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https://hdl.handle.net/2324/8124

出版情報：BIOTRONICS. 15, pp.45-54, 1986. Biotron Institute, Kyushu University

BIOTRONICS **15**, 45–54, 1986

ANALYSIS OF SOIL TEMPERATURE EFFECT ON TRANSPIRATION BY LEAF HEAT BALANCE IN CUCUMBER, CUCURBIT AND THEIR GRAFTED PLANTS

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(Received October 10, 1986; accepted October 16, 1986)

EGUCHI H. and KOUTAKI M. *Analysis of soil temperature effect on transpiration by leaf heat balance in cucumber, cucurbit and their grafted plants.* BIOTRONICS **15**, 45–54, 1986. The effect of soil temperature on transpiration rates in cucumber, cucurbit and their grafted plants (grafted cucumber plant with a stock of cucurbit plant) was examined by heat balance analysis of the leaf in an on-line measurement. In cucumber plant, higher transpiration rates were found at soil temperatures of 15 to 30°C, and soil temperatures below 15 or above 30°C resulted in a decrease in transpiration rate. In cucurbit plant, transpiration rates were higher at soil temperatures of 10 to 40°C and decreased at other soil temperatures. Thus, the transpiration in cucurbit plant was kept higher even at lower and higher soil temperatures of 10 and 35–40°C where the transpiration in cucumber plant decreased. This fact suggests that cucurbit plant is more active in water uptake into roots in wider region of soil temperature, as compared with cucumber plant. In the grafted plant, the pattern of transpiration rates responding to soil temperature was similar to that in cucurbit plant. From this pattern in the grafted plant, it could be conceivable that the activity of the cucurbit roots used as a stock is responsible for water process in the grafted cucumber plant in relation to the soil temperature.

Key words: *Cucumis sativus* L.; *Cucurbita ficifolia* B.; cucumber; cucurbit; leaf temperature; heat balance; transpiration rate; soil temperature; grafted plant; environment control; water uptake.

INTRODUCTION

Environment in rhizosphere is responsible for the activity of roots. In particular, soil water potential and soil temperature influence water uptake into roots, and eventually relate to the transpiration in the leaf through water balance in the plant (*1–4*, *6*, *7*, *13*, *16–18*). Cho *et al.* (1985) analyzed the effect of soil water potential on transpiration rate and found that the transpiration decreases at soil water potentials lower than pH 2.5. Tew *et al.* (1963), and Cox and Boersma (1967) reported that the transpiration reduces at lower soil temperatures. Thus, it appears conceivable that information about characteristics of water uptake into roots in response to the soil condition can be obtained by analysis of the transpiration in the leaf. For a better understanding of environmental effect on water process in plants, it is necessary furthermore to examine the relationship between transpiration and soil condition in wider region.

Present paper deals with analysis of soil temperature effect on transpiration rates in three kinds of *Cucurbitaceae* plants by applying heat balance of the leaf under controlled environments.

MATERIAL AND METHODS

Material plants

Cucumber plant (*Cucumis sativus* L. var. Hort. Chojitsu-Ochiai), cucurbit plant (*Cucurbita ficifolia* B. var. Hort. Kurodane) and grafted cucumber plant (Chojitsu-Ochiai) with a stock of cucurbit plant (Kurodane) were used in this experiment. The plants were grown in stainless steel pots (volume; about 600 cm^3) filled with Vermiculite (soil) moistened with nutrient solution under the air condition of air temperature of 23°C and relative humidity of 70% in artificial light (metal halide lamps) with a radiant flux density of 4.9 mW cm^{-2} (PAR) and photoperiod of 12 h. When each plant reached 5 leaves stage, the intact 3rd leaf of healthy growth was used as a specimen, and the other leaves were excised. Photograph of the plants is shown in Fig. 1.

