

REVIEW

Theoretical Analysis and Experimental Verification of a Remotely Measurable Plant Transpiration Transfer Coefficient

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Abstract

The objectives of this study are to propose a remotely measurable *plant transpiration transfer coefficient* (h_{at}) and to verify its characteristics under various environmental conditions. The h_{at} is defined as $(T_c - T_a) / (T_p - T_a)$, where T_c , T_p , and T_a are the temperatures of the canopy, a non-transpiring canopy, and air, respectively. Theoretically, $h_{at} \leq 1$, and determines transpiration from its minimum value (zero) to its maximum value (potential transpiration rate). Five experiments were conducted between 1994 and 1999 to verify the characteristics of h_{at} , using 3 plant species (sorghum, tomato and melon). Theoretical validation showed that the proposed model agreed well with conventional models. Experimental results showed that the h_{at} value was approximately equal to the value of the ratio of sensible heat fluxes (H/H_p), and the slope of the regression line between them was close to 1, the intercept was close to 0, and the regression coefficient was $r^2 = 0.70$. In addition, h_{at} was not only an indicator of the water status in the plant root zone, but also an indicator of atmospheric variables. Under water-stressed conditions, h_{at} was affected mainly by the water status in the plant root zone. Therefore, h_{at} can be used as an indicator of plant water stress. The main advantages are that h_{at} can be easily measured and applied under various conditions. Due to its simplicity, h_{at} is a suitable coefficient for analyzing the process of transpiration and for determining the transpiration rate.

Discipline: Agro-meteorology

Additional key words: remote sensing, sensible heat flux, surface temperature

Introduction

The surface temperature of vegetation varies with evapotranspiration, photosynthesis, and other environmental factors. Monteith and Szeicz¹⁵ and Monteith¹⁴ presented a theoretical discussion on the relationship between surface temperature and stomatal resistance. An equation relating the canopy–air temperature difference to net radiation, wind speed, vapor pressure gradient, aerodynamic resistance, and canopy resistance was developed. Carlson et al.⁴ reported that the leaf temperature increased as the relative leaf water content and vapor pressure deficit decreased. Ehrler⁵ directly considered the possibility of using the canopy–air temperature difference as a guide to irrigation scheduling. A significant

result of this study was the demonstration of a linear relation between the leaf–air temperature difference and the vapor pressure deficit. Moran et al.¹⁷ proposed the use of surface–air temperature and a vegetation index to estimate crop water deficit. The most significant aspect of this study was the applicability to fields partially covered with vegetation. The canopy–air temperature difference was later applied to the estimation of evapotranspiration^{1,6–8,10,20,22–25} and photosynthesis²⁸. These relations were further extended to the estimation of crop water stress^{9,11,19,21,26}. On the basis of these studies, remote sensing of surface temperature has become an established technique for bioenvironmental information and has been widely applied in the fields of CO₂ flux monitoring, pollution monitoring, and agriculture¹². At the sample sites, combined with multispectral imagery, the measurements

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of soil and crop properties by remote sensing have the potential to produce accurate and timely maps for soil and crop¹³.

However, besides the requirements of remotely sensed surface temperature, most of the above-mentioned methods require some site-measured parameters as inputs, which are sometimes difficult to obtain even by scene measurement. Moreover, as a result of a succession of launchings of several commercial satellites that can provide multispectral images with 3-day repeat coverage and 1–4 m spatial resolution¹⁸, some of the conventional methods are no longer applicable under higher resolution remote sensing conditions because too many empirical constants are involved. Therefore, a method that is theoretically sounder and practically applicable to remote sensing technology should be developed. The objectives of this study are to propose a remotely measurable plant transpiration transfer coefficient and to analyze theoretically and verify experimentally its characteristics.

Definition of plant transpiration transfer coefficient and properties

By introducing the temperature of a non-transpiring canopy (leaf)²⁰, a model to estimate plant transpiration was developed by the equation:

$$T = R_n - R_{np} \frac{T_c - T_a}{T_p - T_a} \quad (1)$$

where T is the transpiration rate ($\text{MJ m}^{-2} \text{d}^{-1}$), R_n and R_{np} are the net radiations on the canopy and the non-transpiring canopy ($\text{MJ m}^{-2} \text{d}^{-1}$), T_c is the canopy temperature (represented by sunlit leaf temperature), T_p is the non-transpiring leaf temperature, and T_a is the air temperature. The unit for temperature is $^{\circ}\text{C}$. The temperature term in Eq. (1) is the key component to calculate transpiration. Therefore, the *plant transpiration transfer coefficient* (h_{at}) is defined as:

