Effect of Air Current Speed on Evapotranspiration Rate of Transplant Canopy under Artificial Light

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Abstract

Evapotranspiration rate (ET) of a sweetpotato transplant canopy (TC) under artificial light was measured at three levels (0.1, 0.3 and 0.5 m s^{-1}) of air current speed (ACS) in a wind-tunnel-type growth chamber and at leaf area indices (L) of 0.9, 1.5, 2.6 and 4.0. The ET was measured based on the weight change over time of a transplant tray, consisting of 72 transplants, soil mixture, water and a plug tray. The Penman-Monteith model (P-M) was used for estimating aerodynamic conductance (g_a) above the TC based on the measured ET and canopy conductance (g_c). It was found that ET of the sweetpotato TC increased as ACS and L increased. The increase in ACS increased g_a above TC. Increase in L increased the g_c and also g_a. Understanding the effect of ACS on ET makes it possible to control ET in the transplant production system with artificial light (TPSAL) by manipulation of ACS. Effects of ACS on the net photosynthetic rate and growth of TC should be further investigated to determine the optimum ACS in the TPSAL.

Keywords: aerodynamic conductance, leaf area index, Penman-Monteith, plug, sweetpotato, *Ipomoea batatas* (L.) Lam., 'Beniazuma'

Introduction

In the last decade, many researchers emphasized the potential benefits of the transplant production system with artificial light (TPSAL)[1,2]. The benefits include the potential to manipulate the environmental conditions in the production system to control transplant growth and development, the efficient use of limited resources and the efficient production scheduling which would be hardly achievable in transplant production under natural light. However, its commercialization has not been widely realized yet. On the other hand, knowledge and expertise for optimizing the production processes and maximizing the performance of the TPSAL have been accumulated[3]. Quantitative understanding of the effects of environmental factors such as light, CO_2 concentration, and temperature on growth and development of transplants in the TPSAL has been investigated.

Air current speed (ACS) is one of the important environmental factors affecting the growth and development of transplants in the TPSAL. In the greenhouses or under field conditions, it is difficult to control ACS in a proper range to optimize the growth of transplants[4]. In contrast, the control of ACS is considered easier in the TPSAL than in the greenhouse. However, there was not enough information available to determine optimum range of ACS in the TPSAL, especially, in the aspects of controlling transplant growth and development.

Insufficient air movement around plants suppresses the gas diffusion in the leaf boundary layer and causes dramatic decreases in transpiration and net photosynthetic rates of the plants[5], while an over-increase of ACS decreases growth of the plants[6].

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For a tomato plug transplant canopy (tomato plug TC) grown in TPSAL, an increase in ACS within a range of 0.1 to 0.6 m s^{-1} resulted in an increase in evapotranspiration rate (ET), but ACS higher than 0.6 m s^{-1} tended to saturate ET[7]. On the other hand, Kitaya et al.[8] reported that the ET of a dwarf-rice canopy linearly increased with an increase in ACS from 0.1 to 1.0 m s^{-1}. Therefore, an increase in ACS higher than 1 m s^{-1} was still effective for the increase in ET of the TC.

The objectives of the present study were to investigate the effects of ACS on the ET of sweetpotato transplant canopy in the TPSAL and analyze the effects based on leaf area index, and stomatal and aerodynamic conductances (L, g_s and g_a, respectively) measured/estimated in the TPSAL.

Materials and Methods

Preparation of TC

TC consisted of 72 sweetpotato (*Ipomoea batatas* (L.) Lam., cv. Beniazuma) transplants originating from single-leaf nodal cuttings (leaf area: 12 cm^2 per cutting, approximately) planted in a 72-cell plug tray (W 270 mm×L 550 mm, Takii Co. Ltd., Japan) filled with commercial soil mixture (Sumirin Co. Ltd., Japan). The transplants were cultured at a photosynthetic photon flux (PPF) on the canopy surface of 200 μmol m^{-2} s^{-1} with a 16 h d^{-1} photoperiod provided by twin-fluorescent lamps (FPL55EX-N, Matsushita Electric Co. Ltd., Japan). CO_2 concentration, air temperature and relative humidity were 1000 μmol mol^{-1}, 30°C, and 70%, respectively. ET of the TC was measured under the same condition as above. The TC was sub-irrigated with nutrient solution (Enshi Standard, Otsuka Chemical Co., Japan) every day throughout

