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THERMAL RADIATION LOAD ON TEMPERATURE REGIMES IN PLANT GROWTH CHAMBERS

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HAMASAKI T. and OKADA M. *Thermal radiation load on temperature regimes in plant growth chambers*. BIOTRONICS **29**, 57–69, 2000. In enclosed environments such as a plant growth chamber, thermal radiation plays an important role in determining heat balance and therefore the resultant temperature regimes. In artificially illuminated chambers, a significant level of thermal radiation is emitted from the lamps and/or the lamp house surface. Though there are both shortwave and longwave components in thermal radiation, our measurements in two different chamber designs, with and without thermal radiation filters, showed the longwave component being 2–3 times larger than the shortwave one. The increased thermal radiation, in particular the longwave component, caused differences in the temperatures of the plant and soil compared to that of the air. The differences were greater with increasing exposure to thermal radiation. Because of greater exposure to thermal radiation, both plant and soil temperatures were higher than the air temperature when plants were grown in isolated pots compared to plants in mutually shaded pots arranged in a block. In field-use chambers under natural light conditions, the longwave component of thermal radiation is modified to a large extent by the transmittance of the cover film. The temperature gradient chamber used in this study was covered with PVC film having low transmittance to longwave radiation and it showed a greater soil temperature relative to the air temperature when compared to a chamber covered with polyethylene film having high transmittance. As a result, across the two chambers and outdoors, the rice plant responses were correlated to the soil temperatures but not to the air temperatures.

Key words: thermal radiation; plant growth chamber; temperature

INTRODUCTION

Chambers used for research on plant responses to environmental factors differ widely in their designs. Chambers with fully controlled environments (including light) were first proposed by Morse and Evans (*4*). In such

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environments it is essential that light conditions are similar in both quantity and quality to those outdoors. Great efforts have been made to increase the light intensity of illumination devices as well as to improve the spectral distribution of light. Because high light intensity leads to increased thermal radiation load on the environment, thermal barriers such as radiation filters are used to minimize the effects on the chamber's temperature regime (*e.g. 2*). The thermal barriers are usually designed to transmit visible light and to reduce the infrared component of light. This design criterion, however, does not consider the influence of longwave (far-red) radiation. The thermal barrier increases in temperature as it absorbs the infrared radiation, and consequently there is an increase in the amount of longwave radiation emitted from its surface. Whether thermal barriers are used or not, the 'sky' temperatures in controlled environment chambers are always very different from the real outdoor sky temperature. The increased 'sky' temperature may greatly modify the temperature regimes inside the chambers. It is therefore important to evaluate the longwave radiation load in individual chamber designs.

In chambers used in the field under natural light conditions, clear materials such as glass and plastic films are used as coverings. They have light transmittance levels as high as 90%, but there are big differences in the transmittance of longwave radiation among the materials. Glass and plexiglass have no transmittance, while the transmittance of soft plastic films ranges from 30–40% for PVC to 70–85% for polyethylene (PE) (depending on the thickness of the film). Again, in terms of longwave radiation, apparent 'sky' temperatures in the chambers vary with the cover material used. Under glass, for example, the apparent sky temperature is similar to the glass temperature, while it is similar to the real outdoor sky temperature under highly-transmissive PE film.

It is reported by previous studies (*e.g. 1*) that the growth of plants in open-top chambers (OTC) is often superior to that in an open field, even though the inside air temperatures are maintained to be similar to those outdoors. As this difference in plant growth inside and outside the chambers seems to be caused by the chamber itself, it is usually called a 'chamber effect'. As shown by Unsworth (*8*), the chamber effect is a result of modifications of the heat balance and temperature regimes by the chamber structure and the control measures. In a theoretical analysis, Unsworth suggested that soil temperatures in chambers were increased by both smaller radiative dissipation and lower convection (airflow) compared to outdoors. In fact, Okada *et al.* (*6*) reported that the soil temperatures in their temperature gradient chambers (TGC) relative to the air temperatures were higher than those observed in an open field.