$$h_{at} = \frac{T_c - T_a}{T_p - T_a} \quad (2)$$

Theoretically, $h_{at} \leq 1$. If $T_c = T_p$, h_{at} assumes its maximum value ($h_{at} = 1$) and transpiration assumes its minimum value ($T = 0$). This limit is determined by the lack of water for transpiration. On the other hand, when the value of h_{at} is minimum, transpiration can reach a maximum value (potential transpiration rate). This limit is determined by the energy available for transpiration. Therefore, h_{at} determines the transpiration rate from zero to the potential transpiration rate. A lower value of h_{at} corresponds to a higher transpiration rate. In Eq. (1), because R_n , R_{np} , T_p and T_a are determined only by the

physical environment, the transpiration properties of a plant itself are determined by T_c and T_a . Under the same physical conditions, the differences in the transpiration properties of different species are indicated by the differences in T_c and T_a .

Theoretical validation

1. Upper limit of transpiration rate

The upper limit of the transpiration rate is determined by the minimum value of h_{at} , when there is no water shortage, and T is approximately equal to the potential transpiration rate. There is no major difference between our model and the canopy–air temperature difference models under these conditions. If the soil heat flux under a fully covered canopy is negligible and stomatal resistance is approximately equal to zero, the canopy–air temperature difference models can be expressed²⁷ as:

$$T = R_n - \rho C_p \frac{T_c - T_a}{r_a} \quad (3)$$

where ρC_p is the volumetric heat capacity of air ($0.0012 \text{ MJ m}^{-3} \text{ }^{\circ}\text{C}^{-1}$) and r_a is the aerodynamic resistance (s m^{-1}). Meanwhile, the Penman–Monteith model gives the relationship between T and vapor pressure deficit¹⁶ as:

$$T = \frac{\Delta R_n + \rho C_p (e_s - e_a) / r_a}{\Delta + \gamma} \quad (4)$$

where Δ is the slope of the saturated vapor pressure–temperature curve at the mean temperature, e_s is the saturated vapor pressure at the air temperature (mb), e_a is the vapor pressure (mb), and γ is the psychrometric constant ($0.66 \text{ mb }^{\circ}\text{C}^{-1}$). Combining Eq. (3) with Eq. (4) gives an equation that expresses the relationship between the canopy–air temperature difference and the vapor pressure deficit by conventional models:

$$T_c - T_a = \left[\frac{r_a}{\rho C_p} \cdot \frac{\gamma}{\Delta + \gamma} \right] R_n - \frac{1}{\Delta + \gamma} \cdot (e_s - e_a) \quad (5)$$

By substituting the variables with measured values and constants, Eq. (5) can be further simplified. Data measured on July 5, 1994 (Experiment 1 for a sorghum field, the experimental procedures will be given later) were chosen for this purpose. The weather on this day was fine, and plenty of water was available in the root zone. $r_a = 258.91 \times 10^{-6} \text{ d m}^{-1}$; $\Delta = 2.51 \text{ mb }^{\circ}\text{C}^{-1}$ (r_a and Δ were calculated from other measured parameters). Therefore, Eq. (5) can be simplified as follows:

$$T_c - T_a = 44,921 \times 10^{-6} R_n - 315,457 \times 10^{-6} (e_s - e_a) \quad (6)$$

Eq. (6) shows that the canopy–air temperature difference is proportional to the available energy for transpiration (R_n) and is inversely proportional to the vapor pressure deficit.

With the same procedures, the canopy–air temperature difference can also be linked with the vapor pressure deficit by our model as:

$$T_c - T_a = \left[\frac{\gamma}{\Delta + \gamma} \cdot \frac{T_p - T_a}{R_{np}} \right] R_n - \frac{1}{\Delta + \gamma} \cdot \frac{\rho C_p (T_p - T_a)}{r_a R_{np}} (e_s - e_a) \quad (7)$$

By replacing the variables with the measured or calculated values obtained for July 5, 1995 [$T_p = 34.91^\circ\text{C}$, $T_a = 31.18^\circ\text{C}$, $R_{np} = 17.78 \text{ MJ m}^{-2} \text{ d}^{-1}$, other variables and constants as for Eq. (6)], Eq. (7) can be simplified as follows:

$$T_c - T_a = 44,942 \times 10^{-6} R_n - 315,601 \times 10^{-6} (e_s - e_a) \quad (8)$$

Clearly, Eq. (6) is approximately equivalent to Eq. (8), which indicates that, in the absence of water shortage, our model agrees well with the conventional models. In the definition of h_{at} , the upper limit of the transpiration rate is determined by the term $T_c - T_a$. In other words, h_{at} is affected mainly by the available energy and water vapor deficit in the absence of water stress.

