Chapter 13
Air Current Around Single Leaves and Plant Canopies and Its Effect on Transpiration, Photosynthesis, and Plant Organ Temperatures

Yoshiaki Kitaya

Abstract Carbon dioxide (CO_2) and water vapor exchanges between plants and the atmosphere are regulated by resistance to gas diffusion from the atmosphere to the chloroplast for CO_2 diffusion (photosynthesis) and from the stomatal cavity to the atmosphere for water vapor diffusion (transpiration). Photosynthesis and transpiration are commonly controlled by stomatal and boundary layer resistances. Several environmental factors have been reported to affect photosynthesis and transpiration through the stomatal aperture. In the present chapter, the boundary layer resistance as affected by air movement is focused, and the effects of air current speeds lower than 1 m s^{-1} on net photosynthetic (P_n) and transpiration (T_r) rates of single leaves and plant seedling canopies through the boundary layer were mainly assessed. The P_n and T_r of leaves doubled as air current speeds increased from 0.01 to 0.3 m s^{-1} and were almost constant at air current speeds of 0.4–1.0 m s^{-1}. The increase in P_n and T_r was greater in the plant canopy than in the single leaf. Air movement is also important to ensure that the environmental variables remain uniform inside the plant canopy. Controlled air movement is important for enhancing the gas exchange between plants and the ambient air and is consequently important for promoting plant growth especially in semi-closed plant production facilities.

Keywords Boundary layer resistance • CO_2 • Humidity • Leaf temperature • Photosynthesis • Transpiration

---

Y. Kitaya (✉)
Graduate School of Life and Environmental Sciences, Osaka Prefecture University, 1-1 Gakuen-cho, Sakai, Osaka 599-8531, Japan
e-mail: kitaya@envi.osakafu-u.ac.jp

© Springer Science+Business Media Singapore 2016

T. Kozai et al. (eds.), *LED Lighting for Urban Agriculture*,
DOI 10.1007/978-981-10-1848-0_13

13.1 Introduction

The exchanges of carbon dioxide (CO_2) and water vapor between plants and the atmosphere are regulated by the resistance to gas diffusion from the atmosphere to the chloroplast for CO_2 diffusion (photosynthesis) and from the stomatal cavity to the atmosphere for water vapor diffusion (transpiration). In general, photosynthesis and transpiration are commonly controlled by stomatal and boundary layer resistance. Several environmental factors, including air temperature, humidity, atmospheric CO_2, light intensity, soil moisture, soil temperature, and soil salinity, have been shown to affect photosynthesis and transpiration mainly through the stomatal aperture. However, there are fewer reports on the effects of environmental factors on photosynthesis and transpiration through the leaf boundary layer. Leaf boundary layer resistance is usually predominantly controlled by air movement.

In agriculture, the utilization of semi-closed plant production facilities such as greenhouses and plant factories has become increasingly popular. In plant production in such facilities without adequate air circulation systems, air movement is extremely restricted as compared to that under field conditions. Insufficient air movement around plants increases the resistance to gas diffusion in the leaf boundary layer and thus limits photosynthesis and transpiration (Yabuki and Miyagawa 1970; Monteith and Unsworth 1990; Jones 1992; Yabuki 2004), resulting in the suppression of plant growth and development. Therefore, the enhancement of the gas exchange in leaves and the growth of plants depend on appropriate control of air movement. Thus, the aim of the present chapter is to emphasize the importance of air movement for promoting photosynthesis and transpiration and, hence, plant growth.

13.2 Effects of Air Current Speed on Boundary Layer Resistance, Photosynthesis, and Transpiration of Single Leaves

A boundary layer occurs on the surface of a plate in a fluid. The boundary layer on the leaf surface in the air is the leaf boundary layer. Inside the boundary layer, laminar airflow is more dominant than turbulent airflow and air movement is more restricted than the outside of the boundary layer. Gas and heat transfer from the surface to the surrounding air is, therefore, significantly restricted. The leaf boundary layer is thinner at higher air current speeds and over the forward edge than the following region of the leaf as shown in Fig. 13.1. The thinner boundary layer promotes more efficient gas and heat transfer.

