

Measurement of Leaf Vapor Conductance of Cucumber Transplants in the Greenhouse with Minimal Invasion

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Abstract. We estimated leaf vapor conductance (g_l) of cucumber grafted transplants under greenhouse growing conditions. Fifty-six transplants were placed on a bench in the greenhouse. The transpiration rate (Tr) of the canopy was estimated by weighing the 16 transplants in the center using an electronic balance. The total vapor diffusion resistance (R_{l+b}) from inside the leaf to the atmosphere was estimated based on the vapor diffusion model, which incorporates the absolute humidity near the leaf surface and that inside the leaf as well as Tr . Next, g_l was estimated from R_{l+b} and the resistance of leaf boundary layer evaluated with a model leaf. The Tr in the afternoon tended to be larger than that in the morning at the same photosynthetic photon flux (PPF) level. By contrast, the g_l in the afternoon tended to be smaller than that in the morning at the same PPF level. The decrease of g_l in the afternoon seems to be induced by the excessive transpiration resulting from an increase of vapor pressure deficit at the leaf surface.

The leaf vapor conductance (g_l) is a useful index for the management of plant water status. The value of g_l is often estimated using porometry (e.g., Bakker, 1991). Bunce (2006) noted, however, that porometry is not suitable to evaluate the actual g_l under growing conditions, because the micrometeorology at the leaf surface is disturbed by covering the leaf with a cuvette. Alternatively, g_l also can be estimated by dividing the leaf transpiration rate (Tr) by the absolute humidity difference between the leaf surface and inside the leaf (Shibuya et al., 2009). Tr can be evaluated easily by continuously weighing the pot containing the plants and medium. This method could be applied effectively for uniform canopy constructed with small plants such as transplants. In addition, this method is especially useful for evaluating plant responses to humidity, because the effects of humidity depend on the

vapor pressure deficit (VPD) within the boundary layer of leaves (Bunce, 1984). We previously evaluated the effects of VPD on g_l of transplants canopy using the described method under a controlled environment (Shibuya et al., 2009). In this study, we tracked the changes in g_l of cucumber transplants in the greenhouse to analyze effects of environmental factors, especially VPD, on g_l under the growing conditions.

Materials and Methods

The estimation of leaf vapor conductance was performed on 20-d-old transplants of cucumber (*Cucumis sativus* L. 'Haigurin 21') grafted onto rootstock of squash (*C. moschata* Duch. 'Yuuyuuikki', black type) grown in a greenhouse (length \times width \times height: 44 \times 5.8 \times 4.0 m) at Yamaguchi-Engei Co., Ltd. (Uwajima, Japan; long. 33°8' N, lat. 132°30' E). The greenhouse was covered with plastic film and ventilated with a side window. Each transplant was grown in a plastic pot (80-mm diameter, 70-mm height) with a soil mix containing peat as the main component. At the time of measurement, each transplant had one foliage leaf and two pairs of cotyledons on the scion and rootstock, and the grafting was completed per-

fectly. The plant height of transplants was \approx 70 mm. The transplants were watered sufficiently before the measuring. Fifty-six transplants were arranged in seven columns and eight rows (Fig. 1) on a bench in the greenhouse. The surface of the growing medium was covered with a plastic film to minimize evaporation. The leaf areas of the transplants were measured with sampling the leaves after the measuring. The leaf area index of the transplant canopy calculated with the leaf areas and the canopy area was 0.90.

The weight of the 16 transplants in the center of the canopy was measured continuously with an electronic balance (BX4200H; Shimadzu Co., Ltd., Kyoto, Japan; resolution = 0.01 g) placed below the canopy. The absolute humidity and air temperature near the leaf surface was measured with humidity sensors (RHM-1000S; Ricoh Elemex Co., Ltd., Nagoya, Japan; resolution = 0.1 g·m⁻³; time for 90% response = 3 s) that estimate absolute humidity based on heat conductivity. The probes (3-mm diameter, 20-mm length) of the sensors were placed 3 mm above and below the center of the foliage leaf (\approx 60-mm length, 70-mm width) of the central transplant of the canopy. Leaf temperature was measured by contacting junctions of three thermocouples (T-type, 0.1-mm diameter) on the abaxial leaf surface. The vapor pressure near the leaf surface was estimated based on the absolute humidity. The VPD near the leaf surface was estimated by subtracting the vapor pressure near the leaf surface from the saturating vapor pressure at the leaf temperature. Air temperature and air velocity near the canopy were measured with a thermocouple (T-type, 0.1-mm diameter) and an anemometer (Anemomaster model 6071; Kanomax Japan Inc., Suita, Japan), respectively. The photosynthetic photon flux (PPF) in the greenhouse was measured with a photometer (ML-020P; EKO Instrument Co., Ltd., Tokyo, Japan). The measurements were carried out from 0600 to 1600 HR on 3 Nov. 2003. All data were collected at 1-min intervals, and 30-min averages were calculated for each parameter. The averaging time of 30 min was required to estimate evapotranspiration accurately from the change in weight of the transplants.

