CONTROL OF EVAPORATIVE DEMAND ON TRANSPIRING PLANTS : I. SENSITIVITIES OF EVAPORATIVE DEMAND TO ENVIRONMENTAL FACTORS

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CONTROL OF EVAPORATIVE DEMAND ON TRANSPIRING PLANTS
I. SENSITIVITIES OF EVAPORATIVE DEMAND TO ENVIRONMENTAL FACTORS

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KITANO M. and EGUCHI H. *Control of evaporative demand on transpiring plants I. Sensitivities of evaporative demand to environmental factors.* BIOTRONICS **20**, 53–64, 1991. Effects of environmental factors on evaporative demand (*ED*) were analyzed, and control characteristics of *ED* were simulated. *ED* was affected by the respective environmental factors of irradiance, air temperature, humidity and wind velocity, and the respective effects on *ED* appeared in different processes. In particular, the effects of irradiance and humidity appeared more remarkable as compared with those of air temperature and wind velocity : *ED* increased almost linearly with increase in irradiance and with decrease in humidity, but the effect of air temperature was not so large under moderate conditions, and the effect of wind became smaller at the higher velocities. Thus, *ED* was more sensitive to irradiance and humidity than to air temperature and wind velocity. In a phytotron glass room (constant air temperature and wind velocity), it can be possible to control *ED* by manipulating humidity even under remarkable variation in irradiance.

Key words: evaporative demand; plant water relations; environmental factors; control; sensitivity analysis.

INTRODUCTION

Several environmental factors are known to be responsible for evaporative demand on transpiring plants through physical and physiological processes of plant water relations. Therefore, it is essential to evaluate effect of each environmental factor on the evaporative demand. In general, leaf-air vapor difference, which is a driving force for vapor transfer from leaf to air, has been used as a relative measure of evaporative demand (*1, 2, 4, 5, 8, 12, 13*). Furthermore, Harrison-Murray (*6, 7*) has developed the leaf-model evaporimeter with a wetted filter paper for sensing potential transpiration rate as a measure of evaporative demand in propagation systems. On the other hand, we have evaluated evaporative demand by using physical environmental factors of irradiance, air temperature, humidity and wind velocity on the basis of leaf heat balance, and the evaluated evaporative demand has been estimated to closely relate to plant water relations (*9, 11*). For the optimalization of plant water

relations in control of evaporative demand, it is necessary to estimate the sensitivity of evaporative demand to each environmental factor.

The present paper deals with quantitative analyses of relationships between evaporative demand and respective environmental factors in consideration of control of evaporative demand by manipulating the environmental factors.

METHODS

On the basis of leaf heat balance, a quantitative measure of evaporative demand (ED) was defined as follows (9, 11)

$$ED = \frac{2 C_P \rho \ G_E \ SD + \Delta \{aR_S - 2\sigma\varepsilon_L (1-\varepsilon_A)T_A^4\}}{\{(2/n)\gamma\ (G_E/G_{AV})+\Delta\}\lambda} \tag{1}$$

with

$$G_E = G_R + G_{AH} \tag{2}$$

where the symbols are explained in APPENDIX : LIST OF SYMBOLS. The radiative transfer conductance (G_R) was defined as

$$G_R = \frac{4\varepsilon_L\sigma\ T_E^3}{C_P\rho} \tag{3}$$

with

$$T_E = \frac{T_A + T_{LP}}{2} \tag{4}$$

T_{LP} is the leaf temperature calculated by

$$T_{LP} = T_A + \frac{(2/n)\gamma\ (G_E/G_{AV})}{(2/n)\gamma\ (G_E/G_{AV})+\Delta}\times\left\{\frac{aR_S-2\sigma\varepsilon_L(1-\varepsilon_A)T_A^4}{2C_P\rho\ G_E}\right.$$
$$\left.-\frac{SD}{(2/n)\ \gamma\ (G_E/G_{AV})}\right\} \tag{5}$$

This T_{LP} calculation was started with $T_{LP} = T_A$ and repeated until the calculated T_{LP} converged.

In the leaf boundary layer at lower wind velocities, buoyancy effect on forced convection was clearly found (10), and the respective boundary layer conductances for heat transfer (G_{AH}) and for vapor transfer (G_{AV}) were evaluated for mixed convection (forced convection and free convection) by a parallel model (8, 11), in which the conductances for forced convection (G_{FO}) and for free convection (G_{FR}) were connected in parallel as follows

$$G_{AH} = G_{FO} + G_{FR} \tag{6}$$

and

$$G_{AV} = G_{FO} / \mathrm{Le}^{0.67} + G_{FR} / \mathrm{Le}^{0.75} \tag{7}$$

with

$$G_{FO} = \frac{0.66 \; \kappa^{0.67}}{d^{0.5} \; \nu^{0.17}} \; U^{0.5} \tag{8}$$

and

$$G_{FR} = \frac{b \beta^{0.25} \; g^{0.25} \; \kappa}{d^{0.25} \; \nu^{0.5}} \; |T_{LP} - T_A|^{0.25} \tag{9}$$

Thus, ED can be evaluated by environmental factors of R_S, T_A, SD and U, and effects of the respective environmental factors on ED can be analyzed quantitatively under various environmental conditions. Furthermore, it can be estimated that the effects of environmental factors on ED are influenced by the leaf dimension (d), because the leaf boundary layer conductances depend on d as indicated by Eqs. (8) and (9). Therefore, the effects of environmental factors can be also analyzed at different conditions of d.

