Important Role of Air Convection for Plant Production in Space Farming

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Abstract

The present paper aims to outline problems for growing healthy plants over a complete ontogenetic cycle in space farming. Possible effects of sub-gravity or microgravity conditions on suppression of plant growth and reproduction were summarized in a view of heat and gas exchanges between leaves and reproductive organs of plants and atmosphere. It is concluded that proper control of air movement would be essential to make the environmental variables uniform inside the plant canopy and to enhance the heat/gas exchange between plants and the ambient air and thus promote growth of healthy plants under microgravity conditions in space farming. ©2010 Jpn. Soc. Biol. Sci. Space; Article ID: 102403009

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Introduction

Plant growth and reproduction in space have been of increasing concern as the possibility increases for long term manned space flights. The feasibility of maintaining long term manned space missions is dependent upon culturing crops in Bioregenerative Life Support Systems (BLSS) or space farms that will provide food, CO₂/O₂ conversion and water purification.

The space environment including such factors as altered gravity and cosmic rays may affect vegetative and reproductive growth of plants in various ways. Several space flight experiments with plants in the early stage have observed poor growth, poor seed production and genetic aberrations (Merkies and Laurinavichyus, 1983; Mashinsky *et al.*, 1994; Salisbury *et al.*, 1995). Insufficient (Porterfield, 2002) or excess supply (Wheeler *et al.*, 1999; Monje and Bugbee, 1998) of CO₂ to plants caused their poor growth in plant growing facilities in space. Exposures to high ethylene concentrations caused by biogenic activity also negatively affected plant growth

and morphology (Klassen and Bugbee, 2002; Stutte and Wheeler, 1997). In addition, waterlogging in the rootzone due to inadequate moisture distribution in the rooting substrate may cause a stress under microgravity conditions (Jones and Or, 1998).

The space-specific stress caused the chromosomal anomalies in cells of plants grown in space (Krikorian, 1996). Bubenheim *et al.* (2003) reported that pollen from super-dwarf wheat grown on the Mir space station contained only one nuclei due to a high level of atmospheric ethylene (1.2 μmol mol⁻¹), while normal viable pollen is tri-nucleate. Carbon dioxide enrichment and air exchange in plant growth chambers allowed pollen and ovule development to occur normally (Musgrave *et al.*, 1997), and the absence of convective air flow caused physiological disorder of pollen development under space flight conditions (Musgrave and Kuang, 2003). The failure in seed production and genetic aberrations may be due to either microgravity or increased dosage of cosmic rays in space or resulting from unfavorable growing conditions in the plant growing facility. However, we still do not know whether these alterations cause significant changes in morphology and function of whole plants and reproductive organs when grown in prolonged space flights. These questions would be answered by long-term experiments conducting with space facilities such as International Space Station.

In space farming under sub-gravity (3/8 G on Mars, 1/6 G on Moon, and microgravity in spacecrafts) conditions, the transfer of heat and gases between plant surfaces and their environment is inhibited due to the absence or retardation of buoyancy dependent convective transport. Yamashita *et al.* (2006) discussed heat and mass transfer in Martian greenhouse dome under the sub-gravity and sub-atmospheric pressure environment. The utilization of closed plant culture facilities is anticipated in space. In such facilities, limited ventilation will possibly cause ethylene accumulation and excess low or high carbon dioxide concentrations in the ambient air and thus poor development of plant reproductive organs and poor yields in space.

In closed facilities without adequate air circulation systems, there may be adverse effects on the crops. Insufficient air movement around plant bodies increases the resistance to gas transfer in the leaf boundary layer and thus limits photosynthesis and transpiration of plants (Yabuki and Miyagawa, 1970; Monteith and Unsworth, 1990; Jones, 1992), resulting in suppression of plant growth and development. Therefore, the enhancement of gas exchange in leaves and resulting promotion of the plant growth would be dependent on appropriate control of air flow in controlled environment facilities (Tibbitts and Kozlowski, 1979; Kitaya *et al.*, 2000a; Kitaya *et al.*, 2000b; Shibuya *et al.*, 2006).

On earth, convection occurs with uneven temperature distribution. Air movements are induced by natural convection driven by gravity even in a closed chamber with no forced ventilation system. There is, however, no natural convective or thermal mixing under microgravity conditions in space because the buoyancy is considered

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to be negligible under microgravity conditions. The limited convection would reduce plant growth by limiting heat and gas exchanges on plant leaves. Control of air movement in a closed plant production facilities is thus essential to enhance the heat and gas exchanges between plants and the ambient air, and consequently promote growth of plants in space.