Table 1 List of symbols and units for variables used in this paper

Symbol	Variable	Unit
A	Tray surface area	m^2
ACS_{ref}	Air current speed at the reference position (Fig. 1)	m s^{-1}
C_p	Specific heat of air (1010 J kg^{-1} K^{-1})	J kg^{-1} K^{-1}
D	Vapor pressure deficit	kPa
E	Evaporation rate	mol m^{-2} s^{-1}
ET	Evapotranspiration rate	mol m^{-2} s^{-1}
ET_0, ET_1	Evapotranspiration rates at L=0 or L=1	mol m^{-2} s^{-1}
G	Soil heat flux	W m^{-2}
K	Extinction coefficient (0.89 for sweetpotato TC under artificial light)	-
L	Leaf area index	-
M_{t1}, M_{t2}	Weights of transplant tray at times t_1 or t_2	g
M_w	Molecular weight of water	g mol^{-1}
RN	Net radiation flux	W m^{-2}
s	Slope of the saturation vapor density with respect to temperature (1.65×10^{-3} kg m^{-3} K^{-1} at 30°C)	kg m^{-3} K^{-1}
g_a	Aerodynamic conductance	mol m^{-2} s^{-1}
g_c	Canopy conductance	mol m^{-2} s^{-1}
g_{sl}	Stomatal conductance of leaves under the canopy	mol m^{-2} s^{-1}
g_{st}	Stomatal conductance of leaves on the top of canopy	mol m^{-2} s^{-1}
k	Gas conversion factor (40.13 mol m^{-3} at 30°C)	mol m^{-3}
t_1, t_2	Time	s
γ	Psychrometric parameter (0.482×10^{-3}kg m^{-3} K^{-1} at 30°C)	kg m^{-3} K^{-1}
λ	Latent heat of vaporization of water (2.43 MJ kg^{-1} at 30°C)	MJ kg^{-1}
ρ	Density of air (1.16 kg m^{-3} at 30°C)	kg m^{-3}

Table 2 Morphological characteristics of sweetpotato transplant canopies 7, 10, 13 and 16 days after planting

Days after planting	Leaf area index	Leaf area per transplant (cm^2)	Canopy height (cm)
7	0.9	15.6±2.7^z	8
10	1.5	26.5±5.1	9
13	2.6	47.2±5.2	11
16	4.0	72.4±9.5	13

z: mean ± standard deviation (n=10)
A transplant canopy consisted of 72 transplants originating from single-leaf nodal cuttings planted in a 72-cell plug tray filled with commercial soil mixture.

the experiment of 16 days from planting.

Measurement of ET

List of symbols and units for variables used in this paper is shown in Table 1. On Days 7, 10, 13 and 16, the TC, as described in Table 2, was transferred into a wind-tunnel-type growth chamber with ET measurement system (Fig. 1). The chamber was designed to resemble the conditions in an existing transplant production system with artificial light[9]. ET was continuously measured based on the weight change over time of the transplant tray consisting of TC, soil mixture, water and a plug tray, using a loadcell (LPOW-20, Sensor System Corp., Japan). ET was calculated using an equation [1].

$$ET=\frac{(M_{t1}-M_{t2})}{M_w\cdot(t_2-t_1)\cdot A} \quad [1]$$

ET were simultaneously measured in each of the two identical chambers at three levels of ACS measured at the reference position (ACS_{ref}, 20 cm away from the punched metal panel, see Fig. 1), that was changed stepwise in the order of 0.1, 0.3, 0.5, 0.1, 0.5 and 0.3 m s^{-1} with a time interval of 1 hour. ACS_{ref} was manually controlled by adjusting an electric current input of an inverter for a fan to the level that has been calibrated at the beginning of each measurement day. Scalar ACS_{ref} was measured at the end of the measurements using a hot-wire anemometer (Climomaster 6522, Kanomax Japan Inc., Japan) and was expressed using an average of 15 measurements. The TC surface was adjusted to the level of the lowest row of holes of airflow on the punched metal panel on each measurement day.