Tr and g_l was estimated according to the previous study (Shibuya et al., 2009) as follows: Tr (mol H₂O m⁻²·s⁻¹) was estimated based on the change in weight of the transplants. The total vapor diffusion resistance (R_{l+b} , s·m⁻¹) from inside the leaf to the atmosphere 3 mm above and below the leaf surface, accounting for the vapor diffusion resistance of leaf (R_l , s·m⁻¹) and the leaf boundary layer resistance from the leaf surface to the atmosphere 3 mm above and below the leaf surface, (R_b , s·m⁻¹), was estimated with Tr and the VPD near the leaf surface based on the vapor diffusion model. The R_l was estimated with the R_{l+b} and the R_b value evaluated using a model plant at different air velocities in a wind tunnel. The leaves of the model plants were made with

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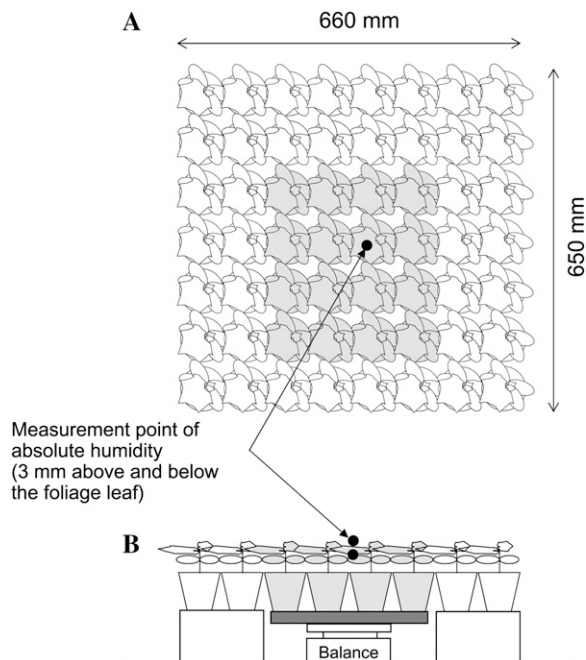


Fig. 1. Measurement setup of the cucumber transplants: (A) top view, (B) cross-section.

a wet cotton cloth. Finally, the g_1 ($\text{m}\cdot\text{s}^{-1}$) was determined from the reciprocal of R_1 . The R_b value at the air velocity near the canopy at every moment was estimated based on the relationship between air velocity and R_b measured with the model leaf and applied to the estimation of g_1 .

Relationships between the variables were analyzed by Pearson's product moment correlation coefficient at $P = 0.05$ and 0.01 .

Results and Discussion

The R_b estimated with a model leaf tended to decrease with increasing air velocity (Fig. 2). The relationship between air velocity and R_b was expressed with the exponentiation function in the same way as previous studies (Harazono and Yabuki, 1979; Jones, 1992; Yabuki, 2004). Because of a limit in ability of the wind tunnel, we could not evaluate R_b with a model plant at air velocity below $0.3 \text{ m}\cdot\text{s}^{-1}$, although air velocity in the greenhouse varied from 0.1 to $0.25 \text{ m}\cdot\text{s}^{-1}$ (Fig. 3C). Therefore, we estimated R_b of the transplants with the relationship between the air velocity and R_b at air velocity from 0.3 to $1.0 \text{ m}\cdot\text{s}^{-1}$ (Fig. 2) by extrapolation. However, R_b at lower air velocity should be evaluated to estimate R_1 and g_1 with a higher degree of accuracy, because a ratio of R_b to R_{1+b} was so large (it was 10% to 30% in this study) that it cannot be disregarded. In addition, change in leaf area during measurement probably cannot be disregarded for log-time continuous estimation of Tr and g_1 , whereas we estimated the leaf area by sampling at the end of the measurement.