Leaf boundary layer resistance against water vapor transfer decreased significantly as air current speeds increased from 0.01 to 0.2 m s^{-1} and decreased gradually at air current speeds ranging from 0.3 to 1.0 m s^{-1} (Fig. 13.2). The leaf boundary layer resistance at the air current speed of 0.2 m s^{-1} was a half of that at

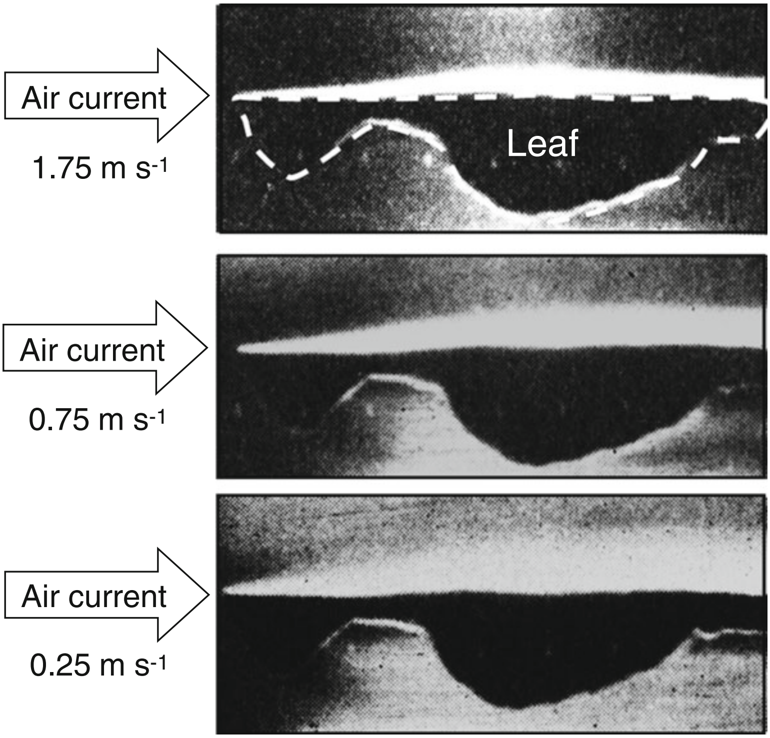


Fig. 13.1 Boundary layers (*white* parts above the leaf) on a cabbage leaf visually identified with a Schlieren optical system at different air current speeds (Yabuki 2004)

0.01 m s^{-1}. The leaf boundary layer resistance was approximately proportional to the minus 0.37 power of the air current speed. Yabuki et al. (1970) reported the same result with cucumber and cabbage leaves at air current speeds lower than 2.0 m s^{-1}. Martin et al. (1999) estimated the boundary layer conductance from energy balance measurements in the field, which is the reciprocal of the boundary layer resistance. The boundary layer conductance increased linearly from 0.01 to 0.15 m s^{-1} as air current speeds increased from 0.1 to 2.0 m s^{-1}.

The net photosynthetic (P_n) and transpiration (T_r) rates increased significantly as the air current speed increased from 0.01 to 0.2 m s^{-1} (Fig. 13.2). The T_r increased gradually at air current speeds ranging from 0.2 to 1.0 m s^{-1}, and the net photosynthetic rate reached an almost constant level at air current speeds ranging from 0.4 to 1.0 m s^{-1}.

P_n and T_r were 1.2 and 1.3 times higher, respectively, at an air current speed of 0.9 m s^{-1} than at an air current speed of 0.1 m s^{-1}, corresponding to a decrease in the leaf boundary layer resistance from 3 to 2 m^2 s mol^{-1}. Increases in air current speeds induced greater increases in T_r than in P_n.