In most of the environment control systems, relative humidity (RH) of ambient air is detected and controlled. RH relates to SD given as

$$SD = (1 - \frac{RH}{100}) \times SAV \tag{10}$$

where saturation vapor density of air (SAV) increases with increase in T_A. Therefore, effect of RH on ED can be analyzed.

Then, on the basis of effect of each environmental factor on ED, characteristics of the ED control by manipulating environmental factors was simulated in a phytotron glass room.

RESULTS AND DISCUSSION

Figure 1 shows effects of R_S on ED under different conditions of T_A, SD, U and d. ED increased almost linearly with increase in R_S. This suggests that evaporative demand remarkably varies with irradiance of light even in control systems where ambient air conditon is kept constant. The increase rate (i. e. sensitivity; $\partial ED / \partial R_S$) of ED to unit increase in R_S was a little influenced by T_A and became larger at higher T_A. This T_A effect on $\partial ED / \partial R_S$ resulted mainly from larger Δ and larger G_R at higher T_A. On the other hand, SD, U and d scarcely influenced on $\partial ED / \partial R_S$.

Figure 2 shows effects of T_A on ED under different conditions of R_S, SD, U and d. Effect of T_A on ED was small, but decrease in ED with increase in T_A were found under the respective conditions of lower R_S, higher SD, higher U and smaller d. This effect of T_A on ED was attributed to larger Δ and larger radiative exchange rate $(2\sigma\varepsilon_L(1-\varepsilon_A) \; T_A^4)$ at higher T_A.
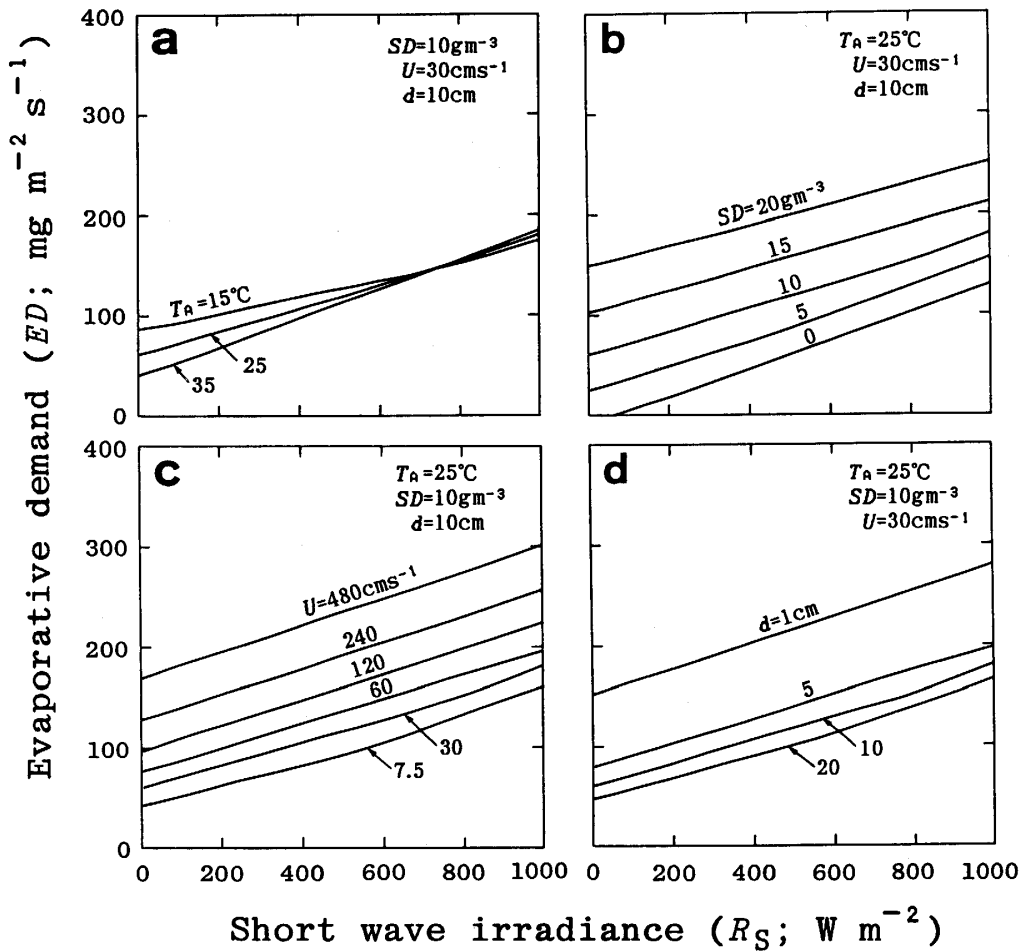
Fig. 1. Effect of short wave irradiance on evaporative demand under different conditions of air temperature (a), saturation deficit (b), wind velocity (c) and leaf dimension (d): ED, evaporative demand; R_S, short wave irradiance; T_A, air temperature; SD, saturation deficit; U, wind velocity; d, leaf dimension.

