).

Furthermore, G_{HB} was observed to respond to the increase in net radiation and W in a similar manner to G_{WVB}. However, for the same W, G_{HB} decreased with decreasing solar radiation, while G_{WVB} did not change. These results indicate that G_{HB} was mainly affected by the solar radiation level. The difference in the wind speed between inside and outside the greenhouse also contributed to the change in ventilation rate.

On the other hand, the G values obtained using the two methods were observed to be affected by the difference between the absolute humidity inside and outside the greenhouse (ΔAH) (Fig. 3), as well as the vapor pressure deficit (VPD, Table 1). The WVB method was particularly affected by the accuracy of the evapotranspiration measured inside the greenhouse. In soilless cultivation greenhouses in which the floor surface is covered by mulch, most of the water vapor is generated by plants. Plant transpiration is in turn related to the LAI, solar radiation, ΔAH (Jolliet and Bailey, 1992; Katsoulas et al., 2001), and wind speed (Jolliet and Bailey, 1992; Thongbai et al., 2010). The measurement of the direct transpiration rate by the gravimetric method is simpler than the measurement of many environmental parameters using the HB method. However, this measurement should be performed under an optimal range of VPD values in a greenhouse. Shamsiri et al. (2018) determined through a review of previous research that the optimal VPD values were in the range of 0.3 to 1.0 kPa for tomato crop.

Table 1 presents the overall performances of the HB and WVB ventilation rate measurement methods. The ventilation rate increased as W increased from 0% to 16% (spring) and to 13% (winter). The HB method had difficulty predicting G when W was 10% or less (S0–S2 and S0–S3 in spring and winter, respectively). When the window apertures were closed, G_{HB} was −0.112 and 0.031 $m^3\ m^{-2}\ min^{-1}$ in spring and winter, respectively, under low radiation levels (in the range of 29–52 $W\ m^{-2}$). These values are less than those for G_{WVB} of 0.173 and 0.167 $m^3\ m^{-2}\ min^{-1}$ in spring and winter, respectively. Likewise, when the window aperture was small (S1, 5–7% of W), G_{HB} was less than G_{WVB} for radiation levels ranging from 62 to 110 $W\ m^{-2}$. The value of G_{HB} was less than that of G_{WVB} under leakage conditions and the smallest ventilator aperture due to the low net radiation level (below 200 $W\ m^{-2}$). However, G_{HB} increased when the ventilator area was greater than 10%, which is the condition present at high radiation levels. As presented in Table 1, for high solar radiation and a moderate value of W (13% and 16%), the HB method agreed well with the WVB method.

The tendency of G_{HB} to decrease under low solar radiation levels has also been reported by Fernandez and Bailey (1992) and Yasutake et al. (2017). It is unclear, however, why this occurs and when this method can be used to predict the ventilation rates properly at higher solar radiation levels. We therefore attempted to elucidate the source of this problem by evaluating HB model in terms of the percentage of net radiation collected in the greenhouse, as presented in Fig. 4. This graph depicts the ratio of each item considered in the HB method to the total absorbed solar radiation in a single-span greenhouse for different window apertures. In Fig. 4, three main energy parameters can be observed to influence the HB ventilation rate prediction performance: thermal loss through the cover (Q'_{cv}), heat storage in the soil (Q'_{st}), and energy lost by ventilation (Q'_{v}). All energy was absorbed from the net radiation inside the greenhouse (Rn).

Figure 4 shows that the Q'_{v} in the greenhouse increases in response to increasing W, corresponding to an increase in Rn. On the contrary, Q'_{st} can be observed to decrease slightly and tend to a flat response to increasing W. The value of Q'_{cv} can be clearly observed to decrease dramatically with increasing W. When $W = 0\%$, the sum of Q'_{cv} and Q'_{st} was 81%, while Q'_{v} was only 19%. Consequently, the ventilation rate predicted using the HB method was lower than those obtained using the other methods (Fig. 2 and Table 1). Furthermore, when ventilation began

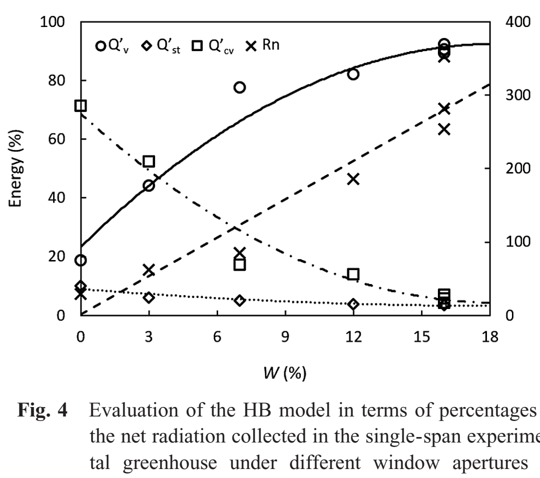

Fig. 4 Evaluation of the HB model in terms of percentages of the net radiation collected in the single-span experimental greenhouse under different window apertures on April 20–22, 2019. Q'_{v} is the ratio of the energy removed from the greenhouse by the leakage processes and ventilation to the net solar energy, Q'_{st} is the ratio of the energy stored in the soil of the greenhouse floor to the net solar energy, Q'_{cv} is the ratio of the thermal energy lost through the cover to the net solar energy, and Rn is the net solar radiation inside the greenhouse.

at $W = 3\%$, Q'_v increased to twice its initial value, reaching over 40%. However, this increase in Q'_v was insufficient to properly predict the ventilation rate because the sum of Q'_{cv} and Q'_{st} was still greater than Q'_v. Consequently, the response of the HB measurements was slow in the morning, even though W began to increase with increasing Rn. This observation indicates that the energy entering the greenhouse in the morning heated the entire greenhouse structure and floor area. The HB method began to exhibit G values equal to those of the other methods when $W =$ 13–16%, as presented in Fig. 3 and Table 1. Figure 4 also demonstrates that when the net radiation level was greater than 200 W m^{-2}, Q'_v was greater than the sum of Q'_{cv} and Q'_{st}, reaching over 80% of the total energy. Thus, the HB method produced more accurate ventilation rates when the window aperture area was moderate to high. This condition often occurs during late spring, summer, and early autumn, when the radiation levels are high. Fernandez and Bailey (1992) and Baptista et al. (2001) have also reported that the HB achieved excellent performance in high ventilation situations.

In conclusion, the HB and WVB methods for ventilation rate measurement were conducted simultaneously in a greenhouse under cultivation and the results were directly compared in spring and winter. An indirect comparison was then conducted between the results of the HB or WVB method and those of the TG method in an empty greenhouse. The HB method provided ventilation rates similar to those provided by the WVB method for moderate W values (13–16%) and inside solar radiation levels greater than 200 W m^{-2}. The WVB method provided ventilation rates similar to those provided by the TG method for small W values, and performed similarly to the HB method for moderate W values under optimal VPD conditions in the greenhouse. However, the WVB method yielded slightly higher ventilation rates under leakage conditions for the lowest VPD. As it is time consuming to monitor the photosynthetic rate of all plants cultivated in a greenhouse to evaluate their yields, it is essential that an efficient method be selected to estimate the ventilation rate. The WVB approach may better facilitate real-time and continuous greenhouse ventilation rate measurement because it is more straightforward than the HB and TG methods for small and moderate W values. Thus, the results of the present study could help to facilitate the achievement of real-time continuous monitoring of greenhouse ventilation rates, as is necessary for photosynthetic rate estimation.

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