To explain the difference of plant and soil temperatures from the air temperature in a chamber, a simple heat balance model is introduced here. By assuming that heat transfer is in steady state and neither latent nor conductive heat transfer is involved, the heat balance of a body in consideration is given by the following equation:

$$Rn = C \tag{1}$$

where, Rn is the net radiation flux (including shortwave and longwave components) and C is the convective flux. The convective flux between the body and the air is usually given as a function of temperature difference, hence:

$$C=h\ (T_{body}-T_{air}) \tag{2}$$

where, h is the heat transfer coefficient, T_{body} is body temperature and T_{air} is ambient air temperature. Therefore, the temperature difference between the body and the air is proportional to the radiative flux and inversely related to the heat transfer coefficient:

$$T_{body}-T_{air}=Rn/h \tag{3}$$

As the heat transfer coefficient is usually linearly related to the airflow speed around the body, the temperature difference decreases with an increase in airflow speed. Though Equation (3) is very simple, it addresses important aspects in temperature regime modifications in chambers. Both radiation and airflow speed are intentionally or unconsciously affected by the chamber design. The increased radiative flux, whether it is shortwave or longwave, causes rises in the temperature of bodies relative to the ambient air temperature. The influence of airflow speed is vice versa.

The work described in this paper had three objectives. (1) To evaluate the radiative components of the heating load on plants and soil in two different chamber designs (with and without thermal barriers) and compare the resultant plant and soil temperatures in different plant canopy densities. (2) To compare changes in soil temperature relative to the air temperature in two TGCs, one being covered with PVC and the other covered with PE and relate plant growth responses to these different conditions. (3) To demonstrate the influence of airflow speed on thermal radiation load in the TGC.

THERMAL RADIATION FROM LAMPS

Materials and Methods

Two different designs of artificially illuminated growth chambers were used in the experiment; one being illuminated with 45×50 W incandescent lamps and 6×115 W and 24×215 W cool-white fluorescent lamps (PGW36, Controlled Environments Limited, hereafter chamber-A) and the other with 18×400 W metal-halide lamps and 18×360 W high-pressure sodium lamps (TGE-10H-3, TABAI ESPEC Corp., hereafter chamber-B). Chamber-A's growth room was 2.46 m long, 1.35 m wide and 2.0 m high, while that of chamber-B was 2.4 m long, 2.4 m wide and 2.4 m high. For chamber-B, thermal radiation filter panel was installed between the lamp housing and the growth room, while for chamber-A, the lamps were suspended in the growth room without any filters. The filter had a transmittance of 70% over spectral range from 400 to 600 nm, with the transmittance gradually decreasing with increasing wavelength, beyond 1,700 nm it was only 10%. This spectral feature of the filter was designed to effectively absorb excessive heat caused by infrared radiation. Outdoor air was blown across the upper surface of the radiation filter panels to decrease their temperature.

In both chambers target air temperature was 12℃, relative humidity was 60% and the light period was 12–hr. Two levels of light intensity were applied; 'full–illumination', where all lamps were turned on and 'reduced–illumination', where the total lamp output was reduced to 52% of the 'full–illumination' in chamber–A and to 67% in chamber–B. The surface temperatures of the lamps and radiation filters were measured with a thermal image camera (JTG–4200, JEOL Ltd.). Photosynthetically–active photon flux density (PPFD) was measured with a photon flux sensor (ML–020P, EKO INSTRUMENTS TRADING CO., LTD.), and shortwave radiation (300–2,800 nm) flux with a phyranometer (MS801, EKO INSTRUMENTS TRADING CO., LTD.). All–wave downward radiation flux was measured with a hemispherical radiometer (MF–11 and NC–01, EKO INSTRUMENTS TRADING CO., LTD.). Longwave downward radiation flux was calculated from the all–wave downward radiation flux minus the shortwave radiation flux. Both horizontal and vertical air temperature profiles were measured with aspirated thermocouple thermometers at a total 45 locations in each chamber.

Pot–grown rice plants (*Oryza sativa* L. cv. Hitomebore) at the pollen developmental stage were placed in the chambers. Two different pot arrangements were used simultaneously in each chamber; 'surrounded', where a pot used for measurement was surrounded by 20 other pots and 'isolated' (Fig. 1). Thermocouples were used to measure the air temperature near the top of the rice plants, the leaf sheath temperatures at 10 cm above the soil surface and the soil temperatures at the center of the pot. Airflow speed was measured with a semi–conductor anemometer (HONFIELD MONITOR and SL–400, HONDA DYNAMICS CO., LTD.) at three heights: 10 cm above the plants, at the top of the plants and near where the leaf sheath temperature was measured.