Soil temperature control and air condition

Figure 2 shows the schematic diagram of soil temperature control system. The water bath system was applied to soil temperature control where temperature-controlled water was circulated into the bath. The planted pot was placed in the water bath, and the soil surface of the pot was sufficiently covered with heat in-

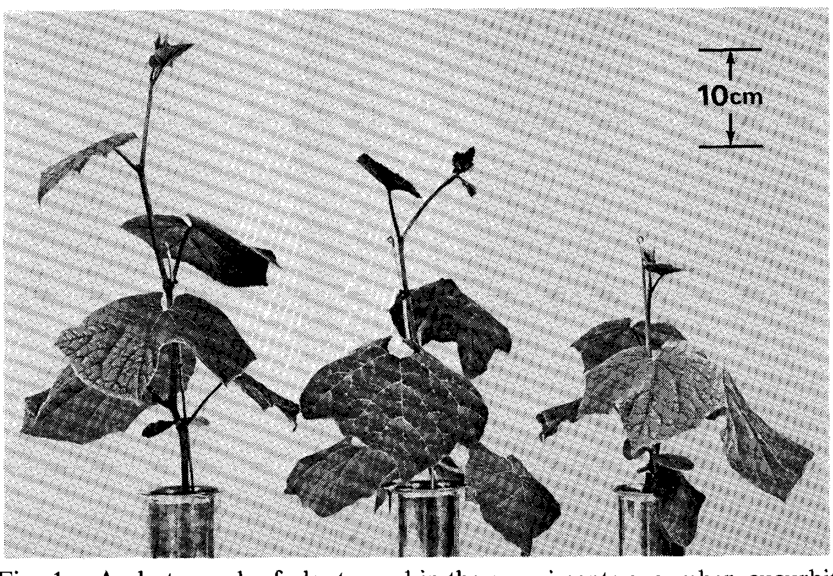

Fig. 1. A photograph of plants used in the experiment; cucumber, cucurbit and grafted plants (left to right).

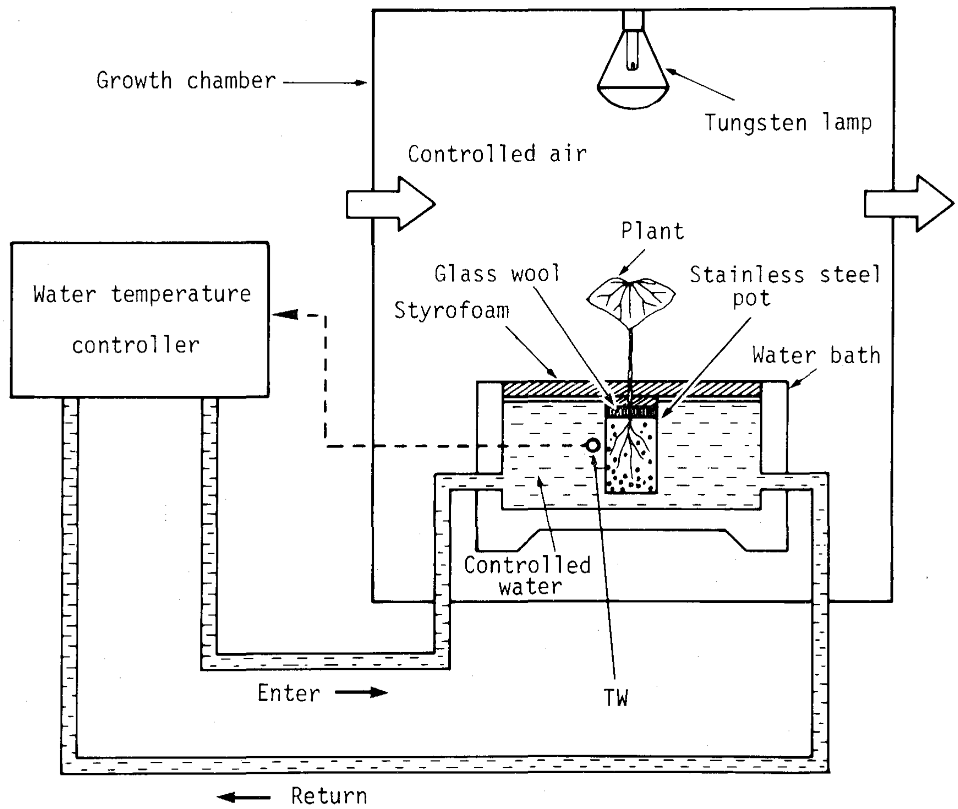

Fig. 2. Schematic diagram of soil temperature control system: water temperature (TW) is used for feedback control.

sulating materials of glass wool and styrofoam. The soil water content in the pot was kept approximately to be maximum water-holding capacity. The soil temperature in the pot settled to the desired value within 1 h after setting, and soil temperatures were almost uniform in a pot. Thus, soil temperature at a central point (at depth of 5 cm below soil surface) in the pot was monitored to represent the soil temperature. In this system, the soil temperature was controlled from 5 to 50 ± 0.1°C. This assembly was installed in a growth chamber (*14*), in which ambient air temperature and relative humidity were controlled at 25 ± 0.2°C and 40 ± 3% for the reason that this air condition is available for increase in transpiration rate (*10*). The air current was parallel to the leaf with a velocity of 30 ± 5 cm s^{-1}.

