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 optimization 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 \((9, 11)\)

\[
ED = \frac{2 C_p \rho G_r SD + \Delta(a R_s - 2 \sigma e_L (1 - e_A)T_A^4)}{(2/n) \gamma (G_e / G_{AV}) + \Delta} \lambda
\]  

\[ED = \frac{(2/n) \gamma (G_e / G_{AV}) + \Delta}{G_e - \frac{a R_s - 2 \sigma e_L (1 - e_A)T_A^4}{2 C_p \rho G_e}} \]

with

\[G_e = G_R + G_{AH}\]

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

\[G_R = \frac{4 \varepsilon_L \sigma T_e^3}{C_p \rho}\]

with

\[T_e = \frac{T_A + T_{LP}}{2}\]

\[T_{LP}\] is the leaf temperature calculated by

\[T_{LP} = T_A + \frac{(2/n) \gamma (G_e / G_{AV})}{(2/n) \gamma (G_e / G_{AV}) + \Delta} \times \frac{a R_s - 2 \sigma e_L (1 - e_A)T_A^4}{2 C_p \rho G_e} \]

\[- \frac{SD}{(2/n) \gamma (G_e / G_{AV})}\]

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

\[G_{AH} = G_{FO} + G_{FR}\]
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\[ G_{AV} = G_{FO} / L_e^{0.67} + G_{FR} / L_e^{0.75} \] (7)

with

\[ G_{FO} = \frac{0.66 \kappa^{0.67}}{d^{0.5} \nu^{0.17}} U^{0.5} \] (8)

and

\[ G_{FR} = \frac{b \beta^{0.25} g^{0.25} \kappa \kappa}{d^{0.25} \nu^{0.5}} \left| T_{LP} - T_{A} \right|^{0.25} \] (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

\[ SD = \left( 1 - \frac{RH}{100} \right) \times SAV \] (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 condition 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 \( \Delta \) 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 \( \Delta \) and larger radiative exchange rate \( (2 \sigma e \left( 1 - e \lambda \right) T_A^4) \) at higher \( T_A \).

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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 W m$^{-2}$.

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
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 $ED$, $Rs$, $TA$, $SD$, $U$ and $d$ are explained in Fig. 1.

by dependence of $G_{FD}$ on $U^{0.5}$ as indicated by Eq. (8). Furthermore, $\partial ED/\partial U$ was scarcely affected by $Rs$ and $TA$ 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 $Rs$, $TA$, $U$ and $d$. $ED$ decreased with increase in $RH$. The decrease rate ($-\partial ED/\partial RH$) was scarcely influenced by $Rs$ but much influenced by $TA$, $U$ and $d$; $-\partial ED/\partial RH$ became larger under the respective conditions of higher $TA$, higher $U$ and smaller $d$. The effect of $TA$ on $-\partial ED/\partial RH$ was attributed to the fact that saturation vapor density ($SAV$) increased with increase in $TA$. 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 conditions 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
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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, Rs, TA, SD, U and d are explained in Fig. 1.

\[
MRHR_s = - \frac{\partial ED}{\partial RS} \frac{\partial RS}{\partial RH}
\]

This humidity manipulation rate has the unit of \( \% \) \( \text{W}^{-1} \text{m}^2 \) and means humidification rate necessary for controlling ED at a given value when \( R_s \) increases by 1 \( \text{W m}^{-2} \). From Figs. 1 and 5, \( MRHR_s \) was estimated to be scarcely affected by \( R_s \) and \( RH \), but appreciably depend on \( TA, U \) and \( d \). Figure 6 shows effect of \( TA \) on \( MRHR_s \) under different conditions of \( U \) and \( d \). \( MRHR_s \) decreased with increase in \( TA \) 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 \( TA \), 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, Rs, TA, U and d are explained in Fig. 1.

rate MRHRs 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 (Gs), Rs, ED and RH observed on a cloudy day and a fair day in the phytotron glass room, where TA and RH of ambient air were controlled at 23±1°C and 70±7%, respectively, and ED varied according to Rs. When ED reached to the higher levels around the fair midday, Gs 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 Rs 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 Gs started to be depressed by water deficit. The simulation indicates that ED can be controlled at the desired value independent of Rs 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.
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±7% 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

\begin{itemize}
  \item $a$ short wave absorption coefficient of a leaf.
  \item $b$ constant ($b=0.50$ on upper leaf surface and $b=0.23$ on lower leaf surface).
  \item $C_P$ specific heat of air at a constant pressure.
  \item $d$ characteristic dimension of a leaf.
  \item $ED$ evaporative demand by Eq. (1).
  \item $g$ acceleration of gravity.
  \item $G_{AH}$ leaf boundary layer conductance for heat transfer.
  \item $G_{AV}$ leaf boundary layer conductance for vapor transfer.
  \item $G_E$ parallel conductance of $G_{AH}$ and $G_{R}$.
  \item $G_{FO}$ leaf boundary layer conductance for forced convection.
\end{itemize}
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\[ G_{FR} \] 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 \((n=2 \text{ in an amphistomatous leaf and } n=1 \text{ in a hypostomatous leaf})\).
\[ RH \] 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.
\[ \beta \] coefficient of thermal expansion of air.
\[ \gamma \] thermodynamic psychrometer constant \((C_P \rho / \lambda)\).
\[ \Delta \] slope of the saturation vapor density curve.
\[ \varepsilon_A \] emissivity of environment.
\[ \varepsilon_L \] emissivity of a leaf.
\[ \kappa \] thermal diffusivity of air.
\[ \lambda \] latent heat of vaporization of water.
\[ \nu \] coefficient of kinematic viscosity of air.
\[ \rho \] density of air.
\[ \sigma \] Stefan-Boltzmann constant \((5.67 \times 10^{-8} \text{ Wm}^{-2} \text{K}^{-4})\).

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