In the present paper, possible suppression of plant growth and reproduction in space farming were summarized in a view of heat and gas exchanges between leaves and reproductive organs of plants and atmosphere under sub-gravity or microgravity conditions from terrestrial research results.

Temperature rises in plant leaves under microgravity conditions

Parabolic airplane flights were carried out for clarifying the short term effects of microgravity and excessive gravity on heat and gas exchanges between plants and atmosphere. Different gravity levels were produced by the acceleration of the airplane during each parabolic flight. Unusual gravity levels of 1.0, 2.0, 0.01, and 1.5 G were produced sequentially and lasted for 20 seconds each during a parabolic flight of the airplane as shown in Fig. 2. Thermal images of the surfaces of intact barley leaves were captured using an infrared thermography system.

The images shows an increase in the leaf temperature with decreasing gravity levels from 1.0 to 0.01 G and a decrease in the leaf temperature with increasing gravity levels from 1.0 to 2.0 G (Fig. 1). The temperature was higher at the broader region in the leaf. The temperature increase with decreasing gravity levels was, however, more significant at the narrow region in the leaf blade.

Fig. 1. Thermal images of the barley leaf at different gravity levels. (from Kitaya *et al.*, 2003)
Ambient air temperature: 28°C, Irradiance: 260 W m⁻², Air velocity: 0.2 m s⁻¹

Fig. 2. Time courses of the leaf surface temperatures at the central portion along the representative leaf blade (a) with gravity profile during a parabolic flight (b). (from Kitaya *et al.*, 2006)
Ambient air temperature: 24°C, Irradiance: 260 W m⁻², Air velocity: 0.2 m s⁻¹.

Figure 2 shows the time courses of the leaf temperatures at five regions with different distances from the tip of the leaf blade corresponding to gravity levels. The temperature decreased for 20 seconds after gravity levels increased from 1.0 to 2.0 G, and increased for 20 seconds after gravity levels decreased from 2.0 to 0.01 G at every region.

The temperature variations along transections on leaf blades show that the temperature increased with increasing distances from the tip of the leaf (Fig. 3). The temperature at the region 10 mm far from the tip was 3.3°C lower than that at the region 100 mm far from the tip at a gravity of 1.0 G. The mean temperatures of five regions were 26.5, 24.6 and 24.0°C, respectively, under gravity levels of 0.01, 1.0 and 2.0 G. The more significant temperature increase was shown at the regions closer to the leaf tip as the gravity levels decreased from 1.0 to 0.01 G (Fig. 3). The decrease in leaf temperatures was tended to be more significant at the regions closer to the leaf tip as the gravity levels increased from 1.0 to 2.0 G.

The reason why the temperature increase was more significant at the narrow regions closer to the leaf tip as the gravity levels decreased seems to be increases in resistances against transfer of water vapor and sensible heat in the leaf boundary layer. The boundary layer resistance is usually less and the surface temperature is lower at the narrower regions at convective situations under the 1 G gravitational condition. The boundary layer resistance, however, would be mostly constant regardless of the leaf width under the microgravity condition. Therefore net temperature increase with decreasing gravity levels was larger at the narrower regions in the

Fig. 3. Profiles of temperature differences between leaf surfaces (T_{leaf}) and ambient air (T_{air}) along the leaf blade as affected by gravity levels (a) and of differences between leaf surface temperatures (T_{leaf}) measured at gravity levels of 1.0 G and 0.01 or 2.0 G (b). (from Kitaya *et al.*, 2006)
Ambient air temperature: 24 °C, Irradiance: 260 W m⁻², Air velocity: 0.2 m s⁻¹. Bars indicate standard deviations (n=5).

leaf.

Figure 4 shows the mean surface temperatures of intact and replica leaves corresponding to gravity levels at two levels of air velocities. The barley leaf temperatures at the air velocity of 0.2 m s⁻¹ decreased by 0.4 and 0.3 °C, respectively, for 20 seconds after gravity levels increased from 1.0 to 2.0 G, and increased by 1.3 and 1.1 °C, respectively, for 20 seconds after gravity levels decreased from 2.0 to 0.01 G. The leaf temperature increase was 0.9 °C for barley as the gravity levels decreased from 1.0 to 0.01 G. The temperature increases in wet paper replicas and copper replicas having the barley leaf shape were 1.9 and 0.7 °C, respectively. As the gravity levels decreased from 1.0 to 0.01 G, the greater temperature increase was shown in the following order: wet paper replicas, intact leaves and copper replicas. Replicas of barley leaves also showed a similar tendency.