2. Transpiration rate at $T_c = T_a$

This is the case where sensible heat is equal to zero, and all the energy from radiation is transformed into latent heat. There is no major difference between our model and Bowen's ratio model² under the following condition: If the soil heat flux under a fully covered canopy is negligible, Bowen's ratio model can be expressed as $T = R_n$, (Bowen ratio = 0 when $T_c = T_a$). Eq. (1) also shows that $T = R_n$. Thus our model agrees with Bowen's. In addition, under this condition, $h_{at} = 0$, which indicates that the transpiration rate is determined only by the net radiation.

3. Lower limit of transpiration rate

The maximum value of h_{at} determines the lower limit of the transpiration rate, which occurs when the plant canopy dries continuously until the surface water content becomes equal to the water content of the reference non-transpiring leaf. Under this condition, $T_c = T_p$, and $R_n = R_{np}$. Consequently, $h_{at} = 1$, and the two terms on the right-hand side of Eq. (1) are equal to each other, and the transpiration rate is equal to zero. In this case, transpiration is determined mainly by the water available in

the plant root zone, rather than by the atmospheric characteristics (available energy, vapor pressure deficit, etc.). This well-defined boundary, represented by h_{at} , is much less apparent in the conventional canopy–air temperature difference models.

Verification experiments

Five experiments were conducted between 1994 and 1999. Experiment 1 was conducted at the Arid Land Research Center, Tottori University, Tottori, Japan. The other 4 experiments were conducted at the National Research Institute of Agricultural Engineering, Tsukuba, Japan. A model non-transpiring leaf was made by cutting a green paper that had nearly the same color as a plant leaf, into the shape of a leaf. The paper leaf was then inserted in the upper part of the canopy to avoid being shaded by the canopy^{20,23}.

1. Experiment 1 (Open field, sorghum plants, July–August 1994)

A 1-ha flat field with coarse sand (95.8% in the 0.25–2.00 mm range) was used in this study. A weighing lysimeter was installed there. Sorghum plants (*Sorghum bicolor* (L) Moench.) were grown in the field. The plant density, both around and inside the lysimeter, was about 8 plants m^{-2} . Actual evapotranspiration was measured with the weighing lysimeter and soil evaporation was measured with a microlysimeter. Temperatures of sunlit leaves and the non-transpiring leaf were measured with thermocouples, and the air temperature was measured with shielded thermocouples (recorded every 10 min). Solar radiation, air vapor pressure, and other meteorological variables were obtained from the meteorological station at the Arid Land Research Center, Tottori University.

2. Experiment 2 (Growth chamber, hydroponically grown tomato plants, May 1997)

The growth chamber had a floor area of 7.3 m^2 and was equipped with lighting and air conditioning. The air temperature was set at 31°C, and the relative humidity was set at 60%. Lighting hours were 5:00–17:00, and the light intensity was 157 W m^{-2} . Five tomato plants (*Lycopersicon esculentum* Mill) of Momotaro variety were cultured hydroponically in a trough 0.5 × 0.3 × 0.2 m in size. A standard nutrient solution (Otsuka Chemistry, Osaka, Japan) was used. Transpiration was measured with an SG32000 balance (Mettler Toledo Inc. Greifensee, Switzerland) every 10 min. Temperatures of sunlit leaves and the non-transpiring leaf were measured with thermocouples, and the air temperature was measured with shielded thermocouples (sampled at 5-s intervals and recorded

every 10 min).

3. Experiment 3 (Growth chamber, 1 potted tomato plant, May 1997)

This experiment was conducted in the same growth chamber as that in Experiment 2. One tomato plant was used. The pot, 0.30 m in height \times 0.26 m in diameter, was filled with soil. The air temperature was set at 35°C. Other conditions and methods were the same as those in Experiment 2.

4. Experiment 4 (Glasshouse, melon plants, June–July 1998)

This experiment was conducted in a glasshouse 60.4 m long \times 14.4 m wide \times 3.9 m high. The soil in the glasshouse consisted of loam (specific gravity 2.60–2.65 g cm⁻³, dry bulk density 0.7–0.8 g cm⁻³, porosity 70%); a plastic film to prevent evaporation covered the soil surface. Melon plants (*Cucumis melo* L.) were planted at uniform intervals of 0.8 m in rows spaced 1.5 m apart. Water was supplied by drip irrigation under the film. Two irrigation treatments were arranged. One area was fully irrigated (area A), and the other was not irrigated (area B). Solar radiation was measured with an Eko-MS 42 radiation meter (Eko Co., Ltd., Tokyo, Japan). Temperatures of the air and the non-transpiring leaf were measured as in Experiment 2. The canopy temperature was measured using infrared thermometers (THI-500, Tasco Co., Ltd.) and the soil water content was measured by time domain refractometry (TDR: 1502B Tester, SDMX50 Multiplexer, 21X Datalogger, Campbell Scientific Inc.).

