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EFFECTS OF AIR CURRENT SPEED ON GAS EXCHANGE IN PLANT LEAVES AND PLANT CANOPIES

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ABSTRACT

To obtain basic data on adequate air circulation to enhance plant growth in a closed plant culture system in a controlled ecological life support system (CELSS), an investigation was made of the effects of the air current speed ranging from 0.01 to 1.0 m s^{-1} on photosynthesis and transpiration in sweetpotato leaves and photosynthesis in tomato seedlings canopies. The gas exchange rates in leaves and canopies were determined by using a chamber method with an infrared gas analyzer. The net photosynthetic rate and the transpiration rate increased significantly as the air current speeds increased from 0.01 to 0.2 m s^{-1}. The transpiration rate increased gradually at air current speeds ranging from 0.2 to 1.0 m s^{-1} while the net photosynthetic rate was almost constant at air current speeds ranging from 0.5 to 1.0 m s^{-1}. The increase in the net photosynthetic and transpiration rates were strongly dependent on decreased boundary-layer resistances against gas diffusion. The net photosynthetic rate of the plant canopy was doubled by an increased air current speed from 0.1 to 1.0 m s^{-1} above the plant canopy. The results demonstrate the importance of air movement around plants for enhancing the gas exchange in the leaf, especially in plant canopies in the CELSS.

INTRODUCTION

Plants cultured in space will play important roles in food production, CO_2/O_2 conversion and water purification in the controlled ecological life support system (CELSS). Life support of crews in space is dependent on both the amount of food and atmospheric O_2 produced by plants grown at a high density in a limited space. Therefore, scheduling of crop production, obtaining high yields with a rapid turnover rate, and converting atmospheric CO_2 to O_2 efficiently should be established with enhancing gas exchange in leaves and controlling environmental variables around plants. The enhancement of gas exchange in leaves and precise control of the environment for plant growth would be dependent on control of air current in a closed chamber.

The air current in a closed chamber without any adequate air circulation systems will be slower than that under greenhouse and field conditions because of less convection. Insufficient air movement around plants generally limits

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their growth by suppressing the gas diffusion in the leaf boundary-layer and thus by decreasing photosynthetic and transpiration rates (Yabuki and Miyagawa, 1970; Monteith and Unsworth, 1990). Furthermore, little air movement was shown to induce spatial variations in air temperature, CO_2 concentration and humidity inside the stand of plants (Kitaya *et al.*, 1998). Nonuniformity of growing plants may thus be attributed to variability in the environmental components around the plants. On earth, air movements are induced by free convection with temperature differences even inside the closed chamber, without any forced ventilation systems. Air movement, however, would be significantly retarded because very little free convection would occur under microgravity in space.

Therefore, control of air movement in a closed plant culture system in the CELSS is essential to enhance gas exchange between plants and the ambient air, and consequently promote plant growth. In the present study, effects of the air current speed on photosynthesis and transpiration of plants were investigated, and the appropriate range of air current speed for enhancing gas exchanges in leaves was determined.

MATERIALS AND METHODS

Measurements of the net photosynthetic rate, transpiration rate and boundary-layer resistance of plant leaves were made with sweetpotato leaves (*Ipomoea batatas* (L.) Lam.) in a leaf chamber as shown in Figure 1. The measurement system was a modification of a commercial system (CIRAS-1, Koito Industries Ltd., Japan) for measuring the net photosynthetic and transpiration rates of a single leaf. A central portion (250 mm^2 in area) of the leaf was covered with the leaf chamber for measurement of gas exchange rates. The net photosynthetic rate and the transpiration rate in leaves were determined with the differences in CO_2 and water vapor concentrations, respectively, between the inlet and outlet of the leaf chamber and the volumetric air exchange rate of the leaf chamber. The boundary-layer resistance (R_b) to water vapor diffusion on the leaf was estimated using a leaf replica made of wet paper placed in the leaf chamber. The resistance was determined by the equation, $R_b = (H_l - H_a) / E$, where E is the evaporation rate of the leaf replica, and H_l and H_a are the absolute humidity on the leaf replica and the atmosphere in the leaf chamber, respectively. H_a was kept at a constant value and H_l was assumed to be the saturated level of water vapor at the surface temperature of the leaf replica. Concentrations of CO_2 and H_2O were measured with an infrared gas analyzer and leaf temperature with an infrared radiation thermometer in the measurement system. The air current speeds examined were varied from 0.01 to 1.0 m s^{-1} by using controllable air circulation fans in the leaf chamber. The air current speed was measured with a modification of an anemometer (Model 6071, Nihon Kanomax, Japan). The light source was metal halide lamps. Leaf temperature was kept precisely at 25 °C. During the experiment, the conditions inside the leaf chamber were maintained at a PPF of 1000 μmol m^{-2} s^{-1}, an air temperature of about 28 °C, a relative humidity of 65% and a CO_2 concentration of 400 μmol mol^{-1}.