Figure 3 shows effects of SD on ED under different conditions of R_S, T_A, U and d. ED increased remarkably with increase in SD. The increase rate ($\partial ED/\partial SD$) of ED to unit increase in SD was scarcely influenced by R_S and T_A but much influenced by U and d; the influences of U and d on $\partial ED/\partial SD$ was attributed to the fact that the boundary layer conductances (G_{AH} and G_{AV}) became higher under respective conditions of higher U and smaller d as indicated by Eqs. (6) – (9). Furthermore, even when the ambient air was saturated with water vapor (i.e. $SD=0$), ED became larger than zero in the case that R_S was higher than 100 Wm^{-2}.

Figure 4 shows effects of U on ED under different conditions of R_S, T_A, SD and d. ED increased with increase in U, and the increase rate ($\partial ED/\partial U$) of ED to unit increase in U became smaller at higher U. This increase in ED was brought
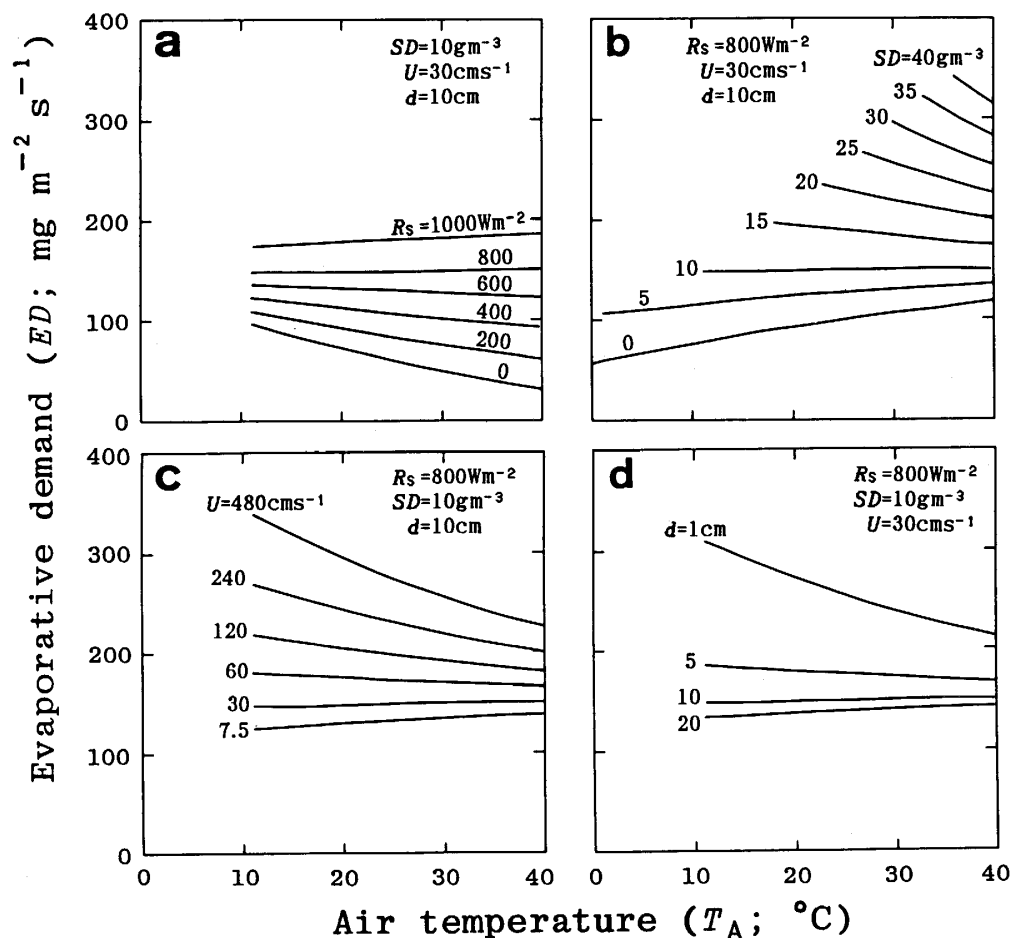
Evaporative demand (ED; mg m^{-2} s^{-1})