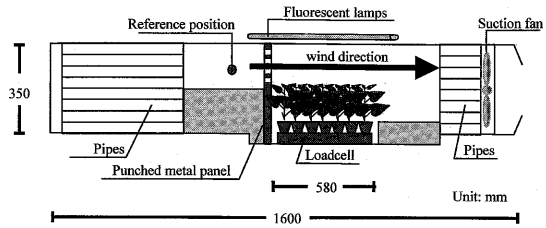

Fig. 1 A wind-tunnel-type chamber, after Kim et al.[22], for the measurement of evapotranspiration rate (ET) of the sweetpotato transplant canopy (TC) as affected by air current speed. Loadcell was used for measuring weight of the transplant tray to measure the ET. A punched metal panel was installed at the windward side of TC to imitate the condition of the closed transplant production system at Chiba University, Japan. A suction fan was installed at the leeward side of the TC to control the air current speed. A number of pipes (30 mm in diameter) were installed at the inlet of wind tunnel to reduce the turbulence, which may occur around the reference position (200 mm apart from the punched metal panel). Shorter pipes were installed at leeward side near the fan to reduce pressure drop. Fluorescent lamps were installed above the wind tunnel to use as a light source.

Estimation of g_a

The Penman-Monteith equation (P-M), which was described by Thornley and Johnson[10], was selected for estimating g_a in the present experiment. Bostick et al.[11] reported that the P-M was adequate for predicting ET in the transplant production system similar to our system when transplants become established and transpiration rate contributed significantly to ET. In order to estimate g_a, the P-M can be rewritten as follows:

$$g_a=k\cdot\frac{s\cdot(RN+G)-((\lambda\cdot ET)\cdot(s+\gamma))}{\left(\left(\frac{k\cdot\lambda\cdot\gamma\cdot ET}{g_c}\right)-(\rho\cdot C_p\cdot D)\right)} \quad [2]$$

The g_c was assumed to be independent of g_a. RN was measured using a net radiometer (C201R, LSI/Lastem, Italy). G was considered to be negligibly small compared with RN[11]. The g_c was calculated by a method of L-weighted average of two parallel conductances[12], using an equation given as,

$$g_c = g_{st} \cdot L \quad \text{when } L \leqq 1 \quad [3]$$

$$g_c = g_{st} + g_{sl} \cdot (L-1) \quad \text{when } L > 1 \quad [4]$$

The g_{st} and g_{sl} were measured using a portable photosynthesis measurement system (LI-6400, LI-COR Inc., USA) one day after the measurement of ET in the growth chamber. Conditions in the leaf chamber of LI-6400 were set to resemble the culture conditions of the TC.

Estimation of evaporation and transpiration rates

Evaporation rate (E) of TC at L=0 was estimated by extrapolating to ET at L equal to zero (ET_0) and assuming that the E decreased with decreasing radiation energy distributed in the TC, which is a function of K and L. Evaporation from the soil surface under TC at L was estimated using an equation [5].

$$E = ET_0 \cdot \exp(-L \cdot K) \quad [5]$$

Transpiration rate (T) was obtained by subtracting E from the ET.

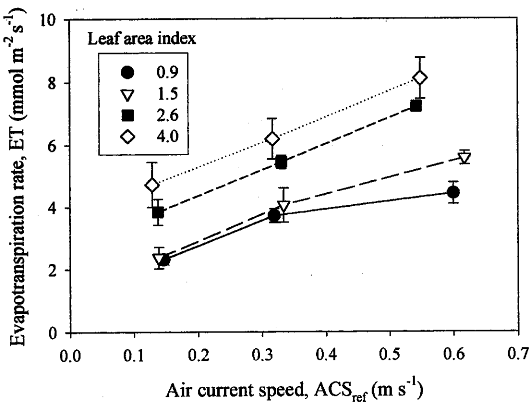

Fig. 2 Evapotranspiration rates (ET) of sweetpotato transplant canopies at leaf area indices of 0.9, 1.5, 2.6 and 4.0 as affected by air current speed at the reference position (ACS_{ref}). ET were measured based on the weight changes over time of a transplant tray, consisting of 72 transplants, soil mixture, water and a plug tray, in the wind-tunnel-type chamber. Vertical bars indicate standard deviations (n=4)