Instrumentation

The leaf was fixed horizontally and radiated vertically by a 300 W tungsten lamp at a distance of 30 cm above the leaf surface after keeping the plant in darkness for 5 h. The total flux density of the light was 181 mW cm^{-2} in a wavelength region of 0.35–60 μm, which consisted of shortwave radiant flux density (R_S) of 65 mW cm^{-2} in 0.35–3 μm (4 mW cm^{-2} in 0.4–0.7 μm) and long wave radiant flux density (L_I) of 116 mW cm^{-2} in 3–60 μm. The leaf temperature was measured with copper-constantan thermocouples (0.1 mm in diameter) inserted into a leaf at three positions near the central part of the leaf (*11*).

RESULTS AND DISCUSSION

Heat balance analysis

For on-line measurement of transpiration in the plant exposed directly to controlled air and light, heat balance (*5*, *8*, *9*) of the leaf was applied in this experiment, and transpiration rate (E) and leaf conductance (C_L) were calculated by following equations (*10*),

$$E = \frac{6\times 10^{-2}}{\lambda}\left\{A_B R_S + L_I - 2\varepsilon\sigma(273.16+T_L)^4 - 10^3\, sm\frac{\mathrm{d}T_L}{\mathrm{d}t} - \frac{2\times 10^3 C_p\rho(T_L-T_A)}{r_{AH}}\right\} \quad (1)$$

and

$$C_L = \left[\frac{1.2\times 10^{-4}\{W(T_L)-(RH/100)W(T_A)\}}{E} - r_{AH}\,\mathrm{Le}^{2/3}\right]^{-1} \quad (2)$$

The shortwave absorptivity (A_B) of the leaf was obtained in the following manners: Stomatal and cuticular transpirations were inhibited by applying 10^{-4} M of abscisic acid (*12*, *15*) and 2×10^{-2} M of microcrystalline wax to the leaf (*10*, *11*). On the other hand, the black body plate was prepared with an aluminium plate coated with camphor soot. The heat capacity (sm) of the plate was almost the same as that of the leaf used. The respective temperatures of the leaf and of the black body plate were measured for a few seconds after radiation of the tungsten light under an air condition (25°C) where the heat transferring between the leaf and the air was minimized. Then, the respective storage heat flux densities of the leaf and of the black body plate were obtained from rising rates of those temperatures, and A_B was given by the ratio of the storage heat flux density of the leaf to that of the black body plate.

Boundary layer resistance (r_{AH}) of the leaf was obtained from following manner: The transpiration was inhibited in a leaf and the equilibrium temperature of the radiated leaf was measured at an air velocity in the growth chamber used. The sensible heat flux density was estimated equal to the net radiant flux density (R_N) when the leaf temperature reached to the equilibrium. Then, r_{AH} was given by

$$r_{AH} = \frac{2\times 10^3 C_p\rho(T_L-T_A)}{R_N} \quad (3)$$

where

$$R_N = A_B R_S + L_I - 2\varepsilon\sigma(273.16+T_L)^4 \quad (4)$$

Boundary layer resistance (r_{AH}) of the leaf was obtained from resistance (r_F) to free convection and resistance (r'_{AH}) to forced convection as follows,

$$r_{AH} = \frac{r_F\, r'_{AH}}{r_F + r'_{AH}} \quad (5)$$

where

$$r_F = \frac{d}{0.405 D_H(\mathrm{Gr\ Pr})^{1/4}} \quad (6)$$

Table 1. Heat capacity (sm), shortwave absorptivity (A_B) of leaf and resistance (r'_{AH}) to forced convection in respective plants used