Air temperature (T_A; °C)

a $SD=10$gm^{-3} $U=30$cms^{-1} $d=10$cm $R_S=1000$Wm^{-2} 800 600 400 200 0

b $R_S=800$Wm^{-2} $U=30$cms^{-1} $d=10$cm $SD=40$gm^{-3} 35 30 25 20 15 10 5 0

c $U=480$cms^{-1} $R_S=800$Wm^{-2} $SD=10$gm^{-3} $d=10$cm 240 120 60 30 7.5

d $R_S=800$Wm^{-2} $SD=10$gm^{-3} $U=30$cms^{-1} $d=1$cm 5 10 20

Fig. 2. Effect of air temperature on evaporative demand under different conditions of short wave irradiance (a), saturation deficit (b), wind velocity (c) and leaf dimension (d), where ED, R_S, T_A, SD, U and d are explained in Fig. 1.

by dependence of G_{FO} on $U^{0.5}$ as indicated by Eq. (8). Furthermore, $\partial ED/\partial U$ was scarcely affected by R_S and T_A but much affected by SD and d; $\partial ED/\partial U$ appeared larger under respective conditions of larger SD and smaller d.

Figure 5 shows effects of RH on ED under different conditions of R_S, T_A, U and d. ED decreased with increase in RH. The decrease rate $(-\partial ED/\partial RH)$ was scarcely influenced by R_S but much influenced by T_A, U and d; $-\partial ED/\partial RH$ became larger under the respective conditions of higher T_A, higher U and smaller d. The effect of T_A on $-\partial ED/\partial RH$ was attributed to the fact that saturation vapor density (SAV) increased with increase in T_A. The effects of U and d on $-\partial ED/\partial RH$ were brought by the higher boundary layer conductances (G_{AH} and G_{AV}) at higher U and at smaller d.

As shown in Figs. 1–5, ED was affected by the respective environmental factors of irradiance, air temperature, humidity and wind velocity. The
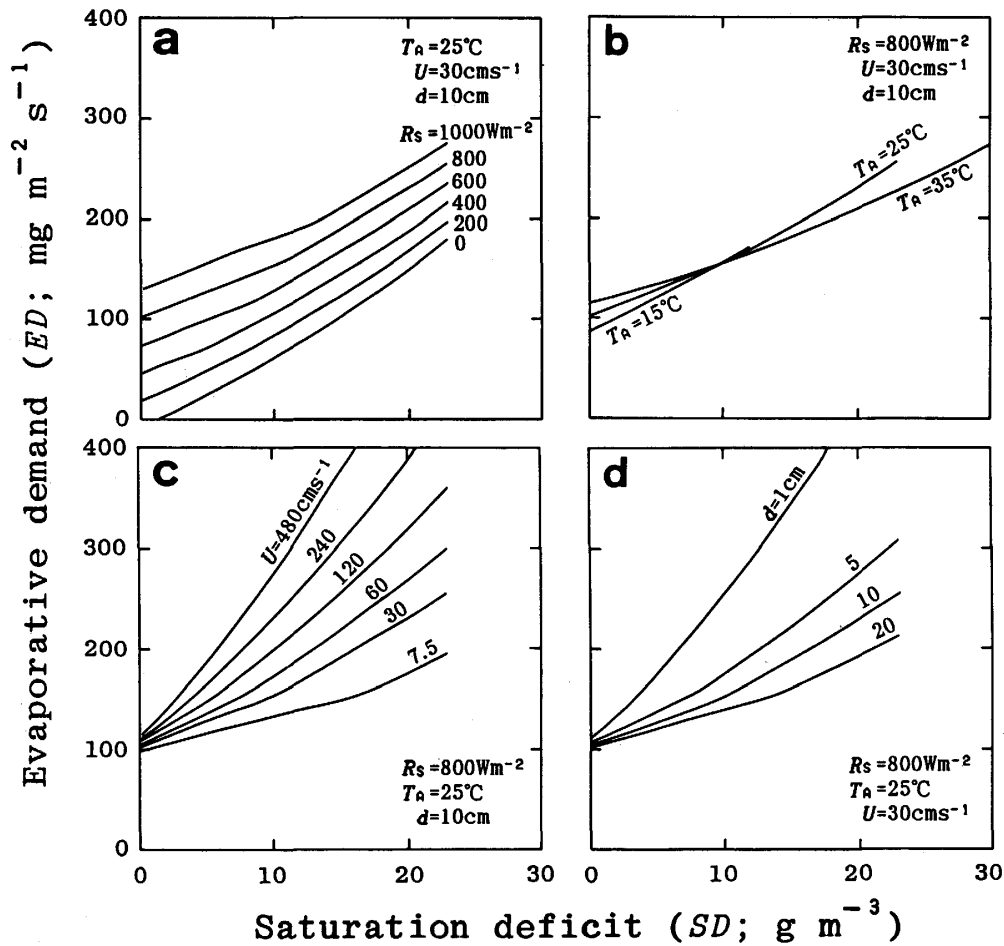
Fig. 3. Effect of saturation deficit on evaporative demand under different conditons of short wave irradiance (a), air temperature (b), wind velocity (c) and leaf dimension (d), where ED, R_S, T_A, SD, U and d are explained in Fig. 1.