The air current speed inside the plant canopy decreased to 30 % of that above the plant canopy (Fig. 13.3). P_n of the plant canopy increased with increasing air

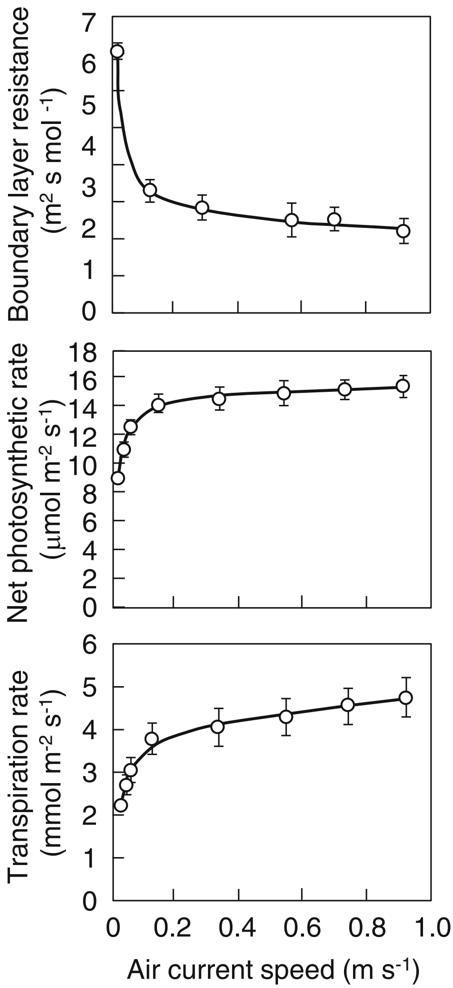


Fig. 13.2 Effect of air current speed on leaf boundary layer resistance, net photosynthetic, and transpiration rates in sweet potato leaves (Kitaya et al. 2003). Measurements were conducted with a leaf chamber method. PPFD, 1000 μmol m^{-2} s^{-1}; air temperature, 28 °C; relative humidity, 65 %; CO_2 concentration, 400 μmol mol^{-1}. *Bars* indicate standard deviations

current speeds to 1.0 m s^{-1} above the plant canopy (Fig. 13.4). P_n in the plant canopy at the air current speed of 1.0 m s^{-1} was two times higher than that at an air current speed of 0.1 m s^{-1} above the plant canopy.

Therefore, forced air movement inside plant production facilities is essential for enhancing gas exchange in leaves and thereby promoting plant growth. Forced air movement is more significant for plant canopies than for single leaves because of a significant reduction of air current speeds inside the canopy (Fig. 13.3). The P_n of plant canopies was also reported to be 1.4 times greater at an air current speed of 0.5 m s^{-1} than at 0.1 m s^{-1} for tomato seedlings (Shibuya and Kozai 1998) and two times greater at an air current speed of 1.0 m s^{-1} than at 0.1 m s^{-1} for rice seedlings (Kitaya et al. 2000). These results confirm that air movement is more important for enhancing gas exchange in plant canopies than in single leaves. The retardation of

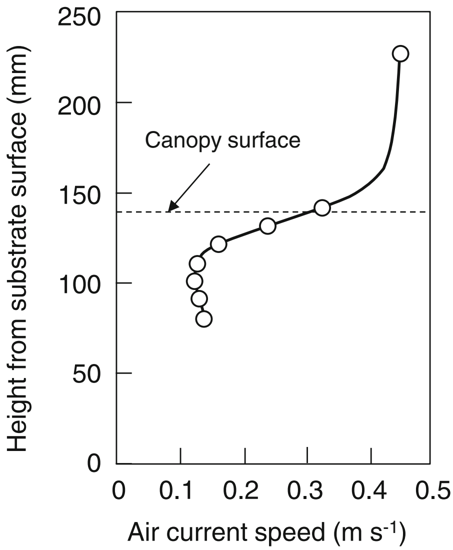


Fig. 13.3 Profile of air current speed inside and outside a tomato seedling canopy (Kitaya et al. 2003)