Results and Discussion

PPFD is the most commonly used measure of light intensity in plant

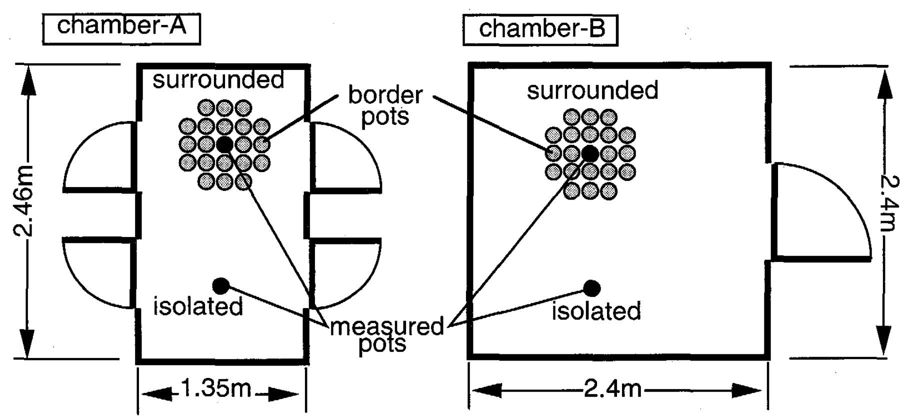

Fig. 1. Experimental arrangement of rice pots in the chambers.

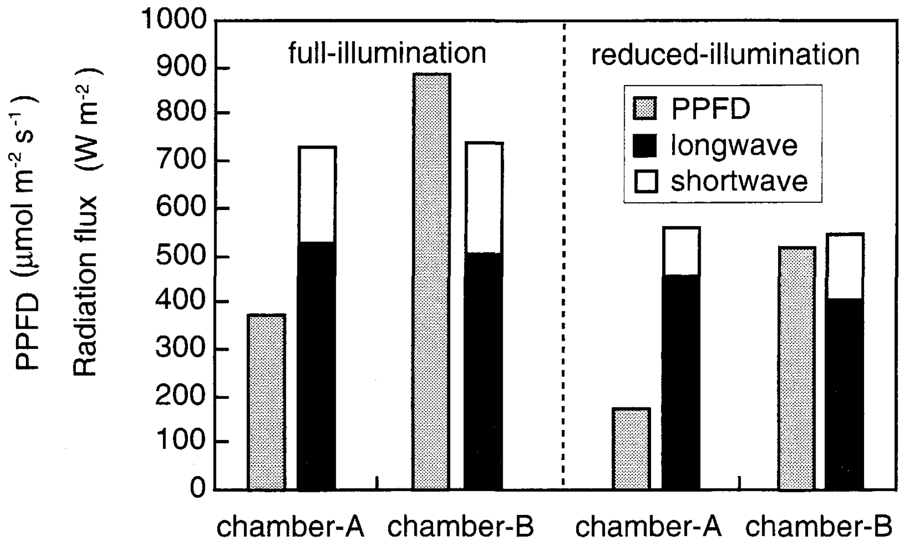

Fig. 2. Comparison of photosynthetically-active photon flux density (PPFD), shortwave radiation flux and longwave radiation flux between chamber-A and chamber-B at full-illumination (left) and at reduced-illumination (right).

research, especially in chamber studies. Under both full- and reduced-illumination, PPFD in chamber-B was approximately double that in chamber-A (Fig. 2). However, both the shortwave and longwave radiation fluxes were similar for two chambers. The lack of correlation between PPFD and shortwave radiation across the chambers is accounted for by the difference in light sources. The small differences in longwave radiation flux across both the chambers and the two illumination levels may be accounted for by the respective 'sky' temperatures. The 'sky' of chamber-A was covered with exposed lamps, while that of chamber-B consisted of the radiation filter panels. The mean surface temperature of the 'sky' measured with the thermal image camera was 43.7℃ for chamber-A at full-illumination and 29.2℃ at reduced-illumination. In chamber -B the mean temperature of the panel surface was 37.2℃ at full-illumination and 31.2℃ at reduced-illumination. Since the longwave radiation flux is proportional to the fourth power of the absolute temperature in Kelvin of a surface, a temperature difference of 10℃ results in a difference of 66 W m^2 in longwave radiation flux. The ratio of the longwave to shortwave radiation fluxes was extremely large when compared to that outdoors. The ratio in the chambers ranged from 2.1 to 4.5, but outdoors at midday on clear sunny day, it ranged from 0.3 to 0.6.