respective effects on ED appeared in different processes, and ED was more sensitive to irradiance and humidity than to air temperature and wind velocity; the effect of T_A was not so large under moderate conditions (Fig. 2), and the effect of U became smaller at higher U (Fig. 4). These facts indicate that ED can be controlled by manipulating the environmental factors responsible for ED. In particular, the manipulations of irradiance and humidity was estimated to be effective methods for the ED control. Under R_S change in environment control systems, the humidity manipulation was estimated to be the most practicable method for the ED control. Therefore, in environment control systems where RH was used for humidity control, a humidity manipulation rate ($MRHR_S$) for unit change in R_S was defined as
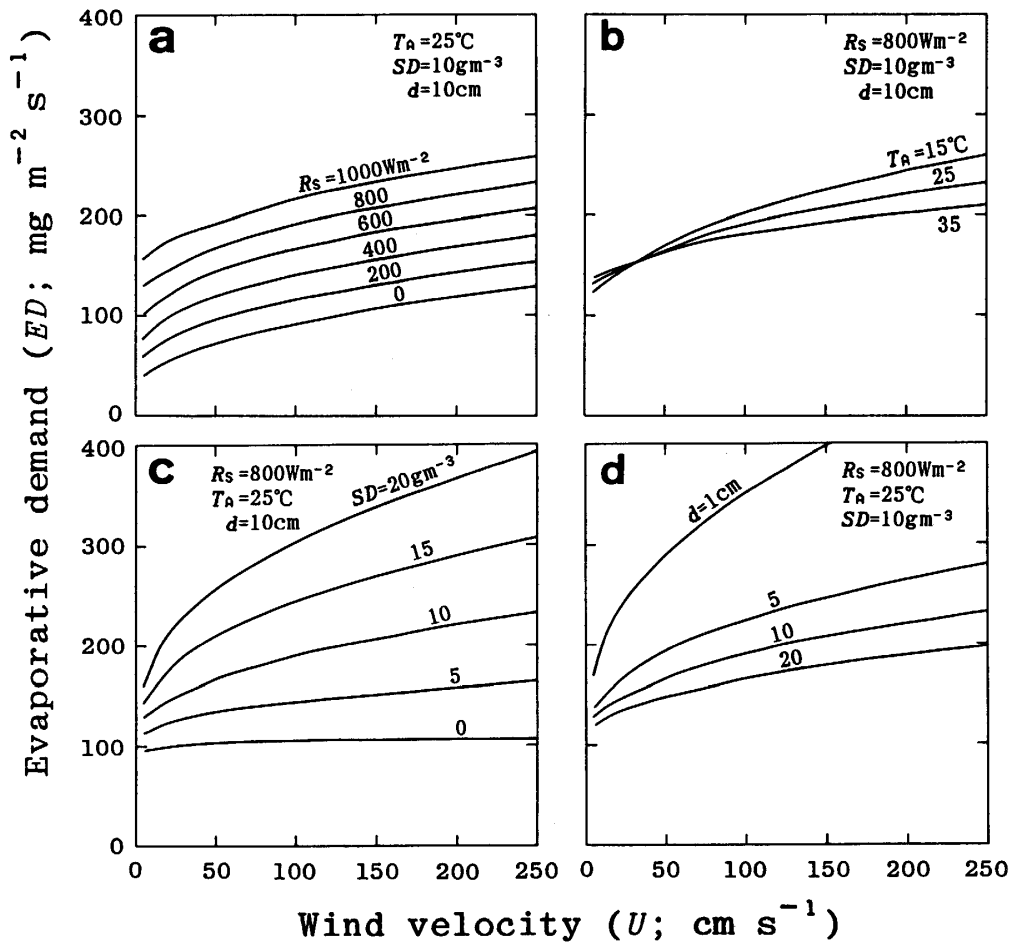
Fig. 4. Effect of wind velocity on evaporative demand under different conditions of short wave irradiance (a), air temperature (b), saturation deficit (c) and leaf dimension (d), where ED, R_S, T_A, SD, U and d are explained in Fig. 1.

$$MRHR_S = - \frac{\partial ED / \partial R_S}{\partial ED / \partial RH}$$ (11)

This humidity manipulation rate has the unit of % $W^{-1}m^2$ and means humidification rate necessary for controlling ED at a given value when R_S increases by 1 W m^{-2}. From Figs. 1 and 5, $MRHR_S$ was estimated to be scarcely affected by R_S and RH, but appreciably depend on T_A, U and d. Figure 6 shows effect of T_A on $MRHR_S$ under different conditions of U and d. $MRHR_S$ decreased with increase in T_A and became lower under the respective conditions of higher U and smaller d. This indicates that the control of ED by manipulating RH is more effective under the respective conditions of higher T_A, higher U and smaller d.