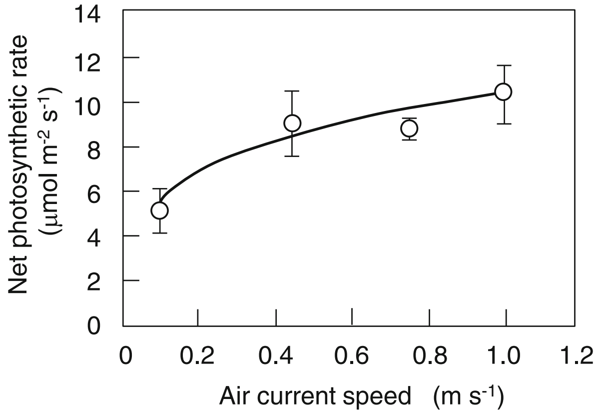


Fig. 13.4 Effect of air current speed on the net photosynthetic rate based on the rooting bed area of a tomato plant canopy (Kitaya et al. 2003). The canopy height was 0.14 m and the leaf area index was 2.1 m^2 m^{-2}. The air current speed was measured 0.1 m above the canopy. PPFD, 250 μmol m^{-2} s^{-1}; air temperature, 28 °C; relative humidity, 65 %; CO_2 concentration, 400 μmol mol^{-1}. *Bars* indicate standard deviations

gas exchange in plant canopies is due to an increased leaf boundary layer resistance (Fig. 13.2). Precise control of air movement inside plant canopies promotes gas exchange in leaves and thereby enables the growth of plants to be controllable. The greater effect of the air current speed on transpiration than on photosynthesis in leaves (Fig. 13.2) indicates that air movement affects transpiration more directly than photosynthesis.

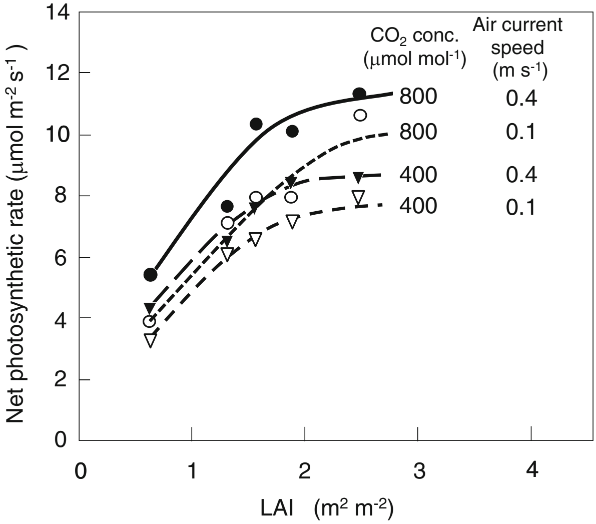


Fig. 13.5 Effects of air current speed, LAI, and CO_2 concentrations on the net photosynthetic rate of a tomato plant canopy (Kitaya et al. 2004). The canopy height was 0.14 m. The air current speed was measured 0.1 m above the canopy. PPFD measured on the canopy, 250 μmol m^{-2} s^{-1}; air temperature, 28 °C; relative humidity, 65 %. *Bars* indicate standard deviations