Measurements of the net photosynthetic rate in the plant canopy were made with tomato (*Lycopersicon esculentum* Mill., cv. Momotaro) seedlings canopies. The seedlings were grown in a plastic tray (320 mm in width and 320 mm in length) having 128 cells (40 x 40 mm^2 and 40 mm in depth each) under fluorescent lamps at a PPF of 260 μmol m^{-2} s^{-1}, a day-length of 12 h, air temperatures of 28/20 °C (photoperiod/dark period), a relative humidity of 75% and a CO_2 concentration of 400 μmol mol^{-1}. Three-week old plants were used in the experiment. The planting density was 625 seedlings per square meter. The plant height was about 0.15 m and the leaf area index was 2.1 m^2 m^{-2}. The net photosynthetic rate of the plant canopy was determined with an open type assimilation chamber (600 x 1700 x 500 mm^3, Figure 2) involving a wind tunnel (480 x 900 x 370 mm^3). The differences in CO_2 concentrations between the inlet and the outlet of the assimilation chamber were measured using an infrared CO_2 analyzer (LI 6262, LI-COR). Air current speeds were measured with an anemometer and controlled with four controllable ventilation fans in the wind tunnel. The light source was fluorescent lamps (FPL55EX-N, Matsushita Electric Co., Japan). The conditions inside the assimilation chamber during the measurement were maintained at a PPF of 250 μmol m^{-2} s^{-1}, an air temperature of 28 °C, a relative humidity of 65% and a CO_2 concentration of 400 μmol mol^{-1}.

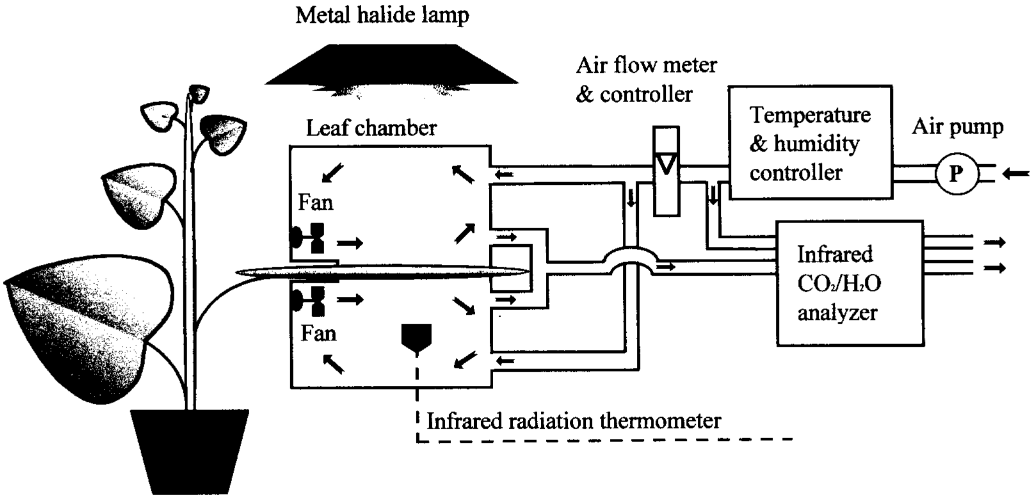

Fig. 1. The apparatus for measuring the transpiration and net photosynthetic rates of a leaf. Arrows indicate direction of air flow.

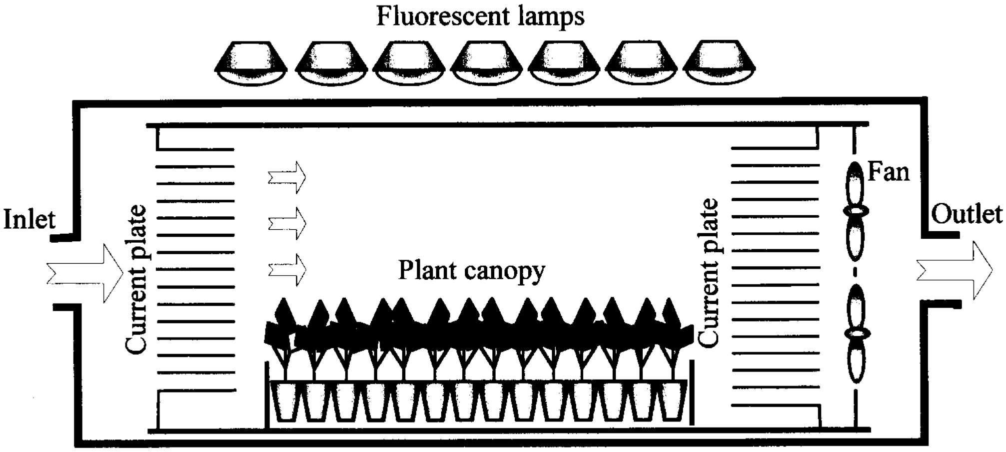

Fig. 2. Apparatus for measuring the net photosynthetic rate of plant canopies. Arrows indicate direction of air flow.