Material plants	sm (J cm^{-2} K^{-1})	A_B	r'_{AH} (s cm^{-1})
Cucumber plant	0.074	0.49	0.65
Cucurbit plant	0.076	0.49	0.64
Grafted plant	0.078	0.51	0.63

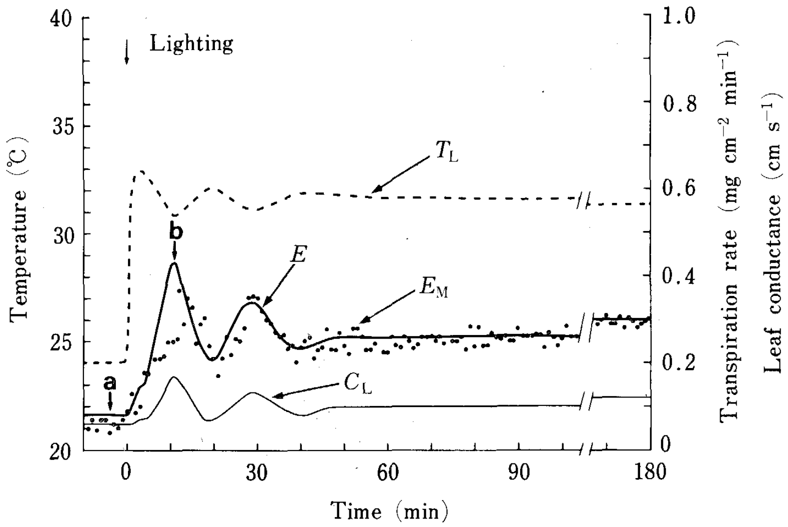

Fig. 3. Time course patterns of leaf temperature (T_L), calculated transpiration rate (E), measured transpiration rate (●, E_M), calculated leaf conductance (C_L) obtained in cucumber plant under an air condition of 25°C and 40% RH in tungsten light: E_M was measured by weighing pot and plant.

A_B, r'_{AH} and sm measured in respective leaves of three kinds of plants used are listed in Table 1.

The transpiration rates calculated from the heat balance of the cucumber leaf were compared with the measured values. Figure 3 shows leaf temperature, measured transpiration rate, calculated transpiration rate, and calculated leaf conductance in a cucumber plant. The measured transpiration rate was obtained by weighing plant and pot, where the soil temperature was uncontrolled and soil surface was covered with polyethylene film to prevent the evaporation. The calculated leaf conductance, measured and calculated transpiration rates increased rapidly after radiation and appeared in oscillatory patterns; the transpiration rates and leaf conductance became maximum at the same time when the leaf temperature was at the minimum, and synchronized with each other. Thus, the calculated transpiration rates conformed to the measured values.

On the other hand, stomatal movement was examined in microscopical observation of adaxial surface; the replica of the intact leaf surface was prepared by using cyanoacrylate adhesive at the times (indicated in Fig. 3) when the leaf was kept in darkness (a) and when the transpiration rate became maximum (b) after radiation.