Figure 13.5 shows P_n of the tomato seedling canopies having different leaf area indexes (LAIs) and being affected by air current speeds and atmospheric CO_2 concentrations. The P_n based on the rooting bed area increased with increasing LAI from 0.6 to 2.0 and then tended to approach a fixed value regardless of the air current speed and atmospheric CO_2 concentrations. Increases in the air current speed and the CO_2 concentration promote photosynthesis. At an air velocity of 0.4 m s^{-1}, P_n at 0.8 mmol mol^{-1} CO_2 were 1.2 times and 1.3 times those at 0.4 mmol mol^{-1} CO_2 when the LAI was 0.6 and 2.5, respectively. At the air current speed of 0.1 m s^{-1}, P_n at 0.8 mmol mol^{-1} CO_2 were 1.2 times and 1.4 times those at 0.4 mmol mol^{-1} CO_2 when the LAIs were 0.6 and 2.5, respectively. The data showed that P_n increased more significantly with elevated CO_2 levels in the plant canopy having higher LAIs and at lower air current speeds.

Figure 13.6 shows the effect of the air current speed inside the plant canopy on P_n based on the leaf area under different LAI and CO_2 conditions. The P_n of the plant canopy increased with increasing air current speeds inside the plant canopy and saturated at 0.2 m s^{-1} (0.5 m s^{-1} above the plant canopy). P_n at the air current speed of 0.2 m s^{-1} was 1.3 times that at 0.05 m s^{-1} at 0.4 and 0.8 mmol mol^{-1} CO_2. The P_n at 0.8 mmol mol^{-1} CO_2 was 1.2 times that at 0.4 mmol mol^{-1} CO_2 at air current speeds ranging from 0.1 to 0.8 m s^{-1}. Forced air movement is more significant for plant canopies than for single leaves because of significant reduction of the air current speed inside the plant canopy compared with that above the plant canopy (Fig. 13.3).

The evapotranspiration rate of a tomato seedling canopy was also reported to increase with increasing air current speeds as well as P_n (Shibuya and Kozai 1998). The appropriate air current speeds for enhancing gas exchanges in leaves must be kept higher than 0.2 m s^{-1} in the vicinity of the leaves. Forced air movement is essential for plant canopies in closed plant culture chambers, and the air current

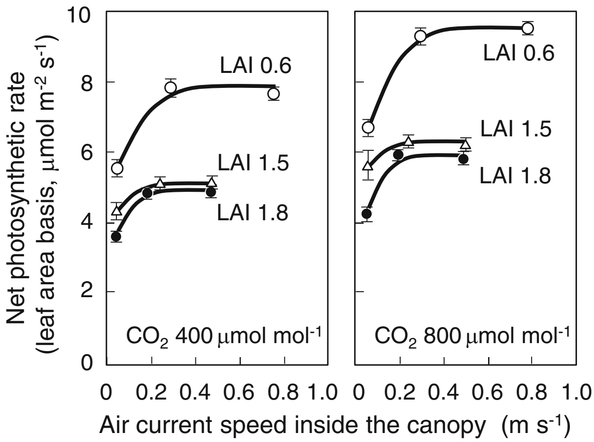


Fig. 13.6 Effect of air current speeds inside tomato seedlings canopies with different LAIs on the net photosynthetic rate based on the leaf area under different CO_2 levels (Kitaya et al. 2004). The measurement condition was the same as Fig. 13.5

speed above the canopy should be higher than 1.0 m s^{-1} to obtain maximal gas exchange rates of the dense plant canopy.

13.3 Effect of Air Current Speed on the Surface Temperatures of Plant Organs

The thermal images of sweet potato leaves showed a decrease in temperatures with increasing air current speeds under a lighting condition (Fig. 13.7). The decrease in temperature is mainly due to the promotion of transpiration and thus an increase in latent heat transfer. The surface temperature was lower at the forward edge than the following regions depending on the thickness of the boundary layer (Fig. 13.1).

Figure 13.8 shows the effect of air movement on the temperature of leaves and reproductive organs of strawberry plants. Leaf temperatures were higher than the temperatures of other organs. The difference in temperatures among the organs may depend on the boundary layer resistance and the heat capacity per surface area of each organ. Temperatures of reproductive organs and leaves decreased with increasing air current speeds. The temperatures of petals, stigmas, anthers, and leaves decreased by 12.8, 11.9, 13.1, and 14.1 °C, respectively, when the air current speed increased from 0.1 to 1.0 m s^{-1}.

