Leaf Boundary Layer Conductance in a Tomato Canopy under the Convective Effect of Circulating Fans in a Greenhouse Heated by an Air Duct Heater

Kensuke Kimura1, Daisuke Yasutake2, Yuta Miyoshi1, Atsushi Yamanami1, Kaoru Daiou1, Haruo Ueno3 and Masaharu Kitano4

1 Graduate School of Bioresource and Biobehavioral Sciences, Kyushu University, Fukuoka 812-8581, Japan
2 Faculty of Agriculture, Kyushu University, Fukuoka 812-8581, Japan
3 Kumamoto Prefectural Agricultural Research Center, Kumamoto 869-4201, Japan

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The optimal design of air currents in greenhouses primarily requires a better insight into convective exchange between leaves and the environment via the leaf boundary layer. The objectives of this study were to establish a method for continuous and multipoint determination of leaf boundary layer conductance \( G_s \) in a tomato canopy within a greenhouse, and to evaluate the convective effect of circulating fans on the air currents in the tomato canopy based on vertical and horizontal profiles of \( G_s \). The operation of circulating fans changed the direction and velocity of air currents by mixing the air in the greenhouse, which reduced vertical differences of air temperature in the tomato canopy. Furthermore, convective exchange between leaves and the environment was significantly enhanced via increases in \( G_s \). However, the vertical and horizontal distributions of \( G_s \) were dependent on the locations of the circulating fans. In particular, the circulating fans set above the canopy resulted in remarkably higher \( G_s \) in the upper canopy. This approach to profiling the spatial distribution of \( G_s \) can contribute to the optimal design of air currents for efficient environmental control in greenhouses.

Keywords: artificial leaf, circulating fan, convection, greenhouse, leaf boundary layer conductance

INTRODUCTION

In greenhouses, ventilation systems and circulating fans are generally employed to improve air currents in crop canopies and to produce spatial uniformity across crop environments. Low efficiency and inadequate management of these air control systems result in poor control over the crop microclimate, which significantly affects yield and the quality of crop production (Katsoulas et al., 2007). Therefore, a method to design the optimal air currents is required to facilitate optimal control over the crop microclimate, i.e., heat and mass exchange between the plant canopy and the environment.

Leaves play a dominant role in heat and mass exchange between crop canopies and the environment as they comprise the majority of the plant surface (Delfraeye et al., 2013). As the primary organs of photosynthesis and transpiration, leaves are considered the most important sources or sinks of heat and mass in the canopy (Schuepp, 1993). The balance of heat and mass on leaf surfaces is strongly influenced by the convective exchange between leaves and the environment through the leaf boundary layer. A key factor in the convective exchange is leaf boundary layer conductance \( G_s \), which represents the transfer coefficient of convection on leaf surfaces. Thus, for optimal design of air currents in crop canopies, \( G_s \) is regulated by the convective airflow adjacent to leaves, must be evaluated. Due to the difficulty of directly measuring the air currents adjacent to leaves (Boulard et al., 2002), \( G_s \) is generally estimated using the semi-empirical formulae of forced convection (e.g., Monteith and Unsworth, 1990). However, such formulae cannot be applied under the lower air velocity in crop canopies within greenhouses, which requires consideration of both free and forced convection (i.e., mixed convection) (Kitano and Eguchi, 1989).

Leaf boundary layer conductance can be measured using the heat balance of electrically heated artificial leaves, and many researches have evaluated \( G_s \) by using various types of artificial leaves (Grace et al., 1980; Dixon and Grace, 1983; Kitano and Eguchi, 1990; Leuning and Foster, 1990; Brenner and Jarvis, 1995; Grantz and Vaughn, 1999; Stokes et al., 2006; Katsoulas et al., 2007; Kimura et al., 2016). Profiles of \( G_s \) in a greenhouse under ventilated conditions have been reported by Katsoulas et al. (2007). However, there is little information on \( G_s \) in closed conditions, which are typical of heated greenhouses during winter nights. Under such conditions, circulating fans are employed to maintain uniformity in air conditions and convective heat transfer in the crop canopies.