The transpiration rate of a barley leaf was 4.0 mmol m⁻² s⁻¹ at 1.0 G. The evaporation rate of the wet paper replica was 7.8 mmol m⁻² s⁻¹. The copper replica showed no evaporation as a matter of course. Potential evaporation or transpiration rates per unit area was higher in the following order: wet paper replicas, intact leaves, and copper replicas. The order of the temperature increase corresponded to the order of the potential transpiration rates. This means that lower gravity levels would suppress vaporization and thus latent heat transfer as well as sensible heat transfer.

These results show that microgravity increases leaf temperatures because sensible and latent heat exchanges between leaves and the ambient air is retarded under the microgravity condition compared with that under the 1.0 G condition. Since stomatal apertures

Fig. 4. Temperatures of barley leaves and leaf replicas at different gravity levels as shown by differences between material surface temperatures (T_{material}) and ambient air temperature (T_{air}) under different air velocities. (from Kitaya *et al.*, 2003)
Mean temperatures of whole surface area except the surrounding region 3 mm wide in each material were averaged for nine repetitive parabolic flights. Bars indicate standard deviations. In each material the plots with different letter(s) indicate a significant difference at a significant level of 95%. Ambient air temperature: 26 °C, Irradiance: 260 W m⁻²

Fig. 5. Transpiration rates of strawberry leaves at different gravity levels. (from Hirai and Kitaya, 2009) Bars indicate standard deviations (n=4). The plots with different letter indicate a significant difference at a significant level of 95%. Ambient air temperature: 28°C, Air velocity: 0.05 m s⁻¹, Irradiance: 60 W m⁻²

Fig. 6. Net photosynthetic rates of barley leaves at different gravity levels. (from Kitaya *et al.*, 2001) Bars indicate standard deviations (n=5). The plots with different letter indicate a significant difference at a significant level of 95%. Ambient air temperature: 20°C, Air velocity: 0.01 m s⁻¹, PPFD: 500 μmol m⁻² s⁻¹, CO₂ concentration: 380 μmol mol⁻¹

showed no microscopic changes for 20 seconds, an increase in resistance in the leaf boundary layer under lower gravity levels would cause less transpiration and thus less latent heat loss.

The increase in leaf temperatures was at most 1.9 °C over 20 seconds as gravity decreased from 1.0 to 0.01 G. The rapidity of temperature increase with additional radiative heat load on leaves was examined in sweet potato leaves (Kitaya *et al.*, 2003). Leaf temperatures increased just after lighting and reached to the equilibrium 100 seconds after the start of lighting. The leaf temperature increase for 20 seconds after lighting was a half of the equilibrium value. The increase in the equilibrium value of the temperature if low gravity conditions are prolonged is expected to be about 4 °C.

The higher air velocity lowered the surface temperatures of all materials (Fig. 4). The higher air velocity also reduced the surface temperature differences among the different gravity levels. Higher radiation and lower air velocity would make the temperature increase greater in space. Excess leaf temperature would disorder the leaf physiological processes such as photosynthesis. An excess temperature in a reproductive organ could also cause fertility impediments.

Possible suppression of transpiration and photosynthesis under microgravity conditions

Measurements of the transpiration rates were conducted with strawberry leaves during the parabolic flights (Hirai and Kitaya, 2009). The transpiration rate was 46% smaller at 0.01 G than at 1.0 G, and 32 % greater at 2.0 G than at 1.0 G (Fig. 5). It was confirmed that the water vapor transfer from plant leaves is suppressed when free air convection was restricted under microgravity conditions in space. Both the increase in the absolute humidity in the vicinity of leaves and increase in the water vapor resistance on leaves would cause the

suppression of the transpiration under microgravity conditions. Suppressed transpiration would cause excess temperature rise in plant organs and restriction of water and nutrient absorption in roots.

Measurements of the net photosynthetic rates were also conducted with barley leaves during the parabolic flights (Kitaya *et al.*, 2001). The net photosynthetic rate was 20% smaller at 0.01 G than at 1.0 G, and 7 % greater at 2.0 G than at 1.0 G at a PPFD of 500 μmol m⁻² s⁻¹ (Fig. 6). The net photosynthetic rate was suppressed by the microgravity condition. Low net photosynthetic rates would retard plant growth at vegetative and reproductive stages.