RESULTS

The air current speed decreased with decreasing voltages applied to the air circulation fan in the leaf chamber. When the air circulation fan stopped, a slight air movement (approximately 0.01 m s^{-1}) was estimated with an air flow rate of 200 mL min^{-1} through the inlet to the outlet of the leaf chamber. The leaf boundary-layer resistance decreased significantly as the air current speeds increased from 0.01 to 0.2 m s^{-1} and it decreased gradually at air current speeds ranging from 0.3 to 1.0 m s^{-1} (Figure 2). The leaf boundary-layer resistance at the air current speed of 0.2 m s^{-1} was one third that at 0.01 m s^{-1}. The net photosynthetic rate and the transpiration rate increased significantly as the air current speeds increased from 0.01 to 0.2 m s^{-1}. The transpiration rate increased gradually at air current speeds ranging from 0.2 to 1.0 m s^{-1} and the net photosynthetic rate was almost constant at air current speeds ranging from 0.5 to 1.0 m s^{-1}.

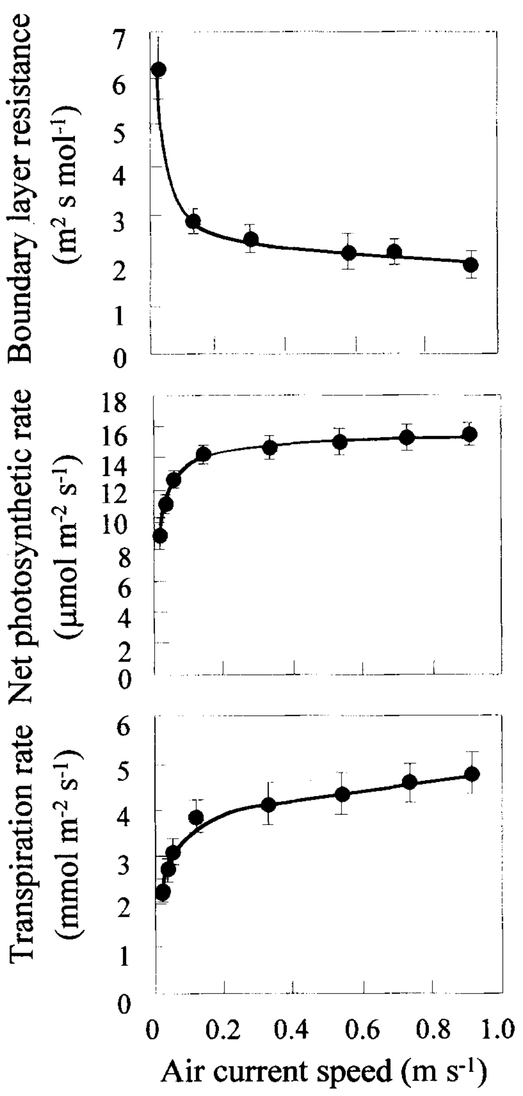

Fig. 3. Effects of air current speeds on leaf boundary-layer resistance, net photosynthetic and transpiration rates in sweetpotato leaves. Bars indicate standard deviations.

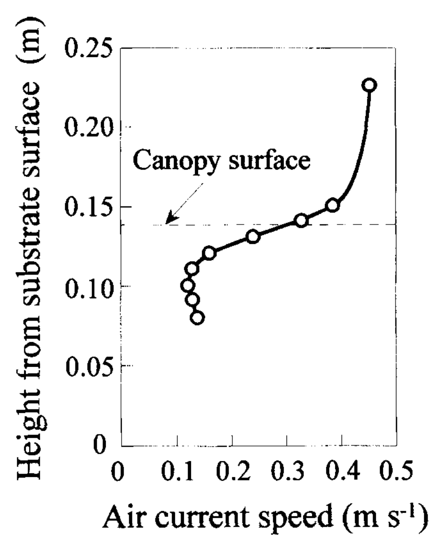

Fig. 4. Profile of air current speeds inside and outside of tomato seedlings canopy.