5. Experiment 5 (Glasshouse, 1 potted tomato plant, May 1999)

This experiment was conducted in the same glasshouse as that in Experiment 4, with a potted tomato plant. The pot size and soil were the same as those in Experiment 3. The humidity of the air was measured with a TDK CHS-PR humidity sensor (TDK Ltd., Tokyo). Transpiration was measured with a balance as in Experiment 2. Other variables and measurement methods were the same as those in Experiment 4.

Results and discussion

1. Correlation between h_{at} and sensible heat flux

The sensible heat flux over the plant canopy (H) and over the non-transpiring leaf (H_p) can be expressed as follows:

$$H = \frac{\rho C_p (T_c - T_a)}{r_a} \quad (9a)$$

$$H_p = \frac{\rho C_p (T_c - T_a)}{r_{ap}} \quad (9b)$$

where r_{ap} is the aerodynamic resistance over the non-transpiring leaf (s m⁻¹). Aerodynamic resistance is a factor least understood and hence more difficult to obtain for estimating the sensible heat flux. Although r_a can be estimated from physically based equations, laborious measurements are required to obtain it, and there is no commonly accepted way to estimate it³. For this reason, we conducted an empirical analysis of the data obtained from measurements over the two surfaces to identify an empirical variable related to the ratio H/H_p . As shown by Qiu et al.²⁰, the slope of r_{ap}/r_a was near unity and its axial intercept was close to zero. Accordingly, the following equation was obtained:

$$h_{at} = \frac{T_c - T_a}{T_p - T_a} \approx \frac{H}{H_p} \quad (10)$$

To test the validity of Eq. (10), a linear regression analysis was conducted using the measured data from Experiment 1 during the period when the soil was fully covered by the canopy. The ratio of sensible heat fluxes was calculated from $H/H_p = (R_n - T) / R_{np}$, where T was the transpiration measured by the lysimeter, and R_n and R_{np} were estimated from the measured solar radiation and surface temperature. The results are shown in Fig. 1. The values of both h_{at} and H/H_p ranged between -0.3 and +0.5. The slope of the regression line was close to 1, the intercept was close to 0, and the coefficient of determination was $r^2 = 0.70$. The results of this test indicated that h_{at} could successfully replace H/H_p . Thus, the correlation between h_{at} and H/H_p showed that h_{at} was a suitable index for the estimation of plant transpiration.

2. Characteristics of h_{at} under various environmental conditions

(1) Hydroponically grown tomato plants in a growth chamber (Experiment 2)

Data measured during an irrigation cycle (May 7–9) were used (Fig. 2). Nutrient solution was added to the trough on the early morning of May 7. Except for the loss of water by transpiration in the trough, other environmental variables were constant. On the first day, the transpiration rate was > 250 g h⁻¹ before 14:00, then it decreased gradually to 200 g h⁻¹ at 16:00. On the second day, the transpiration rate was close to 160 g h⁻¹ before 12:00, then it decreased gradually to 100 g h⁻¹ at 16:00.

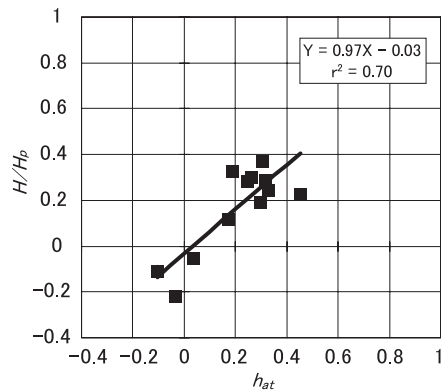


Fig. 1. Relationship between h_{at} and the ratio of sensible heat fluxes (H/H_p) of sorghum plants in an open field (Experiment 1)

On the third day, the transpiration rate was close to 50 g h^{-1} (Fig. 2a). Crop Water Stress Index ($CWSI$) was defined as $CWSI = 1 - T/T_p$, where T is the transpiration rate and T_p is the maximum transpiration rate. The values of the average $CWSI$ were 0.06 on the first day, 0.44 on the second day, and 0.78 on the third day.

Variations in T_p and T_a were relatively small, while T_c changed significantly (Fig. 2b). During 10:00–14:00 of the first day, T_c was around 29°C , then it increased gradually to 30°C at 16:00. On the second day, T_c decreased from 32°C to 31.6°C before 12:00 h, then it increased to 33°C at 16:00. On the third day, T_c was 35°C . T_c varied by 6°C over these 3 days.