In this study, continuous and multipoint measurements of \( G_s \) in a tomato canopy were carried out using electrically heated artificial leaves. In addition, the vertical and horizontal distributions of \( G_s \) in the canopy within the green-
house were examined to evaluate the convective effect of circulating fans in a closed greenhouse heated by an air duct heater.

MATERIALS AND METHODS

Greenhouse facilities and plant material

The experiment was conducted in an experimental plastic greenhouse, N-S oriented (23° declination from north 0°), located in Kumamoto, Japan (Kumamoto Prefectural Agricultural Research Center: 32°33'34"N, 130°39'22"E, 3 m a.m.s.l.), during the night (January 26–27, 2016). Figure 1a shows schematic diagrams of the experimental greenhouse, crop layout, and locations of instrumentation. The total ground area of the greenhouse was 72 m² (12 m × 6 m), and ridge height was 4.5 m. Tomato plants (*Solanum lycopersicum* cv. Momotaro) were planted on September 16, 2015 at a density of 1.5 plants m⁻². The plants were grown in two rows on both the eastern and western sides of the greenhouse, with row spacing of 0.8 m. The canopy height was 2 m, and the canopy depth was 6 m.

At each side of the greenhouse, a circulating fan (AB 273, FULTA ELECTRIC MACHINERY Co., Ltd., Nagoya, Japan) with a motor output power of 40 W was positioned at a height of 2.5 m above the ground. Circulating fans supplied airflow at 40 m³ s⁻¹ horizontally from north to south at the eastern side, and from south to north at the western side. An oil-fueled heater (KA-205, NEPON Inc., Tokyo, Japan) with a motor output power of 23.3 kW was installed at the southwest point of the greenhouse, and a plastic air duct of 220 mm diameter was connected to the heater to distribute warm air around the greenhouse. The duct was divided into two branches at the front of the heater: one was oriented along the northwest edge of the greenhouse, and the other was distributed around the plants along the northeast edge of the greenhouse. In each branched duct, 11 holes of 5 mm diameter were perforated at 55 cm intervals, and warm air of 29°C, supplied at 40 m³ s⁻¹ was transferred from the heater through the ducts and discharged into the greenhouse through the vent holes and each edge of the branched ducts.

Evaluating leaf boundary layer conductance *G_A* for heat transfer

To pragmatically determine leaf boundary layer conductance *G_A*, an electrically heated artificial leaf was used to simplify the complicated process of leaf heat balance in a natural leaf. An artificial leaf of rectangular shape, 7 cm in length, 5 cm in width, and a projected area of 35 cm² was prepared (Fig. 1b). The length and width of the artificial leaf was determined by averaging characteristic dimensions of tomato leaves in the greenhouse, where the characteristic dimension represent the mean effective length along the airflow and was calculated assuming laminar flow across the leaf (Schuepp, 1993; Daudet et al., 1998; Monteith and Unsworth, 2013):

\[
d = \left( \int_0^l \frac{w(y)}{\int_0^l w(y) y^2 dy} dy \right)^2
\]  

(1)
where \( d \) (cm) is the characteristic dimension; and \( w(y) \) is the width of the leaf along the airflow at a given length \( y \) from 0 cm (leaf base) to \( l \) cm (leading edge of the leaf). Each artificial leaf consisted of two layers of brass sheet of 0.1 mm thickness that enveloped a micro heater of constantan wire of 0.1 mm diameter. A pair of thermocouples of copper-constantan wire of 0.1 mm diameter was attached to each leaf surface, and the two pairs of thermocouples (one from the upper and lower surfaces) were wired in parallel to detect the mean leaf-to-air temperature difference on each leaf surface. Electrical power was supplied to the micro heater from a regulated power supply with a voltage of 4.7 V. The electrical heat per unit leaf area \( (P_e) \) was calculated as follows:

\[
P_e = \frac{V^2}{rA} \tag{2}
\]

where \( V \) is the voltage applied to the constantan micro heater in the artificial leaf (4.7 V); \( r \) is the electrical resistance of the constantan micro heater (approximately 45 \( \Omega \)); and \( A \) is the double-sided area of the artificial leaf (70 cm\(^2\)). Therefore, \( P_e \) of approximately 70 W m\(^{-2}\) was calculated from Eq. (2).