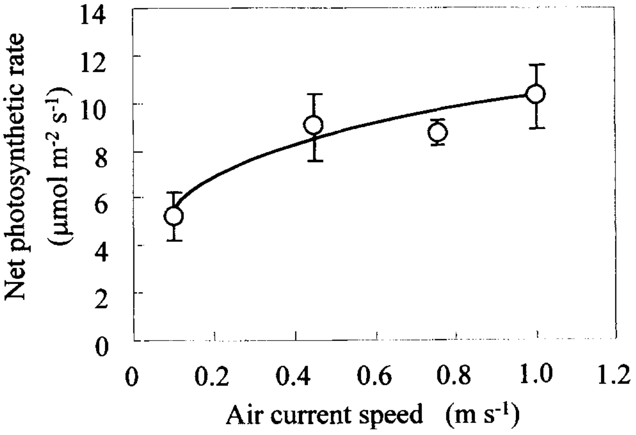

Fig. 5. Effects of the air current speed on the net photosynthetic rate of the tomato plant canopy. Bars indicate standard deviations.

The net photosynthetic rate and the transpiration rate at the air current speed of 0.9 m s^{-1} were 1.8 times and 2.2 times higher, respectively, than at the air current speed of 0.01 m s^{-1}, corresponding to the decrease in the leaf boundary-layer resistance from 6 to 2 m^2 s mol^{-1}. The increment of the transpiration rate was greater than that of the net photosynthetic rate with increases in the air current speeds. The restricted air current speed inside the leaf chamber limited the photosynthesis and transpiration in the leaf through the increase in the leaf boundary-layer resistance.

The air current speed inside the plant canopy decreased to 30% of that above the plant canopy (Figure 4). The net photosynthetic rate of the plant canopy increased with increasing air current speeds to 1.0 m s^{-1} above the plant canopy (Figure 5). The net photosynthetic rate 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.

DISCUSSION

From the viewpoint of air movement, a closed plant culture chamber in space is analogous to a plant tissue culture vessel on earth. Inside the plant tissue culture vessel, an upward air current at the center and a downward air current near the vessel walls were observed by visualizing the currents with tracers. (Kitaya et al., 1997). Air current patterns were affected by the temperature variation and showed air current speeds of less than 24 mm s^{-1}. The net photosynthetic rate of the plantlets decreased by 20 % as the air current speed decreased from 8 to 3 mm s^{-1} in the vessel (Kitaya et al., 1996). Positive effects of forced ventilation on growth during in vitro culture have been demonstrated in several reports (e. g., Nakayama et al., 1991; Kubota and Kozai, 1992). Net photosynthesis of potato plantlets in vitro was greater in forcibly ventilated than in naturally ventilated culture vessels under otherwise identical conditions (Nakayama *et al.*, 1991). Enhancement of photosynthesis in the forcibly ventilated culture vessel would be attributed to improved air movement in the culture vessel. In the present study, the air current speeds of less than 0.1 m s^{-1} significantly affected gas exchange in leaves. Therefore, forced air movement inside the plant chamber would be essential for enhancing gas exchanges in leaves and thereby promoting plant growth, because little free convection would occur under microgravity in space.

Forced air movement is more significant for a plant canopy than for a single leaf because of a significant reduction of the air current speeds inside the canopy (Figure 4). The net photosynthetic rate of a plant canopies was 1.4 times greater under an air current speed of 0.6 m s^{-1} than under 0.1 m s^{-1} for tomato seedlings (Shibuya and Kozai, 1998) and two times greater under an air current speed of 1.0 m s^{-1} than under 0.1 m s^{-1} for rice seedlings (Kitaya et al., 2000). The findings of the present study confirm these results and demonstrate the importance of air movement for enhancing gas exchange in plant canopies. The retardation of gas exchange in plant canopies would be due to the increased leaf boundary-layer resistance (Figure 3) and the considerable differences in the levels of environmental variables between the inside and the outside of the plant canopies (Kim *et al.*, 1996; Kitaya *et al.*, 1998). Precise control of environmental variables inside the plant canopies, with sufficient air movement, will promote gas exchange in leaves and thereby enable the growth of plants to be controllable in the CELSS. The greater effect of air current speeds on transpiration in leaves than on photosynthesis in leaves (Figure 3) indicates that air movement is important, not only for promoting plant growth but also for obtaining efficient water purification by using plant transpiration in the CELSS.

In conclusion, the appropriate air current speeds for enhancing gas exchanges in leaves were determined to be more than 0.2 m s^{-1} in the vicinity of the leaves. Forced air movement is essential for plant canopies in the closed plant culture chamber and the air current speed above the canopy should be more than 1.0 m s^{-1} to obtain maximal gas exchange rates of the plant canopy.

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