Figure 3 compares leaf sheath and soil temperatures in the two chambers using the two pot arrangements. There was the large difference in temperatures between the two pot arrangements. Both the leaf sheath and soil temperatures were higher than the ambient air temperature in the isolated pots during the light period, while they were lower than the air temperature when the pot was surrounded. As air was blown from vents in the floor in both chambers, it was

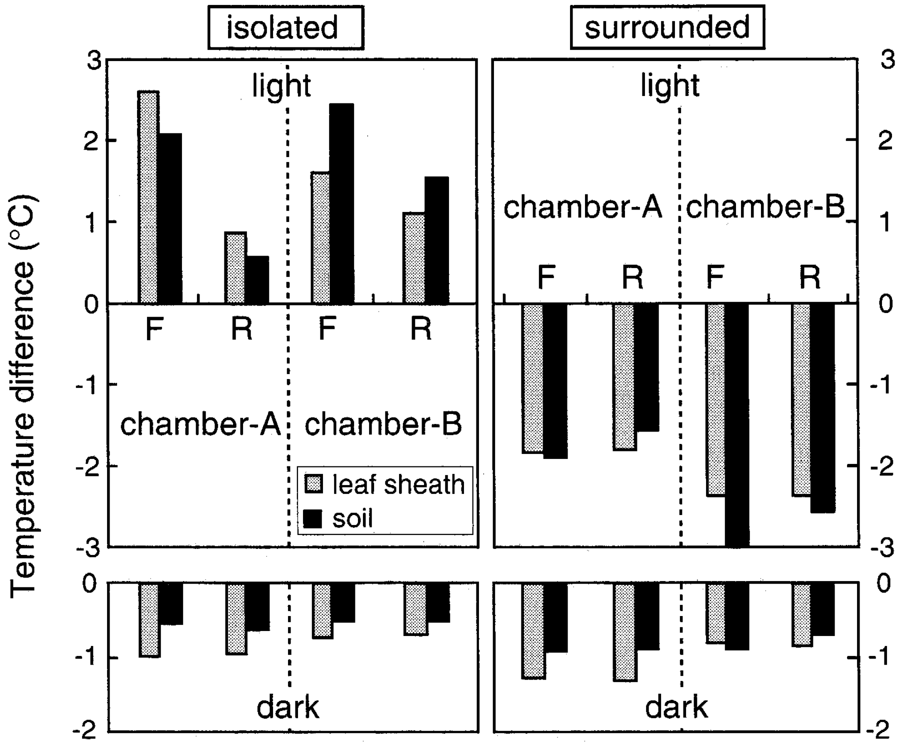

Fig. 3. Influence of the chamber–type, illumination intensity and pot arrangement on the leaf sheath and soil temperature during the light period (top) and dark period (bottom) for isolated pots (left) and surrounded pots (right). F: full–illumination, R: reduced–illumination. Temperature difference: leaf sheath or soil temperature minus air temperature.

suspected that the air temperature at the bottom was lower than that measured at the top of the plants. The vertical air temperature profile showed that the air temperature at 30 cm above the floor was only 0.1–0.4℃ lower than that at 80 cm. The low temperatures observed in the surrounded pot could not be explained with this decreased air temperature at the bottom. In the surrounded pots, both light and thermal radiation were reduced to a large extent by mutual shading compared to the isolated pots. By applying the simple model of light penetration in plant canopies developed by Monsi and Saeki (*3*), the light transmittance of the canopy in the 'surrounded' pot arrangement was estimated to be 2–8%. With reduced radiative heat gain, the other components in heat balance such as sensible and latent heat transfer become dominant. In particular, evapotranspiration (latent heat transfer) affects greatly the plant and soil temperatures during the light period. This dominating effect of evapotranspiration may be the major reason for the lower plant and soil temperatures in the surrounded pots. During the dark period the plant and soil temperatures in the surrounded pots were a little lower than those in the isolated pots. The 'surrounded' pot arrangement increased vertical airflow speed inside the plant canopy, because the canopy limited the space through which the air passed. The increased airflow speed and thus increased evapotranspiration may have contributed to some extent to the lower temperatures. Consequently, the thermal radiation effect on the temperature regimes is large in case of the isolated pot, while it is substantially reduced when pots are arranged in a block.