Results and Discussion

ET as affected by ACS_{ref} and L

Fig. 2 shows the ET of the TC at 3 levels of ACS_{ref} and at L of 0.9, 1.5, 2.6 and 4.0. The ET increased with the increase in ACS_{ref} and the slope of ET was different with different ACS_{ref} and L. At L of 2.6 and 4.0, ET increased linearly with the increase in ACS_{ref} in the range of 0.1 to 0.6 m s^{-1}. The slopes of ET at L of 0.9 and 1.5 were the same as those at L of 2.6 and 4.0 in the range of ACS_{ref} from 0.1 to 0.3 m s^{-1}. However, the slopes of ET at L of 0.9 and 1.5 declined when ACS_{ref} was higher than 0.3 m s^{-1}. The decline of the slope was greater at L of 0.9 than at L of 1.5.

The linear relationship between ACS_{ref} and ET at L>1.5 observed in the present experiment was in agreement with Kitaya et al.[8] where the ET of dwarf-rice canopy linearly increased with increasing ACS (0.1 to 1.0 m s^{-1}) at L of 1.4. The declining slope of ET with increasing ACS_{ref} at L≦1.5 observed in the present experiment was in agreement with Shibuya and Kozai[7] where the slopes of ET of tomato TC declined with increasing ACS from 0.1 to 0.6 m s^{-1} at L of 0.14, 0.43 and 0.87. Those results show that effect of ACS on ET is dependent on L of the TC.

For a given ACS_{ref} the ET increased with increasing L. This was expected because as the TC grew (or L increased), the surface area for transpiration increased. At the time, g_{sl} and g_{st} remained relatively constant (Table 3). However, the g_c at L of 4.0 was

Table 3 Stomatal conductances of leaves on the top of canopy and lower leaves inside the canopy of sweetpotato transplants (g_{st} and g_{sl}, respectively) on leaf area basis and stomatal conductance of the transplant canopy (g_c) on tray area basis

Leaf area index	g_{st} (mol m^{-2} s^{-1})	g_{sl} (mol m^{-2} s^{-1})	g_c (mol m^{-2} s^{-1})
0.9	0.46±0.07^z	–	0.45
1.5	0.37±0.09	0.08±0.04	0.55
2.6	0.49±0.02	0.08±0.01	0.67
4.0	0.50±0.09	0.08±0.03	0.80
AVOVA	NS	NS	–

z: Mean ± standard deviation (n=5)
The g_c was calculated by a method of L-weighted average of two parallel conductances, using an equation given as, $g_c = g_{st} \cdot L$ when L≦1 or $g_c = g_{st} + g_{sl} \cdot (L-1)$ when L>1.

about 2 times that at L of 0. 9. Thus, the increase in the ET with increasing L was partly due to the increased g_c.

ET as affected by g_a and L

Fig. 3 shows the ET of the TC at L of 0. 9, 1. 5, 2. 6 and 4. 0 as affected by the g_a estimated using P-M based on the ET and g_c measured/estimated in the present experiment. The ET increased as g_a and L increased and tended to be saturated with g_a greater than the g_a obtained in the observed range of ACS_{ref}. The maximum ET at saturated g_a may be greater at higher L. The increase in ET as L increased at the same g_a was due to the increase in g_c.

In the present experiment, the ET was measured for well-irrigated TC. The measurement of ET started 2 hours after the start of photoperiod and continued for 6 hours under conditions of nearly constant PPF, D, air temperature, and soil water content. A preliminary experiment showed that there was no significant increase or decrease in the g_c within 10 hours after the start of photoperiod under the similar condition as in the present experiment (data not shown). Smith et al.[13] reported that the g_c of a tree canopy (*Azadirachta indica* A.) was around 0. 8 mol m^{-2} s^{-1} in rainy season, although the g_c varied as the time of day and decreased to 0. 05 mol m^{-2} s^{-1} in the evening (6 p. m.). If g_c drops to 10% of the present value under water-stress conditions, the ET will be decreased by 70-80% at the same L and g_a.