The ED control was simulated in a phytotron glass room, where RH was manipulated according to R_S variation on the basis of the humidity manipulation
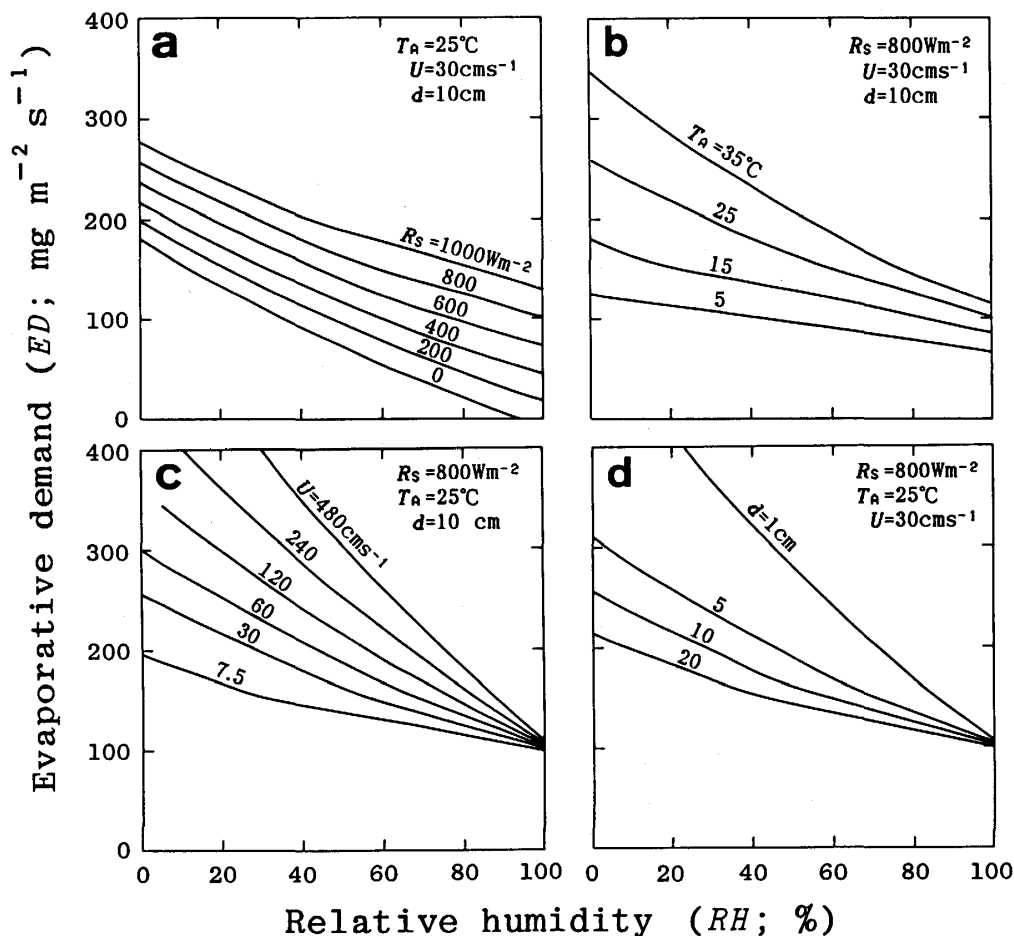
Fig. 5. Effect of relative humidity on evaporative demand under different conditions of short wave irradiance (a), air temperature (b), wind velocity (c) and leaf dimension (d), where RH is the relative humidity, and ED, R_S, T_A, U and d are explained in Fig. 1.

rate $MRHR_S$ calculated. In the previous paper (11), we have reported that water deficit was induced in a 10 leaf stage cucumber plant by the higher ED around a fair midday in a phytotron glass room. Figures 7(a) and (b) show stomatal conductance (G_S), R_S, ED and RH observed on a cloudy day and a fair day in the phytotron glass room, where T_A and RH of ambient air were controlled at $23\pm$ 1℃ and $70\pm7\%$, respectively, and ED varied according to R_S. When ED reached to the higher levels around the fair midday, G_S was extremely depressed by water deficit induced by the higher ED. Then, Fig. 7 (c) shows the simulated ED and RH, where RH was manipulated according to R_S variation for controlling ED at a desired value of 52 mg m^{-2}s^{-1}; this desired value of ED was same to the measured value at 10:00 on the fair day when G_S started to be depressed by water deficit. The simulation indicates that ED can be controlled at the desired value independent of R_S variation by manipulating RH in a range of 62 to 87%.

From the results, it is suggested that even under remarkable variation in R_S, ED can be controlled at a moderate level by manipulating humidity of the ambient air. In particular, this moderate ED was considered to be important in environment control systems under high irradiance and also important in propagation systems for unrooted leafy cuttings (3).