Leaf boundary layer conductance for heat transfer can be calculated using the simplified heat balance for the single, electrically heated artificial leaf (Dixon and Grace, 1983; Kitano and Eguchi, 1990). The simplified heat balance for a single side of the heated artificial leaf is given by the following equation under the assumption of the steady state:

\[
R_c + P_e - G_sC_p(T_{A,m} - T_a) \tag{3}
\]

where \( R_c \) is the net radiation flux; \( C_p \) is the specific heat of air at a constant pressure; \( \rho \) is the air density; and \( (T_{A,m} - T_a) \) is the leaf-to-air temperature difference between the heated artificial leaf and the ambient air. During the night, \( R_c \) is determined by the exchange of longwave radiation between the artificial leaf and the environment. In this study, the brass artificial leaf was highly polished to obtain a significantly low emissivity of 0.03 (Weast and Astle, 1981), resulting in remarkably low exchange of longwave radiation. Therefore, \( R_c \) was negligibly low compared with the supplied electrical heat \( P_e \) (Wang, 1982; Dixon and Grace, 1983; Kitano and Eguchi, 1990). Finally, the heat balance of the artificial leaf can be simply expressed using only the electrical heat and sensible heat flux, and \( G_s \) for a single side of the artificial leaf was calculated by using the measured values of \( P_e \) and \((T_{A,m} - T_a)\) as following equation:

\[
G_s = \frac{P_e}{C_p \rho (T_{A,m} - T_a)} \tag{4}
\]

**Measurements in the greenhouse**

To evaluate the convective effect of the circulating fans, three types of sensors were set in the greenhouse (Fig. 1a). To evaluate \( G_s \), artificial leaves were set at eight measuring points (Fig. 1 L1–L8) at two heights of 1.2 m and 2.0 m in the middle of canopy, and temperature differences between the artificial leaves and the ambient air were measured. Air velocity \( U \) was measured using an ultrasonic anemometer (model 81000, R. M. Young Company, Traverse, MI, USA) at the center of the canopy. Data for \( G_s \) and \( U \) were recorded at 5 s intervals using a data logger system (CR1000, Campbell Scientific Inc., Logan, UT, USA). Air temperatures \( T_e \) ambient to the artificial leaves were also measured using T-type thermocouples of 0.1 mm diameter, of which sensor heads were spaced about 5 cm apart from the respective artificial leaves and the surrounding real leaves. Data of \( T_e \) were recorded at 5 s intervals using a data logger (model GL820, Graphtec Inc., Yokohama, Japan).

Measurements were recorded for 40 min from 23:50 to 0:30. The air duct heater was operated alone for the first 20 min of the 40 min, and then the circulating fans and the air duct heater were operated together for the second 20 min. Both the air duct heater and circulating fans were stopped before recording the measurements.

**Data analysis**

The convective effect of the circulating fans was evaluated by comparing changes in \( U, T_e \), and particularly \( G_s \) between periods when the air duct heater operated alone (H), and when the circulating fans and air duct heater operated together (HF). Data sampled at 5 s intervals were used in time series analyses, and significant differences between mean values for the last 10 min within the respective time periods of H and HF were tested using Tukey’s HSD.

**RESULTS AND DISCUSSION**

The convective effect of the circulating fans on the airflow in the greenhouse was measured using the 3D ultrasonic anemometer. Figure 2 shows time courses of three orthogonal components of \( U \) (i.e., \( u_x, u_y, \) and \( u_z \)) during the periods of H and HF. The east-west component \( u_x \) was remarkably increased at 0:10 in the HF period. This indicated that the convective airflow was enhanced from the eastern to the western side of the greenhouse as the airflow was affected by the air supplied from the circulating fan at the eastern side, which was closer to the measuring point of \( U \) (Fig. 1a). In addition, the north-south component \( u_z \) was somewhat increased under the influence of the airflow from the circulating fan at the eastern side. The vertical component \( u_y \) fluctuated around 0 m s\(^{-1}\) during HF, which suggests that the direction of the airflow in the canopy at 1.2 m above ground height was nearly horizontal. Katsoulas et al. (2007) reported a similar result for horizontal airflow in a plant canopy even under the greenhouse condition with roof ventilation.