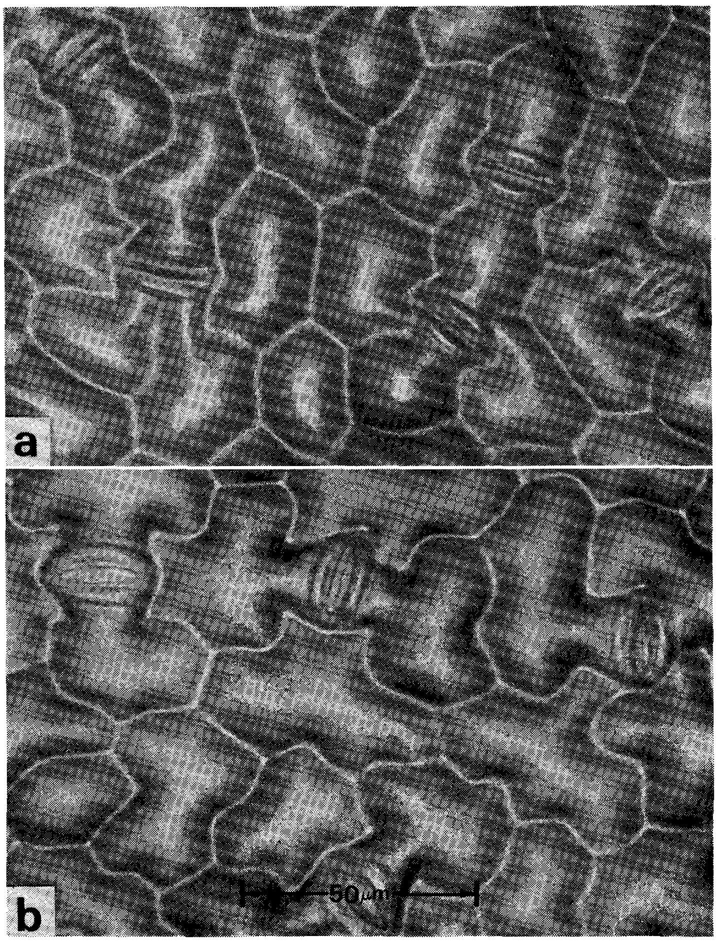

Fig. 4. Micrographs of adaxial surface replica of the intact 3rd leaf of cucumber plant; the replica was prepared with cyanoacrylate adhesive at the times in darkness (a) and when the transpiration rate was at the maximum (b) after radiation as indicated in Fig. 3.

Figure 4 shows the micrographs of stomata at the respective times stated above. As can be seen in the micrographs, the stomata closed in darkness, while the stomata opened when the transpiration rate and the leaf conductance were at their maxima. Thus, stomatal movement corresponded to the patterns of transpiration rate and leaf conductance shown in Fig. 3.

From these facts, it could be estimated that the calculation from heat balance of the leaf is useful for evaluation of the transpiration rate and the leaf conductance in an on-line system.

Effect of soil temperature

Figure 5 shows time course patterns of transpiration rates in cucumber, cucurbit and grafted plants at respective soil temperatures of 5 (a), 10 (b), 25 (c), 40 (d) and 50 (e) °C, under an air condition of 25°C and 40% RH in tungsten light: The leaf temperatures are plotted for referring correspondence to the calculated transpiration