Thus, the respective environmental factors of irradiance, air temperature, humidity and wind velocity were responsible for the evaporative demand. In particular, the evaporative demand was more sensitive to irradiance and humidity. So, it became conceivable that in the phytotron glass room with variation in irradiance, humidity manipulation is remarkably effective for control of the evaporative demand.
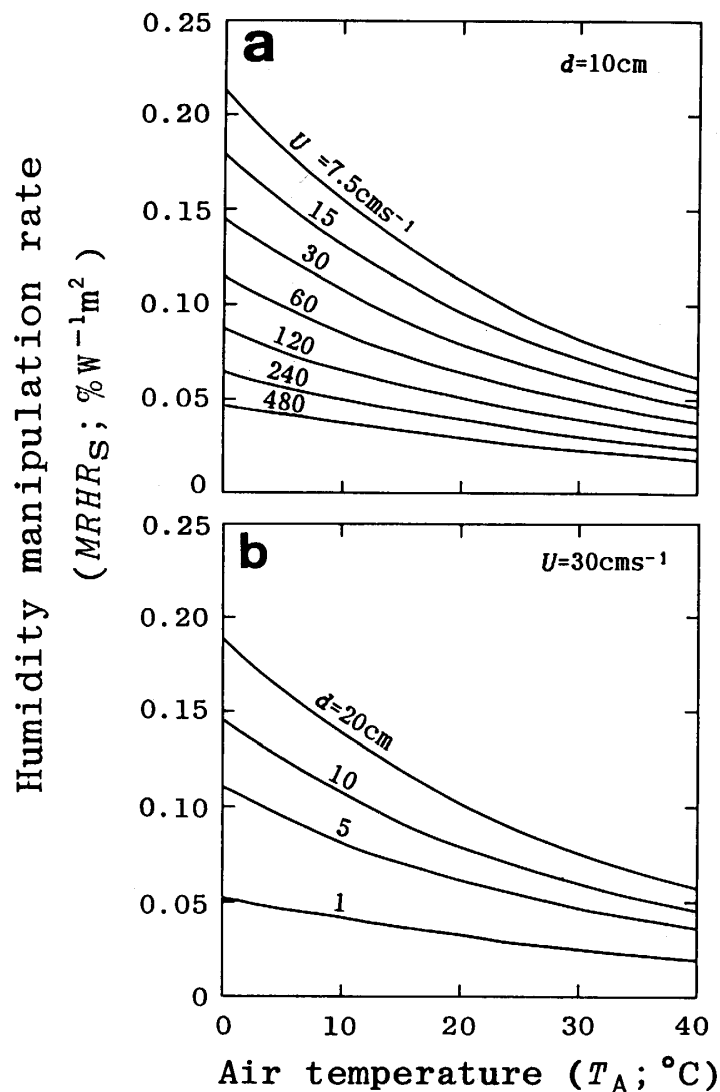

Fig. 6. Effect of air temperature on humidity manipulation rate under different conditions of wind velocity (a) and leaf dimension (b), where $MRHR_S$ is the humidity manipulation rate defined by Eq. (11), and T_A, U and d are explained in Fig. 1.
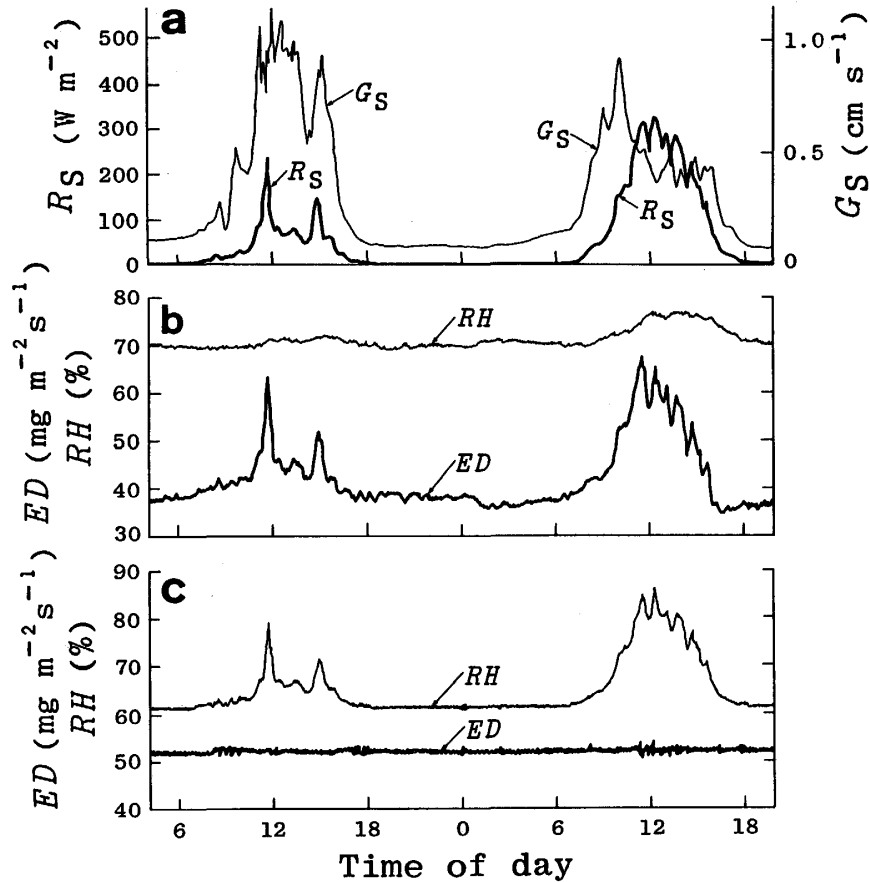
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Fig. 7. Diurnal variations of short wave irradiance (R_S), stomatal conductance (G_S), evaporative demand (ED) and relative humidity (RH) in a phytotron glass room on a cloudy day and a fair day: R_S and G_S in (a) and ED and RH in (b) are the measured values in the phytotron glass room where RH is controlled at $70\pm7\%$ and ED varies with R_S. RH and ED in (c) are the simulated values for controlling ED at a level lower than that at 10: 00 on the fair day when G_S starts to be depressed by water deficit.