The decrease in leaf temperatures was similar when affected by air current speeds at different relative humidity levels in the surrounding air (Fig. 13.9). Leaf temperatures decreased with decreasing relative humidity from 92 % to 66 % due to an increase in differences of water vapor pressures between leaves and air. However, leaf temperature increased with decreasing relative humidity to 52 %. This phenomenon is due to an increase in stomatal resistance caused by stomatal closure to avoid excess water loss.

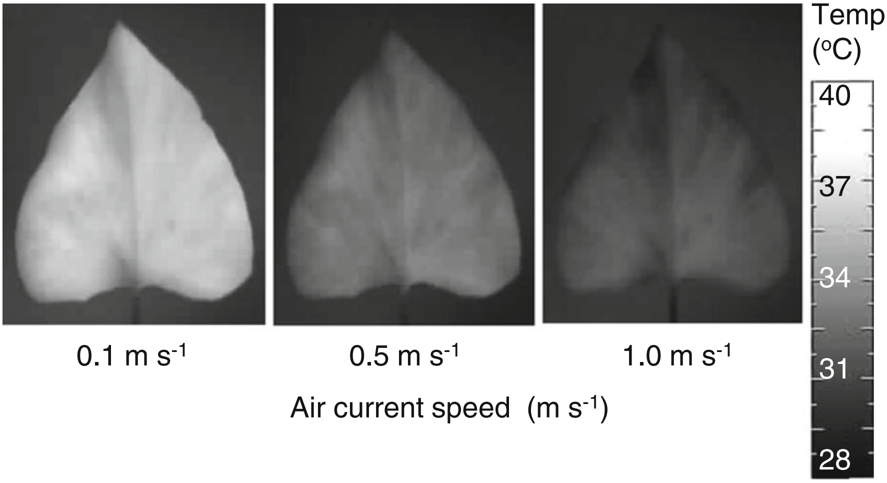
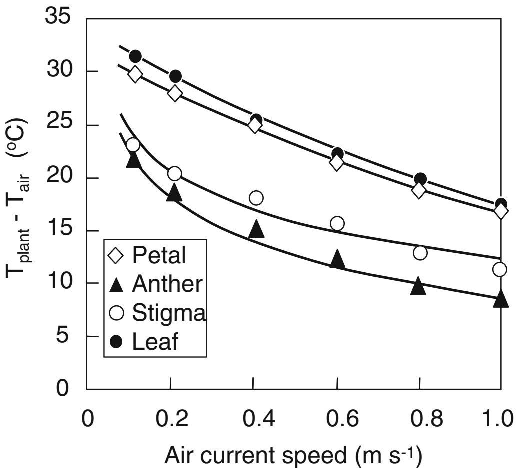


Fig. 13.7 Thermal images of the sweet potato leaf as affected by air movement. Airflow direction was from the *top* to the *bottom* in each figure. Air temperature, 29 °C; relative humidity, 50 %; irradiance, 350 W m^{-2}

Fig. 13.8 Effect of air current speed on temperatures (T_{plant}) in reproductive organs and leaves of strawberry plants (Kitaya and Hirai 2007). Mean values ($n = 3$) and logarithmic approximation curves are shown. Light source, metal halide lamp; irradiance, 100 W m^{-2}; air temperature (T_{air}), 10 °C; relative humidity, 75 %



13.4 Effects of Light Intensity and Air Current Speed on the Air Temperature, Water Vapor Pressure, and CO_2 Concentration Inside Plant Canopies

Restricted air movement induced spatial variations of environmental variables such as air temperature, water vapor pressure, and CO_2 concentration inside eggplant seedling canopies (Kim et al. 1996; Kitaya et al. 1998). Under a photosynthetic photon flux density (PPFD) of 500 μmol m^{-2} s^{-1}, 2–3 °C higher air temperatures,