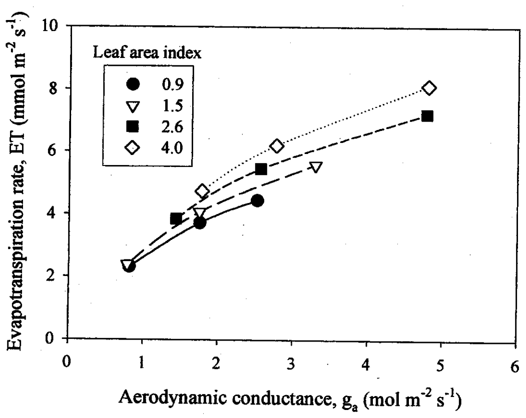

Fig. 3 Evapotranspiration rates (ET) of sweetpotato transplant canopies at leaf area indices of 0. 9, 1. 5, 2. 6 and 4. 0 as affected by aerodynamic conductance (g_a). ET were measured based on the weight changes over time of a transplant tray, consisting of 72 transplants, soil mixture, water and a plug tray, in the wind-tunnel-type chamber. The g_a was estimated using the Penman-Monteith equation given as, $g_a = k \cdot (s \cdot (RN+G)-(\lambda \cdot ET \cdot (s+\gamma)))/((k \cdot \lambda \cdot \gamma \cdot ET/g_c)-(\rho \cdot C_p \cdot D))$. The g_a was simulated under the assumption that RN was 50 W m^{-2} and D was 1. 273 kPa (70% RH at 30°C).

g_a as affected by ACS_{ref} and L

The g_a as affected by ACS_{ref} at L of 0. 9, 1. 5, 2. 6 and 4. 0 is shown in Fig. 4. The g_a estimated for TC in the present conditions was in the similar range of those reported by Smith et al.[14] for a tree canopy (*Azadirachta indica* A.) under field conditions, although the ACS (0. 7 to 3. 2 m s^{-1}) was higher than in the present experiment.

The g_a increased as ACS_{ref} increased. Teklehaimanot and Jarvis[15] and Smith et al.[14] showed that the g_a above tree canopy linearly increased with increasing ACS under field conditions. Such linear relationship was not obtained in the present experiment except at L of 1. 5. The slopes of g_a were

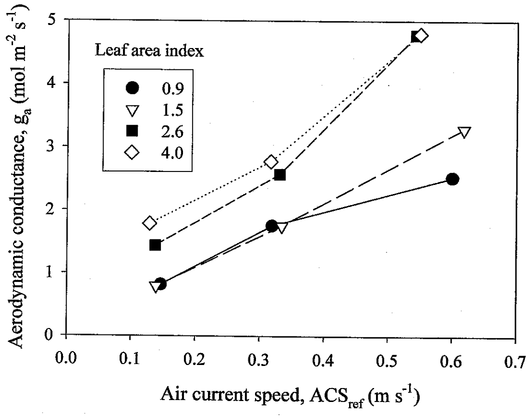

Fig. 4 Aerodynamic conductance (g_a) above the sweetpotato transplant canopy at leaf area indices of 0. 9, 1. 5, 2. 6 and 4. 0 as affected by air current speed at the reference position (ACS_{ref}). The g_a was estimated using the Penman-Monteith equation given as, $g_a = k \cdot (s \cdot (RN+G)-(\lambda \cdot ET \cdot (s+\gamma)))/((k \cdot \lambda \cdot \gamma \cdot ET/g_c)-(\rho \cdot C_p \cdot D))$. The g_a was simulated under the assumption that RN was 50 W m^{-2} and D was 1. 273 kPa (70% RH at 30°C).

similar in the range of ACS_{ref} from 0.1 to 0.3 m s^{-1} regardless of L. When ACS_{ref} was higher than 0.3 m s^{-1}, the slope of g_a declined at L of 0.9, while the slopes rose at L of 2.6 and 4.0. It was suggested that not only ACS_{ref} but also L affected the g_a. The g_a is a function of shearing stress, which increases with the increase in ACS and surface roughness of the TC[16,17]. The L altered the surface roughness of TC, and thereby affected g_a.