Figure 3 shows time courses of \( U \) at 1.2 m height in the canopy and the mean \( T_e \) of four artificial leaves at a height of 1.2 m (L1–L4) and 2.0 m (L5–L8) during time periods H and HF. By turning on the circulating fans at 0:10, \( U \) was slightly increased but remained under almost 0.2 m s\(^{-1}\) during the measurement period, which was considered typical of the airflow within a plant canopy under greenhouse conditions (Wang et al., 1999). The difference in \( T_e \) between the heights of 2.0 m and 1.2 m gradually expanded during H as the warm air supplied was transferred upward by convection, however, the addition of the
circulating fans tended to reduce the vertical gap of $T_A$ by mixing the air in the greenhouse.

Figure 4 shows time courses of leaf boundary layer conductance $G_A$ at the eight artificial leaves ($L_1$-$L_8$) in the canopy during periods H and HF. At all the artificial leaves, $G_A$ showed greater changes during HF compared with that during H, reflecting an increase in turbulence in the canopy. Furthermore, no remarkable differences in $G_A$ between the heights of 1.2 m and 2.0 m were observed during H. However, during HF, the circulating fans set above the canopy resulted in remarkably higher $G_A$ at 2.0 m above ground height than at 1.2 m, which resulted in vertical differences of the convective airflow in the canopy. Such vertical differences of $G_A$ in plant canopies have been previously observed under field conditions (Grantz and Vaughn, 1999) and ventilated greenhouse conditions (Katsoulas et al., 2007). There were no remarkable differences in $G_A$ values between the eastern and western sides of the greenhouse during H. However, during HF, $G_A$ values at the eastern side were about 1.5 times higher than those at the western side. This may be attributed to the locations of the air ducts and circulating fans; the air ducts were symmetrically distributed in the greenhouse, whereas the circulating fans were not, as the eastern circulating fan was closer to the artificial leaves than the western one. Therefore, detection of the vertical and horizontal gaps in $G_A$ confirms that the measurement of $G_A$ using artificial leaves can accurately represent the convective airflow within the plant canopy, even under the conditions of light air velocity that are generally found in closed greenhouses.

Figure 5 shows the mean $G_A$ of four artificial leaves at 1.2 m ($L_1$-$L_4$) and 2.0 m ($L_5$-$L_8$) in the time periods H and HF. During H, there were no significant differences between $G_A$ at 1.2 m and 2.0 m height ($n=120, P<0.05$, Tukey’s HSD). By operating the circulating fans with the air duct heater, $G_A$ was significantly increased to 1.2 cm s$^{-1}$ and 2.5 cm s$^{-1}$ at heights of 1.2 m and 2.0 m, respectively. Moreover, there were significant differences in $G_A$ between 1.2 m and 2.0 m height ($n=120, P<0.05$, Tukey’s HSD) during HF.

In conclusion, a method for continuous and multipoint measurements of leaf boundary layer conductance under closed greenhouse conditions was established using artificial leaves. In addition, the convective effect of circulating fans in a closed greenhouse heated by an air duct heater was evaluated. The operation of circulating fans enhanced the convective airflow adjacent to tomato leaves by increasing the leaf boundary layer conductance $G_A$. Furthermore, during the operation of the circulating fans, there were vertical and horizontal differences in $G_A$ in the canopy, which was attributed to the asymmetrical location of the circulating fans in the greenhouse. Therefore, evaluation of three-dimensional profiles of $G_A$ is required to reveal the convective effects of the circulating fans on the entire canopy in the greenhouse.
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Fig. 4  Time courses of leaf boundary layer conductance G, at eight artificial leaves (L1–L8) during the periods when the air duct heater operated alone (H), and when the circulating fans and air duct heater operated together (HF). The artificial leaves (L1–L8) are shown in Fig. 1.

Fig. 5  Leaf boundary layer conductance G, at two heights of 1.2 m and 2.0 m during the periods when the air duct heater operated alone (H), and when the circulating fans and air duct heater operated together (HF). Data show the mean values of each of the four artificial leaves L1–L4 at 1.2 m and L5–L8 at 2.0 m, and are averaged for the second halves of the H and HF periods. Error bars represent standard deviation, and different small letters represent a significant difference at P < 0.05, using Tukey’s HSD test.