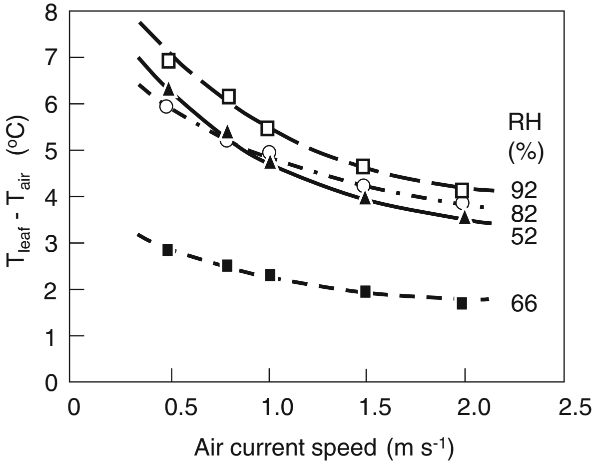


Fig. 13.9 Effects of air current speed and relative humidity (RH) on temperature differences between the leaf (T_{leaf}) of sweet potato and air (T_{air}). Mean values ($n = 3$) and logarithmic approximation curves are shown. Light source, metal halide lamp; irradiance, 360 W m^{-2}, air temperature (T_{air}), 25 °C

0.6 kPa higher water vapor pressures, and 25–35 μmol mol^{-1} lower CO_2 concentrations were observed at around the canopy height than at a height 60 mm above the canopy (Fig. 13.10). Air temperatures and water vapor pressures increased and CO_2 concentrations decreased inside the canopy with increasing PPFD. Lower air temperature and higher CO_2 concentration inside the canopy were observed at an air current speed of 0.3 m s^{-1} than at that of 0.1 m s^{-1} (Fig. 13.11).

Considerable differences in the levels of environmental variables were observed between the inside and outside of plant canopies. Control of environmental variables surrounding plants is important for scheduling crop production and obtaining high yields with a rapid turnover rate in plant production. Precise control of environmental variables inside plant canopies, with sufficient air movement, is necessary for enabling the growth of plants to be controllable.

13.5 Concluding Remarks

Control of air movement is important for enhancing gas exchange between plants and the ambient air and is consequently important for promoting plant growth. Environmental variables surrounding plants must be controlled precisely under adequate air currents for scheduling plant production associated with rapid growth and a high turnover rate. Effective air movement is essential to promote plant growth and development during vegetative and reproductive growth stages. More suitable air movement can also ensure that the environmental variables remain more homogeneous inside the plant canopy.

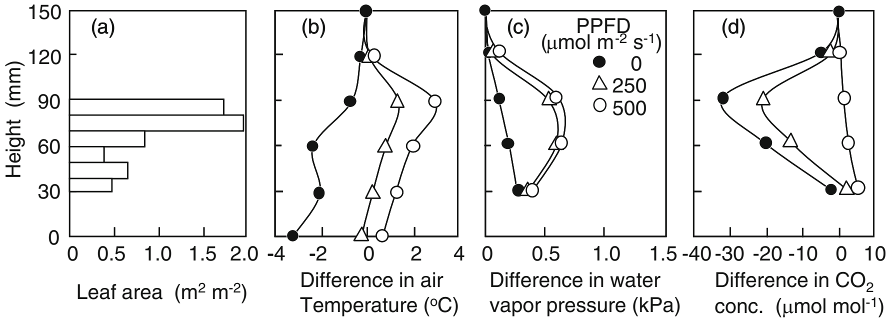
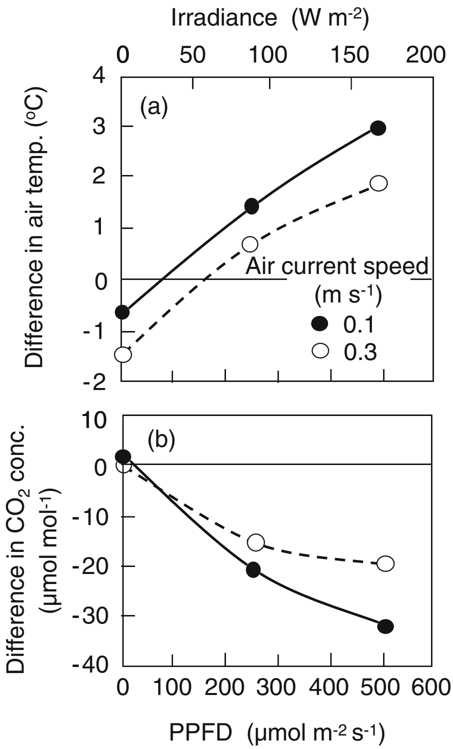