INFLUENCE OF COVER FILM ON THERMAL REGIMES

Materials and methods

Two TGCs were used in the experiment; one being covered with clear PE film and the other with clear PVC film. The longwave radiation transmittance of the film, measured by the emissiometer method (*5*), was 0.85 for the PE and 0.33 for the PVC. The light transmittance was measured with a photon flux sensor in the TGCs under overcast sky conditions. There was no significant difference in transmittance between the two TGCs: 0.78 in the PE-covered TGC and 0.79 in the PVC-covered TGC. These values were comparable to those reported as the transmission of shortwave radiation in the same TGCs by Okada *et al.* (*6*). A detailed description of the design and performance of the TGCs were given by Okada *et al.* (*6*).

Germinated rice (*Oryza sativa* L. cv. Akitakomachi) seeds were sown in 50 hole cell trays (each cell was $25\,cm^2 \times 5\,cm$ in depth) on September 25th, 1995. At the 1st-leaf emergence stage, the trays were soaked into 6-7 cm deep water contained in plastic containers. The containers were placed at 3, 8.5 and 14 m from the air inlet of each TGC as well as outdoors. Soil temperature at a depth of 2 cm was measured at the center cell in each tray. Air temperatures at 50 cm above the ground were measured outdoors and at 1, 6, 11 and 16 m from the air inlet of the TGCs. Leaf emergence was recorded every day.

Results and discussion

Since the air temperature gradient was controlled, the changes in mean air temperature along the longitudinal axis were similar in the two TGCs (Fig. 4). The changes in soil temperature, however, differed significantly between the two TGCs with temperatures consistently higher under PVC than under PE. As the PE film has a high longwave transmittance, the 'sky' temperature in the PE-TGC is similar to the actual outdoor sky temperature. In contrast, it is much closer to the film temperature in the PVC-TGC. Longwave radiative dissipation from the soil surface, therefore, was larger under PE than under PVC. This is clearly shown by Figure 5, where the relationships between the soil and the air temperatures under PE are similar to those outdoors, while those under PVC are different.

In order to compare crop responses between the TGCs and outdoors, the leaf emergence rate of rice seedlings was calculated as a reciprocal of the number of days from the emergence of the 2nd-leaf to the emergence of the 4th-leaf. The leaf emergence rate had a good correlation to soil temperature across the data from the two TGCs and outdoors, but poorly correlated to air temperature (Fig. 6). The growing points of rice leaves are located at the bottom of their shoots in the paddy water or underground. This morphological characteristic of rice

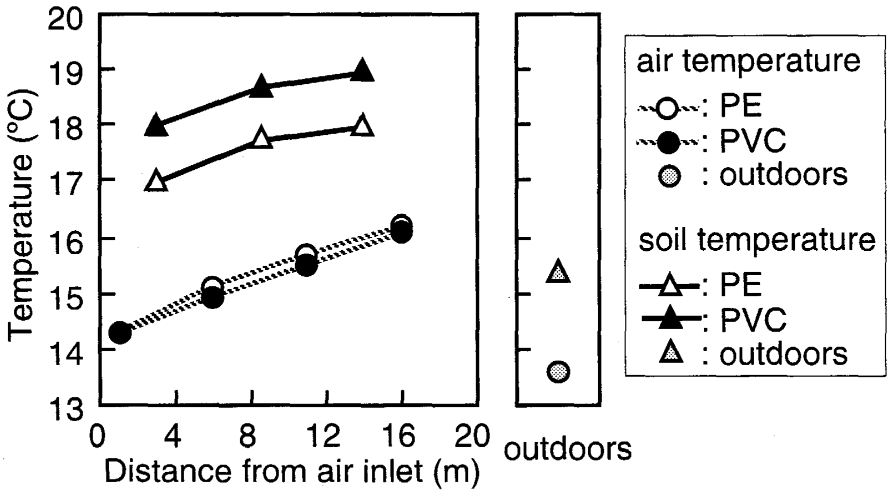

Fig. 4. Comparison of mean air and soil temperature gradients in PE and PVC covered TGCs. Temperatures are averaged from October 1st to October 20th. Outdoor temperatures are also shown.