The corresponding value of h_{at} is displayed in Fig. 2c. On May 7, the value of h_{at} was minimum (-0.4). On the second day, the value of h_{at} averaged 0.2 and was relatively lower in the middle of the day. On the third day, the value of h_{at} was close to 0.6. The value of h_{at} increased as crop water stress increased. During these 3 days, the average $CWSI$ values were 0.06, 0.44, and 0.78, respectively. A lower value of h_{at} (-0.4) indicated that the plants did not experience water stress, while a higher value (0.6) indicated that the plants experienced water stress.

(2) Potted tomato plant in a growth chamber (Experiment 3)

Data measured during 1 irrigation cycle (May 24–26) were used. Irrigation was applied on the night of May 23. In this experiment, the only variable environmental factor was the soil water content which decreased by transpiration and all the other environmental variables were constant (Fig. 3). The transpiration rate was in the range of $120\text{--}140 \text{ g h}^{-1}$ on May 24, $80\text{--}120 \text{ g h}^{-1}$ on May 25, and $30\text{--}70 \text{ g h}^{-1}$ on May 26 (Fig. 3a). The corresponding average $CWSI$ values were 0.08, 0.22, and 0.54, respectively. During this period, T_p was 44°C and T_a was

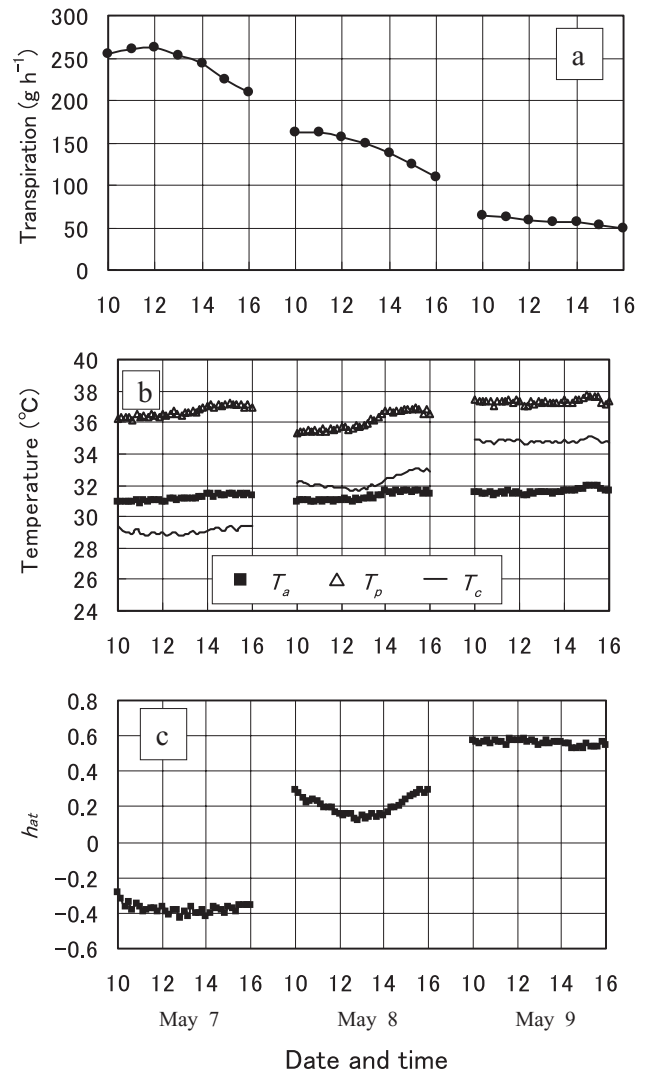


Fig. 2. Transpiration rate (a), temperatures of non-transpiring leaf, canopy and air (b), and h_{at} (c) in hydroponically grown tomato plants during the 3-day drying period (May 7–9, 1997)

Irrigation was applied on the night of May 6.

35°C . On the first day, T_c was around 33°C , 2°C less than T_a . On the second day, T_c gradually increased to 38°C at 17:00, 3°C higher than T_a . On the third day, T_c increased continuously to almost 43°C (Fig. 3b). The lower and upper values of h_{at} were -0.2 and 0.8 , which determined the variation in the transpiration rate from 140 to 30 g h^{-1} . Over the same period, the $CWSI$ values varied from 0.08 to 0.54. These results also show that the h_{at} value increased with water stress.

(3) Melon plants in a glasshouse (Experiment 4)

This experiment was conducted during the period June–July of 1998. Irrigation was applied twice: on the nights of June 21 and July 3. The volumetric soil water content (θ), solar radiation, temperatures, and h_{at} data

for melon plants in a glasshouse were all daytime averages (Fig. 4). The θ value in area A was always larger than in area B (Fig. 4a), but the corresponding h_{at} value in area B was always larger than that in area A (Fig. 4d). These results again verified the assumption that the h_{at} value increases as the soil water content decreases.