During the experimental measurements, the PPF began to increase at 0730 HR, reached its maximum level at 1200 HR (Fig. 3A), and began to decrease at 1230 HR. The

temporary decrease in PPF at 1400 HR was the result of the closing of a shade in the greenhouse. The air temperature also began to increase at 0730 HR and reached its maximum level at 1230 HR (Fig. 3B). The air temperature was stable at $\approx 30^\circ\text{C}$ from 1230 to 1430 HR and then decreased from 1500 HR. The air velocity was stable at $0.1 \text{ m}\cdot\text{s}^{-1}$ from 0600 to 1000 HR and at $0.2 \text{ m}\cdot\text{s}^{-1}$ from 1100 to 1430 HR; it began to increase at 1030 HR and reached its maximum level at 1100 HR (Fig. 3C). The VPD near the leaf surface began to increase at 0800 HR and reached its maximum level at 1230 HR (Fig. 3D); it was maintained at 2.0 kPa from 1230 to 1430 HR and began to decrease at 1500 HR. The Tr began to increase at 0800 HR and reached its maximum level at 1200 HR (Fig. 4A). The temporary decrease in Tr at 1400 HR was probably the result of the decrease in PPF that occurred with the closing of the shade. The g_1 was maintained at $\approx 2 \text{ mm}\cdot\text{s}^{-1}$ from 0600 to 0730 HR, increased to $6.7 \text{ mm}\cdot\text{s}^{-1}$ at 0800 HR, and was stable at $\approx 6 \text{ mm}\cdot\text{s}^{-1}$ from 0800 to 1100 HR (Fig. 4B). The g_1 decreased by 64% from 1100 to 1300 HR and was stable at $\approx 2.5 \text{ mm}\cdot\text{s}^{-1}$ from 1300 to 1600 HR.

The Tr increased linearly with increasing PPF ($P < 0.05$; Fig. 5A). After the peak PPF , air temperature, and VPD were reached (1300 to 1600 HR), Tr tended to be larger than that before at the same PPF level. By contrast, there was no significant correlation between PPF and g_1 ($P > 0.05$; Fig. 5B). The g_1 after 1300 HR tended to be smaller than that before 1300 HR at the same PPF level. Tr increased after 1300 HR, whereas g_1 decreased after 1300 HR, which was the result of excessive increasing VPD. The lower g_1 after 1300 HR was probably the result of effects of VPD, as described subsequently.

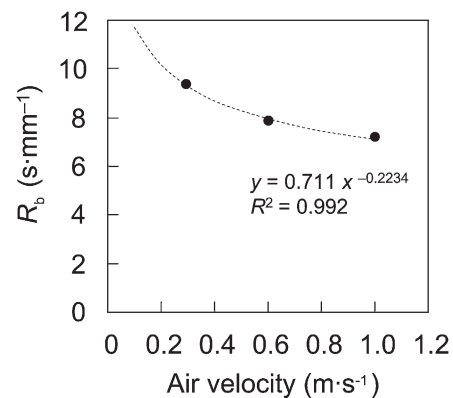


Fig. 2. Effects of air velocity on vapor diffusion resistance of the leaf boundary layer (R_b) evaluated with a model leaf.

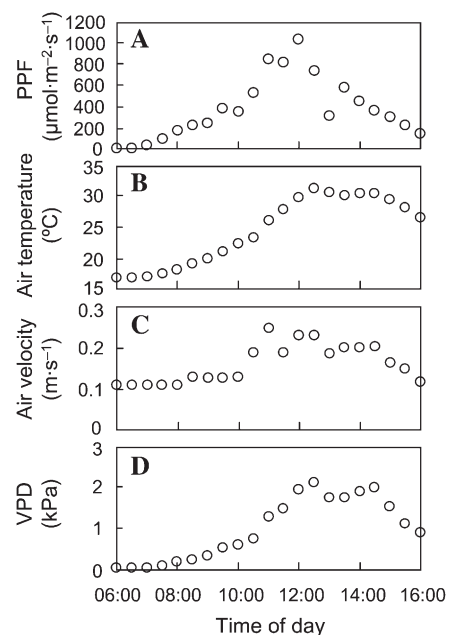


Fig. 3. Time courses of (A) photosynthetic photon flux (PPF), (B) air temperature, (C) air velocity, and (D) vapor pressure deficit (VPD) near the leaf surface of cucumber grafted transplants. Data are 30-min averages.

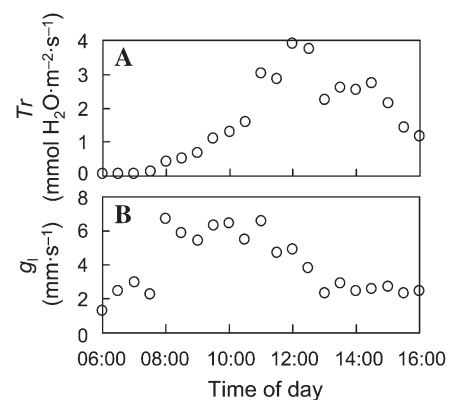


Fig. 4. Time courses of (A) transpiration rate (Tr) and (B) leaf vapor conductance (g_1) of cucumber grafted transplants. Data are 30-min averages.