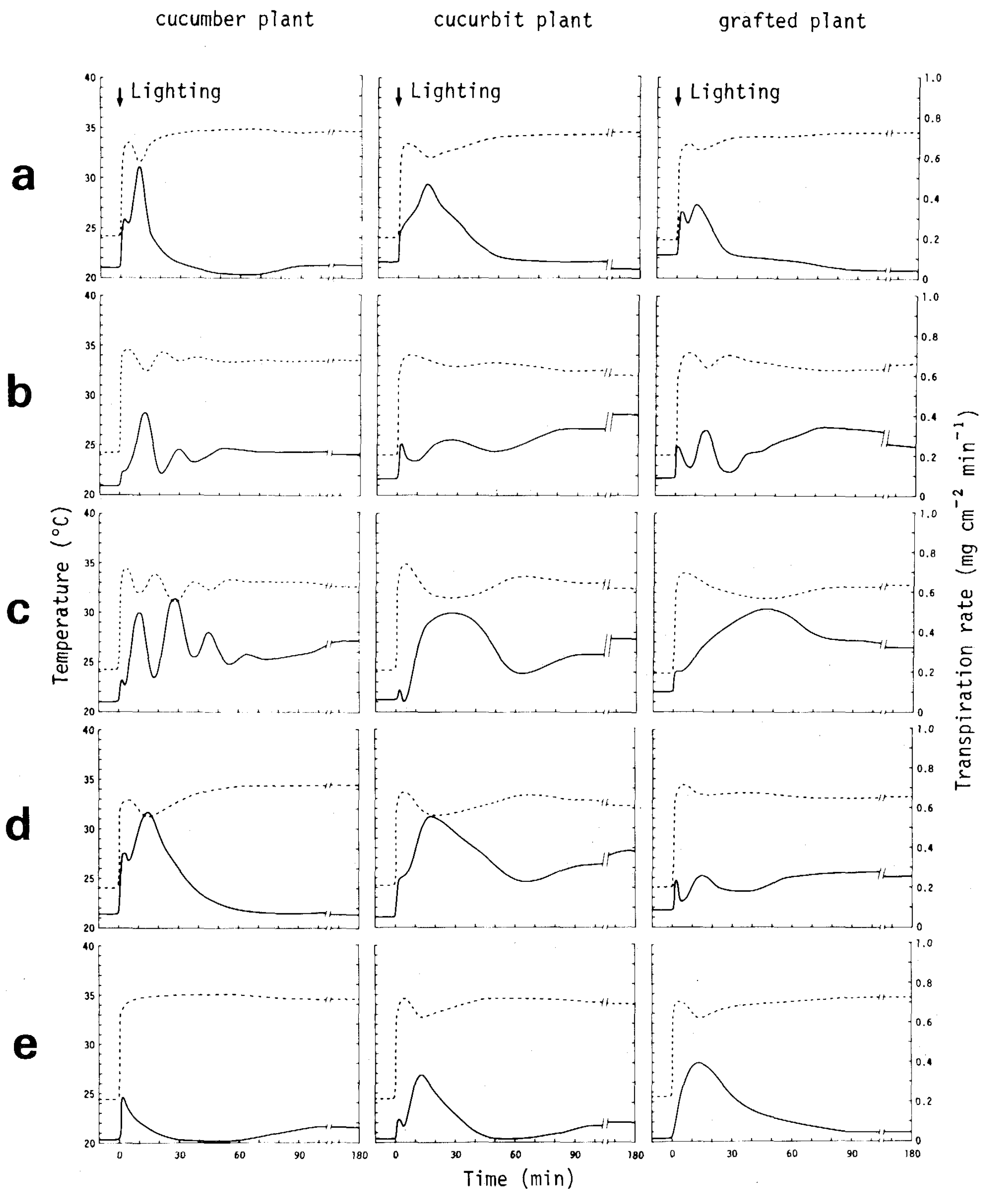

Fig. 5. Time course patterns of leaf temperature (-----) and transpiration rate (——) in cucumber, cucurbit and grafted plants at respective soil temperatures of 5 (a), 10 (b), 25 (c), 40 (d) and 50 (e)°C under an air condition of 25°C and 40% RH in tungsten light.

rates.

In cucumber plant, remarkable oscillations of leaf temperature and transpiration rate were found at soil temperature of 25°C, and thereafter the transpiration rate was kept at relatively high elevation. At higher or lower soil temperatures, the transpiration rates settled to lower levels after little oscillation. Particularly at soil temperatures of 5 and 50°C, the transpiration rates decreased more rapidly to the same level as those in darkness.

In cucurbit plant, transpiration rates settled to higher elevation at respective soil temperatures of 10, 25 and 40°C. At soil temperatures of 5 and 50°C, the transpiration rates reached once at a peak after radiation and decreased to remarkable low level. It is noticeable that transpiration rates in cucurbit plant were kept higher even at soil temperatures of 10 and 40°C, unlike cucumber plant.

In grafted cucumber plant with a stock of cucurbit plant, the patterns of transpiration rates appeared to be similar to those in cucurbit plant in response to soil temperatures; the transpiration rates were kept relatively high at soil temperatures other than 5 and 50°C.

In order to estimate the soil temperature effect on transpiration rate more clearly, the means of transpiration rates for 180 min after radiation were calculated by using 4 plants in each species at respective soil temperatures. Figure 6 shows distributions of the means of the transpiration rates on soil temperature. In cucumber plant, the higher transpiration rates were found in the soil temperature region of 15 to 30°C, but soil temperatures below 15 or above 30°C resulted in a decrease in transpiration rate. On the other hand, in cucurbit plant, the transpiration rates were higher in a region of soil temperatures between 10 and 40°C, and decreased at soil temperatures below 10 or above 40°C. At the soil temperature region of 15 to 30°C, any appreciable differences in transpiration rate were not found between cucumber and cucurbit plants. However, at the respective soil temperatures of 10, 35 and 40°C, the differences in transpiration rate between those two species were significant at 5% level. In grafted cucumber plant with the cucurbit stock, the transpiration rates were higher at a soil temperature region of 10 to 35°C.