The differences among the slopes of g_a at L of 0.9, 1.5, 2.6 and 4.0 when ACS_{ref} was higher than 0.3 m s^{-1} might be because L affected the surface roughness of the TC or TC density, and thereby altered the airflow pattern above and inside the TC. In the present experiment, TC surface was adjusted to the level of lowest row of holes for airflow on the punched metal panel. Therefore the g_a was affected mainly by shearing stress or surface friction, and the effect of drag force around the TC was relatively small at higher L. At $L<1.5$, T was estimated to be less than 80% of the ET (Fig. 5), while it was estimated to be greater than 90% at $L \geqq 1.5$. This might suggest that the increase in ACS_{ref} affected E from the soil surface at a greater extent at $L<1.5$ than at $L \geqq 1.5$. At $L>1.5$, the g_a increased exponentially with ACS_{ref}, which might be a result of the increase in turbulence above the TC with increasing ACS_{ref}, as indicated by Monteith and Unsworth[18]. The extent of the effect of L on g_a in the present study might be greater than that in the open field because of the smaller headspace (height above the TC) in the growth chamber.

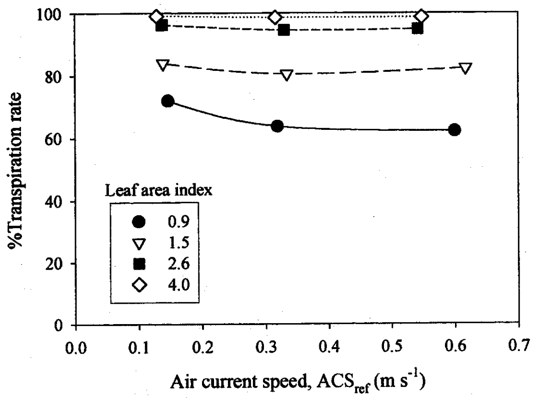

Fig. 5 Percent transpiration rate (T) over evapotranspiration rate (ET) of the sweetpotato transplant canopy at leaf area indices of 0.9, 1.5, 2.6 and 4.0 as affected by air current speed at reference position (ACS_{ref}). Evaporation rate (E) of TC was estimated by extrapolating to ET at L equal to zero and assuming that the E decreased with an increase in L as a function of K and increased L.

Control of ACS in the TPSAL

An aim of the present experiment was to find the optimum ACS_{ref} in TPSAL for maximizing or controlling growth of the TC. Results obtained in the present experiment suggest that the control of ET in the TPSAL is possible by controlling ACS_{ref}, and an increase in ACS_{ref} to 0.6 m s^{-1} or higher was necessary for the increase of ET at high L. However, when TC is not well-irrigated, an excessive ET causes the soil to dry out quickly and may result in a decrease in the soil water potential and the soil hydraulic conductivity, and consequently interruption of the water absorption of plants from the soil[19]. Thus, the plant water potential decreases rapidly, the stomata tend to close, and thereby ET and the net photosynthetic and growth rates of the TC decrease[20].

The optimum ACS should be determined with consideration of not only ET but also net photosynthetic rate of the TC. In practice, slight water stress is usually recommended for producing short and compact transplants and for hardening them before transplanting to harsh environments[21]. Thus, according to the ACS selected, irrigation should be scheduled to avoid excessive water stress, but provide a mild water stress on the TC.

Conclusion

Evapotranspiration rate (ET) of the sweetpotato transplant canopy (TC) increased as increasing air current speed at the reference position (ACS_{ref}). The increase in ACS_{ref} increased g_a above TC. Increase in L increased the canopy conductance and also aerodynamic conductance. Understanding the effects of air current speed (ACS) and leaf area index (L) on ET makes it possible to control ET in the transplant production system with artificial light by manipulation of ACS. In the determination of optimum ACS, the effects of ACS on the net photosynthetic rate and growth of TC should be further investigated.

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風速が人工光下における苗群落の蒸発散速度に及ぼす影響

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