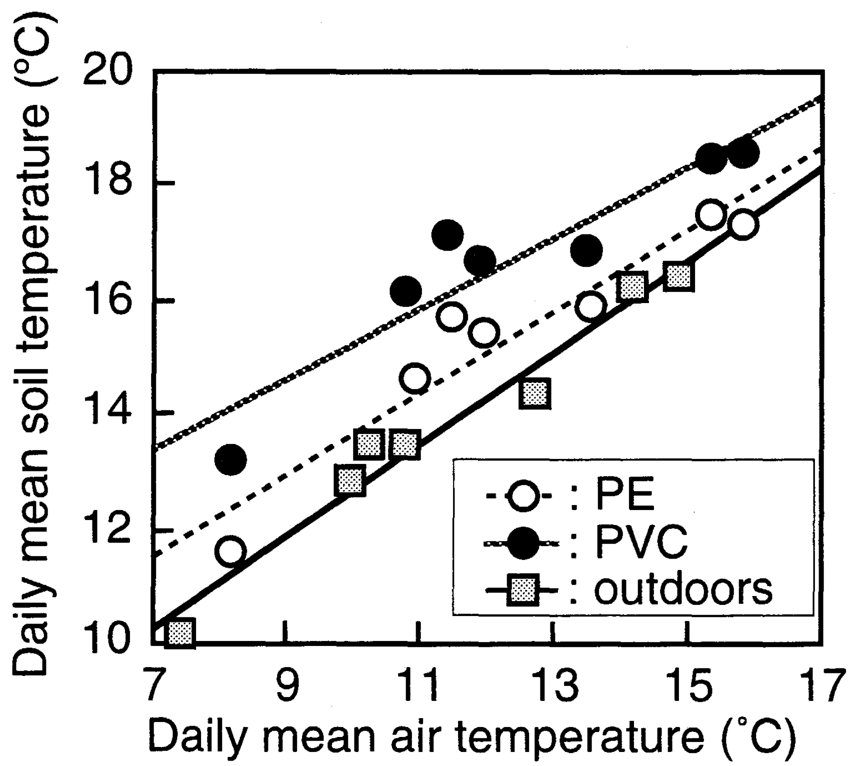

Fig. 5. Relationship between soil and air temperature in TGCs and outdoors. Data on clear sunny days are shown.

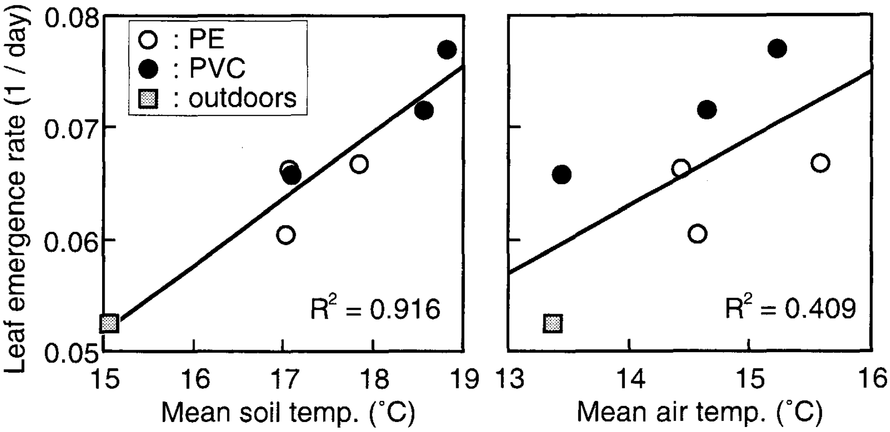

Fig. 6. Correlation between rice leaf emergence rate and soil temperature (left) or air temperature (right). Leaf emergence rate is defined as the reciprocal of the number of days from the emergence of the 2^{nd}–leaf to the emergence of the 4^{th}–leaf.

may be a reason of this strong correlation between soil temperature and leaf development. Since modification of the air–soil temperature relations resulted from the heat balance of radiation and convection as shown by Equation (3), such modification may also occur in air–plant temperature relations. Therefore, not only in rice plants but also in other types of plants with the growing points in the air, growing point temperatures are possibly modified and growth analysis based on air temperature alone will lead to erroneous results.

INFLUENCE OF AIRFLOW ON THERMAL RADIATION LOAD

Materials and methods

The pre–air–conditioned TGC described by Okada *et al.* (7) was used in this experiment. This TGC has a light transmittance similar to the TGCs described in the previous section and is covered with 0.05 mm thick ethylene–tetrafluoro ethylene copolymer (ETFE) film. The longwave transmittance of this film is 0.45; that is, in between that of PE and PVC. In this TGC airflow speed varies along the longitudinal axis, because of air circulation induced by the heater at the end. By using this airflow speed profile, the influences of convection on the air–soil temperature relations and resultant plant growth are discussed here.