Fig. 4 also shows that, despite the decrease in θ by transpiration, the soil water content remained relatively high ($\theta \geq 0.25 \text{ m}^3 \text{ m}^{-3}$). Therefore, the melon plants did not experience or experienced little water stress. The value of θ was 0.30–0.40 $\text{m}^3 \text{ m}^{-3}$ in area A and 0.25–0.30 $\text{m}^3 \text{ m}^{-3}$ in area B (Fig. 4a). Solar radiation was 50–210 W m^{-2} (Fig. 4b) and the air temperature was 17–38°C (Fig.

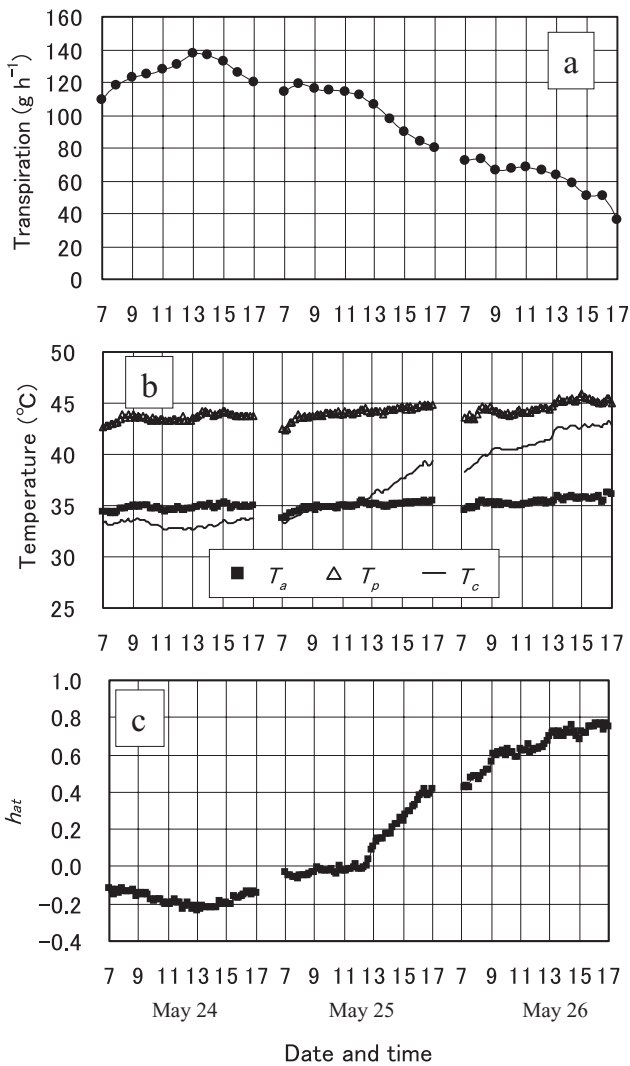


Fig. 3. Transpiration rate (a), temperatures of non-transpiring leaf, canopy, and air (b), and h_{at} (c) in soil-cultivated (potted) tomato plant during the 3-day drying period (May 24–26, 1997)
 Irrigation was applied on the night of May 23.

4c). The corresponding values of h_{at} ranged from -4 to -1 . Compared with the changes in θ , the variations in the h_{at} values were relatively larger. The fluctuations in h_{at} were caused mainly by the changes in weather. These results suggest that, under little or no water stress, h_{at} is affected mainly by atmospheric variables.

(4) Potted tomato plant in a glasshouse (Experiment 5)
 Data obtained in 1 irrigation cycle (May 21–23)