Fig. 13.10 Profiles of leaf area (**a**), air temperature (**b**), water vapor pressure (**c**), and CO_2 concentration (**d**) inside and outside the canopy of eggplant seedlings as affected by PPFD at an air current speed of 0.1 m s^{-1} (Kitaya et al. 1998)

Fig. 13.11 Effects of PPFD and air current speed on differences in the air temperature (**a**) and CO_2 concentration (**b**) between two heights at around the canopy height and 60 mm above the canopy (Kitaya et al. 1998)



References

Jones HG (1992) Plants and microclimate. Cambridge University Press, Cambridge

Kim YH, Kozai T, Kubota C et al (1996) Effects of air velocities on the microclimate of plug stand under artificial lighting. Acta Hortic 440:354–359

Kitaya Y, Hirai H (2007) Thermal situation of plant reproductive organs affected by gravity and light intensity. J Jpn Soc Micrograv Appl 24(4):325–329
Kitaya Y, Shibuya T, Kozai T et al (1998) Effects of light intensity and air current speed on air temperature, water vapor pressure and CO_2 concentration inside a plants stand under an artificial lighting condition. Life Support Biosph Sci 5:199–203
Kitaya Y, Tsuruyama J, Kawai M et al (2000) Effects of air current on transpiration and net photosynthetic rates of plants in a closed plant production system. In: Kubota C, Chun C (eds) Transplant production in the 21st century. Kluwer Academic Publishers, Dordrecht, pp 83–90
Kitaya Y, Tsuruyama J, Shibuya T et al (2003) Effects of air current speed on gas exchange in plant leaves and plant canopies. Adv Space Res 31:177–182
Kitaya Y, Shibuya T, Yoshida M et al (2004) Effects of air velocity on photosynthesis of plant canopies under elevated CO_2 levels in a plant culture system. Adv Space Res 34:1466–1469
Martin TA, Hinckley TM, Meinzer FC et al (1999) Boundary layer conductance, leaf temperature and transpiration of *Abies amabilis* branches. Tree Physiol 19:435–443
Monteith JL, Unsworth HM (1990) Principles of environmental physics. Edward and Arnold Publishing Co, London
Shibuya T, Kozai T (1998) Effects of air velocity on net photosynthetic and evapotranspiration rates of a tomato plug sheet under artificial light. Environ Control Biol 36:131–136 (in Japanese with English summary)
Yabuki K (2004) Photosynthetic rate and dynamic environment. Kluwer Academic Publishers, Dordrecht
Yabuki K, Miyagawa H (1970) Studies on the effect of wind speed on photosynthesis (2) the relation between wind speed and photosynthesis. J Agric Methods 26:137–141 (in Japanese with English summary)
Yabuki K, Miyagawa H, Ishibashi A (1970) Studies on the effect of wind speed on photosynthesis (1) boundary layer near leaf surfaces. J Agric Methods 26:65–70 (in Japanese with English summary)