Temperature rise in plant reproductive organs under a microgravity condition

Figure 7 shows the effect of irradiance levels on the surface temperatures of reproductive organs at different gravity levels (Kitaya and Hirai, 2007). The values were determined just before the gravity changed. Temperatures of reproductive organs were 1.5-2.5°C lower than the surrounding air temperature under the dark due to the latent heat transfer associated with transpiration in the organs. Temperatures of reproductive organs increased with increasing irradiance levels. Temperatures of glumes of rice and wheat and anthers of tomato were 4.2, 5.9 and 5.4°C, respectively, higher at the irradiance of 150 W m⁻² than at 0 W m⁻² at 1.0 G. The difference in heating trends among the organs may be dependent on the heat capacity per surface area and the transpiration rate of each organ. The temperature increments of glumes of rice and wheat and anthers of tomato were 5.5, 6.3 and 6.0°C, respectively, at 0.01 G, and 3.8, 5.7 and 5.4°C, respectively, at 2.0 G. The temperature increase of plant reproductive organs as affected by the irradiance level was more significant under 0.01 G gravity level and less significant under 2.0 G gravity level than under 1.0 G gravity level.

Fig. 7. Effects of gravity and irradiance levels on temperatures of reproductive organs as shown by differences between organ temperatures (T_{plant}) and ambient air temperature (T_{air}). (from Kitaya and Hirai, 2007)
Ambient air temperature: 31.5 °C, air velocity: 0.05 m s⁻¹

As the gravity levels decreased from 1.0 to 0.01 G for 20 seconds, the greater temperature increase was shown in the following order: glumes of rice, anthers of tomato and glumes of wheat. The temperature increase in relatively small organs such as the glumes of rice and the anthers of tomato was more significant than in relatively large organs such as the glumes of wheat under microgravity conditions. The reason why the temperature increase was more significant at the smaller organs as the gravity levels decreased seems to be increases in resistances against transfer of water vapor and sensible heat in the boundary layer in the same manner as mentioned in Fig. 3. In addition, possibly higher transpiration rates of organs such as anthers would increase the temperature more significantly as the gravity levels decreased. There was slightly a forced air flow during the experiment. The temperature rise would be more remarkable under the microgravity condition with less forced air flow.

Reproductive disorders were reported under high temperature (30–33 °C) stress conditions. Early development and differentiation of wheat anthers were very sensitive to high-temperature (30 °C day/25 °C night) stress causing major alterations in gene expression (Abiko *et al.*, 2005). Fertilization of bell pepper was sensitive to high temperature (33 °C) stress (Erickson and Markhart, 2002). Temperatures of reproductive organs can rapidly rise to significantly high levels under lighted conditions in the present experiment. This temperature rise could cause reproductive disorders when ambient air temperatures are in the neighborhood of 30 °C. *Arabidopsis* and wheat plants grown in space were found to produce and develop flowers, but their flowers produced more sterile seeds than did ground control plants (Merkies, and Laurinavichyus, 1983; Mashinsky *et al.*, 1994; Salisbury *et al.*, 1995).

There is a possibility that the disorder was caused by an increase in temperatures of reproductive organs

Fig. 8. Profiles of leaf area (a), air temperature (b), water vapor pressure (c) and CO₂ concentration (d) inside and outside the canopy of eggplant seedlings as affected by PPFD at an air velocity of 0.1 m s⁻¹ (from Kitaya *et al.*, 1998).

Fig. 9. Effects of PPFD on differences in the air temperature (a) and in the CO₂ concentration (b) between two heights at the canopy surface and 60 mm above the canopy at air velocities of 0.1 and 0.3 m s⁻¹. (from Kitaya *et al.*, 1998).

such as anthers and stigmas due to limited convection under microgravity conditions. Musgrave and Kuang (2003) reported that the absence of convective air movement caused a disorder of pollen development under space flight conditions. The temperature increase would be greater at smaller organs such as anthers and stigmas under microgravity conditions with the absence of convective air movement. Higher irradiation of light and lower air velocity would make the temperature increase greater in space. The more temperature rise in reproductive organs could cause more fertility impediments.