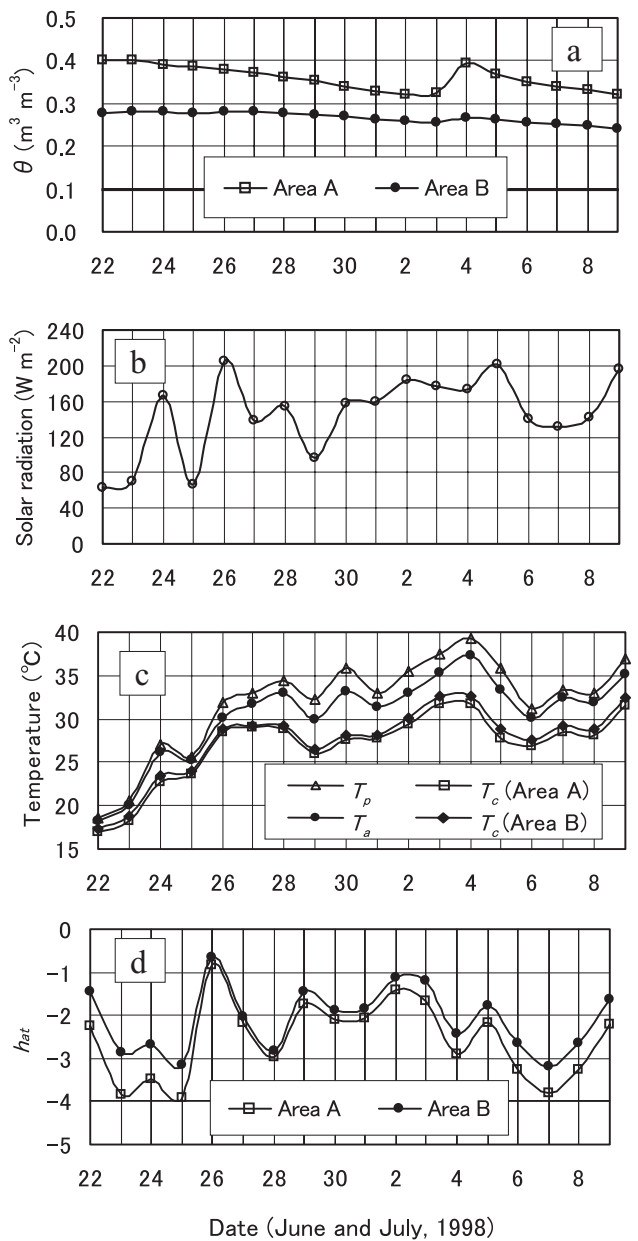


Fig. 4. Volumetric soil water content (θ , a), solar radiation (b), temperatures of non-transpiring leaf, canopy, and air (c), and h_{at} (d) in melon plants grown in a glasshouse in June–July 1998
 All the data are daytime averages. Irrigation was applied twice: on the nights of June 21 and July 3.

were used. Irrigation was applied on the night of May 20. Fig. 5 shows the solar radiation, relative humidity, θ , transpiration rate, temperatures, and h_{at} of 1 potted tomato plant during the 4-day drying period. Data were averaged hourly values. Compared with Experiment 4, θ in this experiment was relatively lower, in the range of 0.1–0.3 $\text{m}^3 \text{m}^{-3}$, mostly $< 0.15 \text{m}^3 \text{m}^{-3}$ (Fig. 5c). Therefore, the tomato plant experienced water stress most of the time. The weather also changed significantly during the period. From May 21 to 23, the weather was fine. The solar radiation was usually $> 300 \text{W m}^{-2}$ (Fig. 5a), and the relative humidity was usually $< 30\%$ (Fig. 5b). However, on May 24, it was cloudy and rain started to fall in the afternoon. The solar radiation was $< 150 \text{W m}^{-2}$, and the relative humidity was $> 50\%$. On May 21, the transpiration rate was high ($\geq 150 \text{g h}^{-1}$). Afterwards, it decreased gradually to 1g h^{-1} at 16:00 on May 24 (Fig. 5d). T_p and T_a were affected by the atmosphere and varied with the solar radiation (Fig. 5e). On the other hand, T_c was affected by both atmospheric variables and the soil

water. When the water content was lower, however, T_c was affected mainly by the soil conditions. On May 21, T_c was lower than T_a , and afterwards, it increased over T_a . As in the case of T_c , the h_{at} values also increased gradually from the lower boundary of -0.1 to the upper boundary of 0.8 (Fig. 5f). These results show that, although h_{at} was affected both by the atmospheric variables and the soil water, it was affected mainly by the soil water content under water-stressed conditions.

Conclusions

By using the temperature of a non-transpiring leaf, the transpiration transfer coefficient was defined as $h_{at} = (T_c - T_a) / (T_p - T_a)$, where T_c , T_p , and T_a are the temperatures of the canopy, a non-transpiring canopy (leaf), and air, respectively. Theoretically, $h_{at} \leq 1$ and determines the transpiration rate from its minimum value (zero) to its maximum value (potential transpiration rate). These well-defined boundaries are much less apparent in con-