APPENDIX : LIST OF SYMBOLS

a short wave absorption coefficient of a leaf.

b constant ($b=0.50$ on upper leaf surface and $b=0.23$ on lower leaf surface).

C_P specific heat of air at a constant pressure.

d characteristic dimension of a leaf.

ED evaporative demand by Eq. (1).

g acceleration of gravity.

G_{AH} leaf boundary layer conductance for heat transfer.

G_{AV} leaf boundary layer conductance for vapor transfer.

G_E parallel conductance of G_{AH} and G_R.

G_{FO} leaf boundary layer conductance for forced convection.

G_{FR} leaf boundary layer conductance for free convection.
G_R radiative transfer conductance $(4\,\varepsilon_L\sigma\,T_E{}^3/C_P\rho)$.
G_S stomatal conductance.
Le Lewis number.
$MRHR_S$ manipulation rate of relative humidity for unit change in irradiance.
n constant ($n=2$ in an amphistomatous leaf and $n=1$ in a hypostomatous leaf).
RH relative humidity of ambient air.
R_S short wave irradiance.
SAV saturation vapor density of air at T_A.
SD saturation deficit of ambient air.
T_A temperature of ambient air.
T_{LP} leaf temperature estimated by Eq. (5).
T_E $(T_A+T_{LP})/2$
U wind velocity of ambient air.
β coefficient of thermal expansion of air.
γ thermodynamic psychrometer constant $(C_P\rho/\lambda)$.
$\varDelta$ slope of the saturation vapor density curve.
ε_A emissivity of environment.
ε_L emissivity of a leaf.
κ thermal diffusivity of air.
λ latent heat of vaporization of water.
ν coefficient of kinematic viscosity of air.
ρ density of air.
σ Stefan-Boltzmann constant $(5.67\times10^{-8}\,\mathrm{W\,m^{-2}K^{-4}})$.

REFERENCES

1. Assmann S. M. and Grantz D. A. (1990) Stomatal response to humidity in sugarcane and soybean: Effect of vapor pressure difference on the kinetics of the blue light response. *Plant, Cell Environ.* **13**, 163–169.
2. Farquhar G. D. and Cowan I. R. (1974) Oscillations in stomatal conductance: The influence of environmental gain. *Plant Physiol.* **54**, 769–772.
3. Grange R. I. and Loach K. (1983) The water economy of unrooted leafy cuttings. *J. Hort. Sci.* **58**, 9–17.
4. Grantz D. A. and Zeiger E. (1986) Stomatal responses to light and leaf-air water vapor pressure difference show similar kinetics in sugarcane and soybean. *Plant Physiol.* **81**, 865–868.
5. Grantz D. A. and Meinzer F. C. (1990) Stomatal response to humidity in a sugarcane field : Simultaneous porometric and micrometeorological measurements. *Plant, Cell Environ.* **13**, 27–37.
6. Harrison-Murray R. S. (1991) A leaf-model evaporimeter for estimating potential transpiration in propagation environments. *J. Hort. Sci.* **66**, 131–139.
7. Harrison-Murray R. S. (1991) An electrical sensor for potential transpiration: Principle and prototype. *J. Hort. Sci.* **66**, 141–149.
8. Kitano M. and Eguchi H. (1989) Dynamic analysis of stomatal responses by an improved method of leaf heat balance. *Environ. exp. Bot.* **29**, 175–185.
9. Kitano M., Hamakoga M. and Eguchi H. (1990) Physical evaluation of effective

    evaporative demand with reference to plant water relations. *Biotronics* **19**, 109–119.
10. Kitano M. and Eguchi H. (1990) Buoyancy effect on forced convection in the leaf boundary layer. *Plant, Cell Environ.* **13**, 965–970.
11. Kitano M. and Eguchi H. (1991) Dynamics of pant water relations as affected by evaporative demand.   Pages 367–372 *in* Y. Hashimoto and W. Day (eds) *The proceedings of IFAC / ISHS Workshop on Mathematical and Control Applications in Agriculture and Horticulture.* Pergamon Press, London.
12. Schulze E.-D., Lange O. L., Buschbom U., Kappen L. and Evenari M. (1972) Stomatal responses to changes in humidity in plants growing in the desert. *Planta* **108**, 259–270.
13. Schulze E.-D. (1986) Carbon dioxide and water vapor exchange in response to drought in the atmosphere and in the soil. *Ann. Rev. Plant Physiol.* **37**, 247–274.