Importance of air movement for controlling environment inside plant canopies and their gas exchange

Precise control of environmental variables around plants is important for scheduling of crop production and obtaining high yields with rapid turnover rates in plant production especially in space farming. Low air movement induced spatial variations of environmental variables, such as the air temperature, water vapor pressure and CO₂ concentration inside plant canopies as shown in Fig. 8 (Kitaya *et al.*, 1998). The environmental variables inside the plant canopy consisted of 0.1 m length eggplant seedlings were characterized by 2-3°C higher air temperature, 0.6 kPa higher water vapor pressure

Fig. 10. Effects of the leaf area index (LAI) on the net photosynthetic rate (Pn) based on the rooting bed area (shown with solid symbols) and the leaf area (shown with blank symbols) of tomato seedlings canopies under different air current speeds above the canopies and atmospheric CO₂ concentrations. (from Kitaya *et al.*, 2004) PPFD: 250 μmol m⁻² s⁻¹, air temperature: 23 °C, RH: 55%, Plant heights: 0.05-0.2 m

and 25-35 μmol mol⁻¹ lower CO₂ concentration than those outside the canopy under the velocity of 0.1 m s⁻¹ under a normal atmospheric CO₂ level. These differences became smaller at higher velocity (Fig. 9).

The net photosynthetic rates of a tomato seedlings canopy increased more significantly with increasing CO₂ levels in the plant canopy having higher LAI and at lower air velocity (Fig. 10) (Kitaya *et al.*, 2004). At the air velocity of 0.4 m s⁻¹, the net photosynthetic rates at 800 μmol mol⁻¹ CO₂ were 1.2 times and 1.3 times that at 400 μmol mol⁻¹ CO₂ when the LAI was 0.6 and 2.5, respectively. At the air velocity of 0.1 m s⁻¹, the net photosynthetic rates at 800 μmol mol⁻¹ CO₂ were 1.2 times and 1.4 times that at 400 μmol mol⁻¹ CO₂ when the LAI was 0.6 and 2.5, respectively. These results confirmed the importance of controlling air movement for enhancing the canopy photosynthesis under elevated CO₂ levels as well as under a normal CO₂ level.

Control of air movement is essential to make the environmental variables uniform inside the plant canopy and to enhance the gas/heat exchange between plants and the ambient air, and consequently to promote plant growth especially in space farming.

Concluding remarks

Plant growth facilities used in space farming need to be highly reliable for a long term over the plant life cycles with little additional control. Restricted free air convection under microgravity conditions in space would limit plant growth by retarding heat and gas

Fig. 11. Possible mechanisms of reproductive disorders under microgravity conditions.

exchanges between leaves and the ambient air. Excess leaf temperature would disorder the leaf physiological processes. The temperature increase would be greater at smaller regions such as anthers and stigmata. An excess temperature in the reproductive organ could also cause fertility impediments. There is a possibility that the reproductive disorder was caused by an excess increase in temperatures of reproductive organs such as anthers and stigmata under microgravity conditions (Fig. 11). Low net photosynthetic rates would also retard plant growth at the reproductive growth stage as well as the vegetative growth stage (Fig. 11).

The control of air movement is shown to be important to enhance the heat and gas exchanges between plants and the ambient air, and consequently promote growth of plants in a closed plant production system especially with a large number of plants at a high density even on the earth (Kitaya *et al.*, 2000b). Proper air movement is essential to promote the plant growth not only in the vegetative growth stages but also in the reproductive growth stages especially in space.

In the recent research onboard the International Space Station (ISS), long term experiments have been conducted with well designed spaceflight plant growth chambers that allowed more precise control of environmental elements including air circulation and/or ventilation systems than in the previous research. In the results of the prolonged plant experiments, for example, microgravity did not affect evapotranspiration and net photosynthetic rates of dwarf wheat plant stands grown for 73 days at moderate light levels and saturating CO₂ concentrations in the Biomass Production System loaded on ISS (Monje *et al.*, 2005). Developmental and genetic characteristics of pea plants grown over a complete ontogenetic cycle (73-76 days) in

the Rada Greenhouse implemented on ISS were similar to the ground controls and they yielded viable seeds with no alteration of the biological properties (Sychev *et al.*, 2007).

Plant growth facilities used in the future space farming must be large-sized and highly reliable for producing large number of plants with rapid turnover rates for large number of crews in long-term space missions. Proper control of air movement, therefore, would be essential to enhance the heat/gas exchange of plants and thus promote growth of healthy plants under sub-gravity or microgravity conditions in space farming.

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