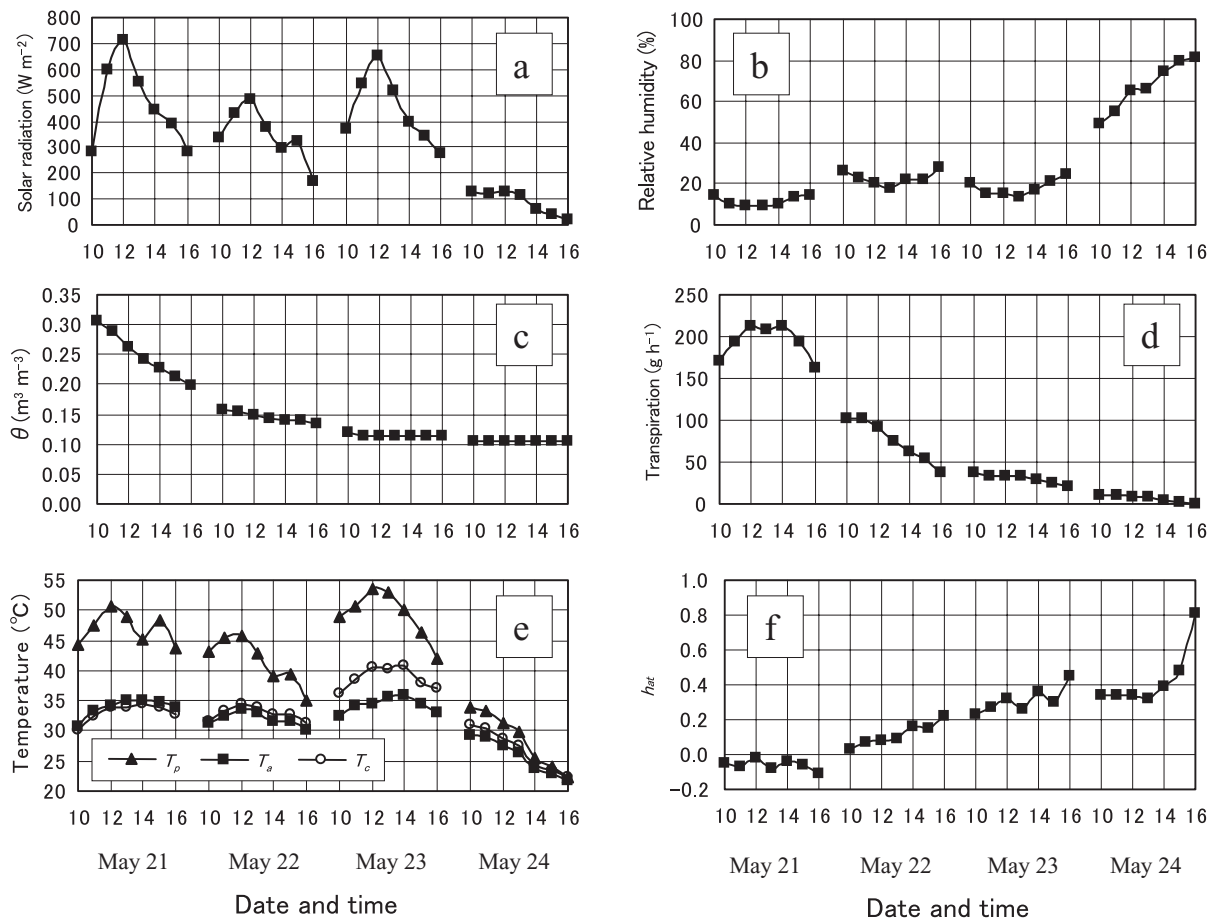


Fig. 5. Comparisons of solar radiation (a), relative humidity (b), volumetric soil water content (θ , c), transpiration rate (d), temperatures of non-transpiring leaf, canopy, and air (e), and h_{at} (f) in soil-cultivated (potted) tomato plant during the 4-day drying period (May 21–23, 1999)
Irrigation was applied on the night of May 20.

ventional models. The main advantages of h_{at} are that it can be easily measured and is applicable under various environmental conditions. Furthermore, h_{at} quantitatively summarizes the air–canopy temperature relationship. Due to its simplicity, h_{at} is a suitable coefficient for analyzing the process of transpiration and for determining the transpiration rate.

Five verification experiments were conducted between 1994 and 1999. Temperature, transpiration, radiation, soil water content, humidity, and other related variables were measured using standard methods. The proposed model agrees well with conventional models. The value of h_{at} is approximately equal to the value of the ratio of sensible heat fluxes (H/H_p). The slope of the regression line of the relationship between the two parameters was close to 1, the intercept was close to 0, and the regression coefficient was $r^2 = 0.70$. Therefore, h_{at} can replace earlier models related to aerodynamic resistance. In addition, the experimental results showed that h_{at} was not only an indicator of the water status in the plant root zone, but also an indicator of atmospheric variables. Under water stress, h_{at} was affected mainly by the water status in the plant root zone. Therefore, h_{at} could be used as an indicator of plant water stress. In this study, the measured minimum and maximum values of h_{at} ranged from -0.5 to $+0.5$ for sorghum (open field), from -0.4 to $+0.8$ for tomato, and from -4 to -1 for melon (little or no water stress). Although other plant species have not yet been studied, based on theoretical considerations, it is suggested that the method could be applied to other plant species as well.

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