Rice plants (*Oryza sativa* L. cv. Akitakomachi) were seeded in 5–liter pots on May 15^{th} 1997 and placed at 2, 8, 14, and 20 m from the air inlet of the TGC as well as outdoors on May 19. Soil temperatures at a depth of 8 cm at the center of the pots and air temperature at plant–height were measured every 10 seconds and averaged over 10 minutes. The emergence dates of the main stem leaves were recorded. The airflow speed at 50 cm above the floor was measured with a hot wire anemometer (ANEMOMASTER MODEL6071, Kanomax Japan Inc.) at 2, 5, 8, 14 and 20 m from the air inlet.

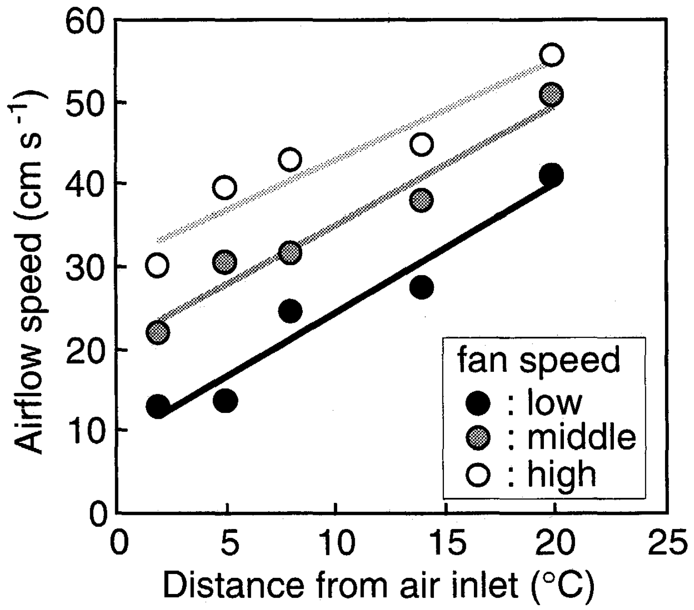

Fig. 7. Longitudinal changes in airflow speed at three fan speed levels in the TGC.

Results and discussion

Figure 7 shows the longitudinal changes in airflow speed under three different fan rotation modes. The airflow speed was the lowest at the air inlet and the highest at the outlet. Compared to outdoors, the air–soil temperature relations were again modified by the chamber (Fig. 8). The shift in the soil temperature relative to the air temperature, however, was not consistent along the longitudinal axis, though it was consistent with that of the TGCs discussed in the previous section. The shift was the largest at the air inlet end and the smallest at the outlet end, and it appeared that the shift was correlated to the longitudinal changes in airflow speed. As estimated from Equation (3), the temperature difference between the soil and the air becomes large under the low airflow speed at the air inlet end.

Figure 9 show the relationships between the mean air temperature and leaf emergence rate of rice plants. The leaf emergence rate of rice seedlings was calculated as a reciprocal of the number of days from the emergence of the 2nd –leaf to the emergence of the 9th–leaf. When compared to the outdoor data, the relationship observed in the TGC showed a faster leaf emergence at the same range of air temperatures. A leaf emergence rate similar to outdoors would be obtained in the TGC if the outdoor temperature was approximately 5℃ lower than the measured values. As long as the analysis is based on air temperature, we can estimate the 'chamber effect' of the TGC to be equivalent to an air temperature increase of 5℃. However, there was a good correlation between leaf emergence rate and soil temperature again across the two data sets obtained in the TGC and outdoors.