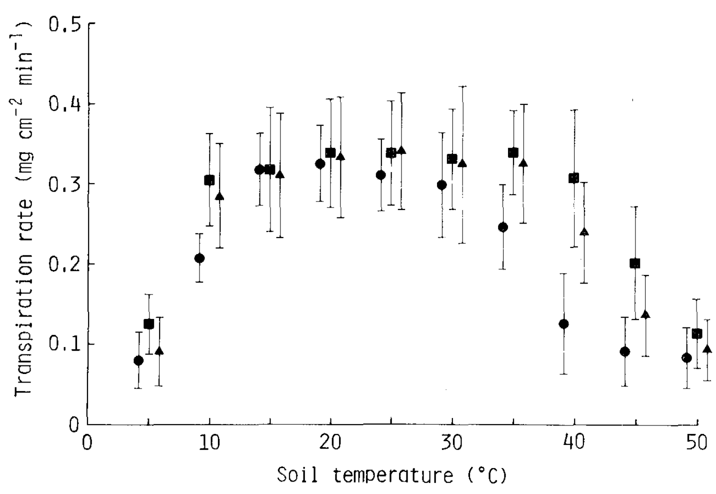

Fig. 6. Distributions of transpiration rates in cucumber (●), cucurbit (■) and grafted (▲) plants on soil temperature; means of the transpiration rates calculated for 180 min after radiation by using 4 plants in each species are plotted with corresponding 95% confidence intervals.

At a soil temperature of 40°C, transpiration rate in the grafted plant was relatively higher as compared with that in cucumber plant, but it was slightly lower than that in cucurbit plant. At soil temperatures of 5 and 50°C, the transpiration rates decreased as well as those in other plants. The differences in transpiration rate at soil temperatures of 10 and 40°C were significant between cucumber and grafted plants, but not significant between cucurbit and grafted plants at 5% level. Thus, the pattern of the transpiration rates in the grafted plant appeared close to that in cucurbit plant used as the stock.

In this experiment, soil temperature effect on transpiration rate was found clearly in three kinds of *Cucurbitaceae* plants, where broad patterns increasing in transpiration rates appeared in middle region of soil temperatures. In those patterns, species specificity was observed between cucumber and cucurbit plants at respective soil temperatures of 10 and 35–40°C; the transpiration rates in cucurbit plant were kept higher even at lower and higher soil temperatures where the transpiration in cucumber plant decreased. This fact suggests that cucurbit plant is more active in water uptake into roots in wider region of soil temperatures, as compared with cucumber plant. From the pattern of the transpiration rate in the grafted plant responding to soil temperature, which was similar to that in cucurbit plant, it could be conceivable that the activity of cucurbit roots used as the stock is responsible for water process in the grafted cucumber plant in relation to the soil temperature.

In general, cucumber plant grafted on the stock of cucurbit plant (*Cucurbita ficifolia*) has been utilized for production, as this grafted plant is more vigorous. The event in this experiment may help to understand the characteristics of the grafted plant in practical cultivation.

APPENDIX: LIST OF SYMBOLS

A_B	=shortwave absorptivity of leaf.
C_L (cm s^{-1})	=leaf conductance.
C_p (J g^{-1} K^{-1})	=specific heat of air.
d (cm)	=characteristic length of leaf.
D_H (cm^2 s^{-1})	=thermal diffusivity of air.
E (g cm^{-2} min^{-1})	=transpiration rate.
Gr	=Grashof number.
Le	=Lewis number
L_I (mW cm^{-2})	=long wave radiant flux density.
m (g cm^{-2})	=leaf weight per unit area.
Pr	=Prandtl number.
r_{AH} (s cm^{-1})	=boundary layer resistance of leaf to heat transfer.
r'_{AH} (s cm^{-1})	=resistance to forced convection.
r_F (s cm^{-1})	=resistance to free convection.
RH (%)	=relative humidity.
R_N (mW cm^{-2})	=net radiant flux density.
R_S (mW cm^{-2})	=shortwave radiant flux density.
s (J g^{-1} K^{-1})	=specific heat of leaf.
t (s)	=time.
T_A (°C)	=air temperature.
T_L (°C)	=leaf temperature.

$W(T_A)$ (g m^{-3})	=saturation vapour density at air temperature of T_A.
$W(T_L)$ (g m^{-3})	=saturation vapour density at leaf temperature of T_L.
ε	=emissivity of leaf.
λ (J g^{-1})	=latent heat for vapourization of water.
ρ (g cm^{-3})	=density of air.
σ (mW cm^{-2} K^{-4})	=Stefan-Boltzmann constant.

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