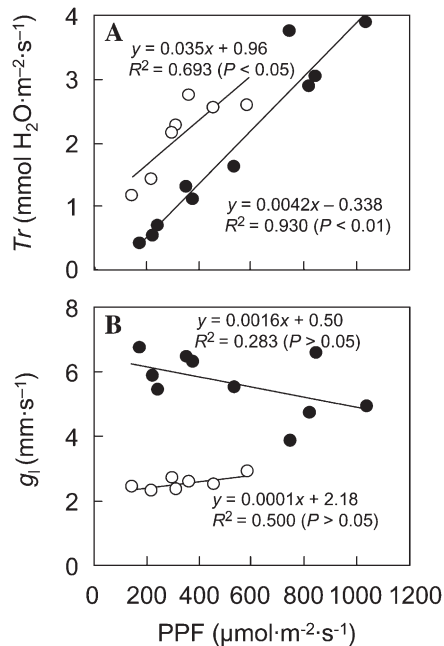


Fig. 5. Effects of photosynthetic photon flux (*PPF*) on (A) transpiration rate (*Tr*) and (B) leaf conductance (*g*_l) of cucumber grafted transplants. Solid circles: 0800 to 1230 HR; open circles: 1300 to 1600 HR.

Tr increased linearly with increasing VPD ($P < 0.01$; Fig. 6A). After the peak *PPF*, air temperature, and VPD were reached (1300 to 1600 HR), *Tr* tended to be smaller than that before (0800 to 1230 HR) at the same VPD level. This decrease in *Tr* was the result of the lower *g*_l after 1300 HR, as described subsequently. By contrast, *g*_l decreased linearly with increasing VPD from 0800 to 1300 HR ($P < 0.05$; Fig. 6B). The *g*_l after 1300 HR was lower than that before 1300 HR and did not have a significant correlation with VPD.

A high VPD could lower *g*_l by the decrease in water potential resulting from excess transpiration (Shibuya et al., 2006). The

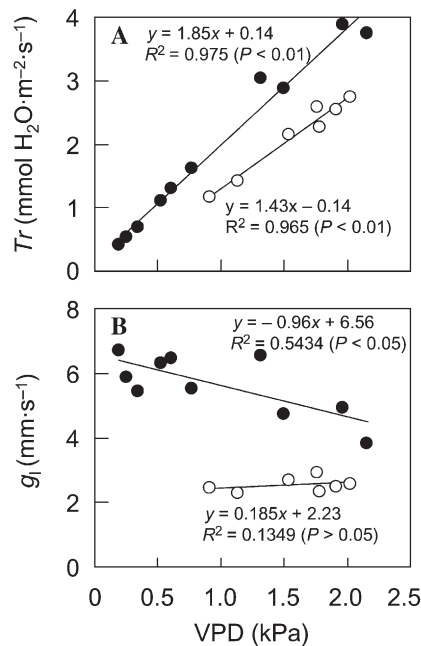


Fig. 6. Effects of vapor pressure deficit (VPD) on (A) transpiration rate (*Tr*) and (B) leaf conductance (*g*_l) of cucumber grafted transplants. Solid circles: 0800 to 1230 HR; open circles: 1300 to 1600 HR.

decrease in *g*_l after 1300 HR was probably induced by an increase in *Tr* resulting from the increasing VPD before 1300 HR. Previously, we reported that *g*_l of cucumber seedlings decreased by 45% to 65% in 30 min when VPD increased from 0.4 kPa to 2.0 kPa in a growth chamber (Shibuya et al., 2009), which is in agreement with the decreasing *g*_l with increasing VPD in this study. The *g*_l did not recover after 1430 HR, although VPD continued to decrease. This result was probably the result of hysteresis of the high VPD. For instance, Shibuya et al. (2003) reported that the effect of high VPD treatment on *g*_l remained for a few hours after the

end of the treatment. The decrease in *g*_l resulting from high VPD could simultaneously induce a decrease in carbon dioxide accumulation of the plants (Shibuya et al., 2009). The solar energy introduced to the greenhouse after 1300 HR probably did not contribute to an increase in photosynthesis, but did contribute to a decrease in *g*_l resulting from the increasing VPD.

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