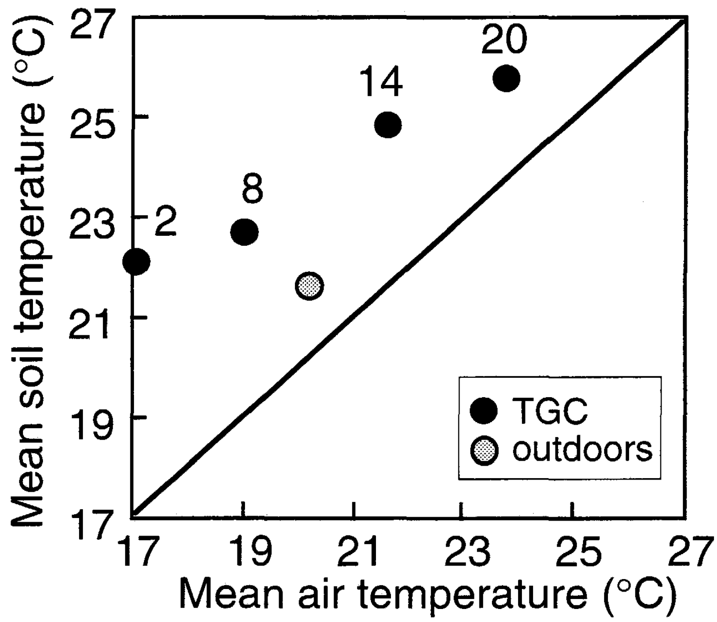

Fig. 8. Relationship between air and soil temperature in the TGC and outdoors. The numbers above the TGC data are the distance from the air inlet (m). Temperatures are averaged from May 20th to August 31st.

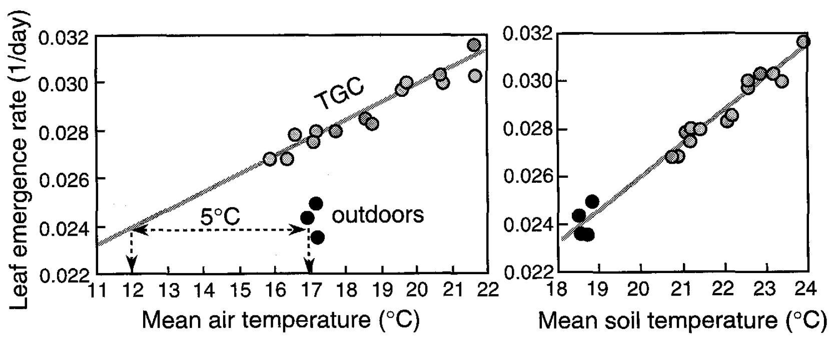

Fig. 9. Correlation between rice leaf emergence rate and mean air temperature (left) or mean soil temperature (right). Leaf emergence rate is defined as the reciprocal of the number of days from the emergence of the 2nd–leaf to the emergence of the 9th–leaf.

CONCLUSIONS

Thermal radiation is composed of shortwave and longwave radiation, but when considering temperature regimes in plant growth chambers, special emphasis is laid on the contribution of the longwave component to the heating load in the chamber. As represented by the simple heat budget Equation (3), the temperature difference between a certain body and its surrounding air is proportional to the net radiation received by the body and is modified by convection (namely the airflow conditions around the body).

The measurements made in the two artificially illuminated chambers show that whether thermal filters are installed between the lamps and the growth room or not, an extremely high level of the downward longwave radiation is emitted from the surface of the lamps or the filters. This results in the apparent 'sky' temperatures in the chambers being approximately 50℃ higher than that outdoors. In addition, the ratio of the downward longwave radiation to the shortwave radiation is 5–10 times larger than that usually observed on a clear sunny day outdoors. The increased downward thermal radiation exerts an influence on both plant and soil temperatures. The influence was particularly large when plants are grown in isolation in the chamber, because they are fully exposed to the extra radiation in such conditions. In contrast the influence of the thermal radiation is minimized when plants are grown as a dense canopy because of mutual shading.

When field chambers are covered with the films having different levels of longwave radiation transmittance, but similar shortwave radiation transmittance, the air–soil temperature relations can vary greatly between the films. The air–soil temperature relation was similar to that outdoors in the highly longwave–radiation transmissive PE chamber, but the soil temperature increased relative to the air temperature in the low transmissive PVC chamber. These relationships are also modified by the airflow speed in the chamber, as predicted by Equation (3). When rice growth is compared across chambers and outdoor plots, the leaf emergence rate is correlated to the soil temperature but not to the air temperature. This is especially true when the growing points are located underground in plants such as rice. It is also suggested that the air–plant temperature relations may be modified in the chambers and the resultant plant growth may not be correlated to the air temperature.

In terms of the thermal radiation load, as long as artificial illumination or enclosure materials are used in chambers, a change in temperature regimes is inevitable. Hence, it is very important to 1) evaluate the thermal radiation load for each individual chamber design, 2) measure the temperatures which directly affect the plant growth, 3) not use the air temperature when comparing across experiments using different chamber designs and outdoor grown plants and 4) minimize the effect of thermal radiation load by the measures such as increasing the airflow speed in the chamber.

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