JARQ 34, 29–37 (2000)

# Detection of Crop Transpiration and Water Stress by Temperature-Related Approach under Field and Greenhouse Conditions

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**Abstract**

A new method for estimating crop transpiration and crop water stress index (*CWSI*) by using a temperature-related approach was developed and verified this study. In the proposed method, 3 temperatures and a few meteorological variables (net radiation and humidity) are required. The 3 temperatures include sunlit leaf temperature, imitation leaf temperature, and air temperature. The imitation leaf refers to an artificial leaf without transpiration. The major advantage of the proposed method is that plant correction factors, empirical coefficient, and canopy and aerodynamic resistances are not required. Experiments for verification were conducted in a sandy field with sorghum crop and in a greenhouse with melon crop. Data obtained by the proposed method were compared with the amount of transpiration determined with lysimeters, soil water status determined by TDR, and *CWSI* estimated by Jackson's method. The calculated transpiration by the proposed method was consistent with the results obtained with lysimeters, with regression coefficient $1^2$=0.88. Values of *CWSI* calculated by the proposed method were in agreement with Jackson's *CWSI*, with a regression coefficient approximately equal to 1. These results indicate that the proposed method can be applied to estimate crop transpiration and water stress index under both field and greenhouse conditions.

**Discipline:** Agro-meteorology
**Additional key words:** imitation leaf, sorghum, melon

## Introduction

Water management in modern agriculture requires the determination of the crop water requirement and irrigation time as accurately and quickly as possible. Transpiration (*T*) is the key factor to estimate crop water requirement and crop water stress index (*CWSI*) is the key factor to evaluate the time when irrigation should be applied. Among the methods of estimation of *T* and *CWSI*, a temperature-related approach can be adopted. As cited by Jackson[13] and Jackson et al.[16], research on foliage temperature was started in 1843. The literature on this topic was rather sparse until the 1920s when thermocouples became standard equipment. Many of these early studies focused on the leaf and air temperature differences[18,32]. Subsequently, research results showed that the soil moisture status, foliage temperature, and plant transpiration rates were closely related[3,4,6–8,12,14,30].

As a result, a temperature difference method was developed to estimate *T* [5,12,17,21,30,31]. Mitchell and Hanks[19] derived an empirical equation to predict *T* based on the temperature difference between canopy and air. Hatfield[5], O'Toole and Real[23], and Ben-Asher et al.[1,2] evaluated aerodynamic and canopy resistances by using air temperature, canopy temperature, and vapor pressure deficits. Due to the complexity in evaluating the aerodynamic resistance, the temperature difference method is mainly applied for estimating the aerodynamic resistance with an already known *T*, rather than for the direct estimation of *T*. No studies have been reported on the direct estimation of *T* by air and canopy temperature without the use of aerodynamic resistance or empirical coefficients.

*CWSI* is another key factor for agricultural water management. Although maximum yields of crops are achieved only under non-limiting water supply, it remains to be determined how early water shortage should be detected to avoid a significant decrease in productivity. The use of canopy temperatures to detect water stress in plants is based upon the assumption that, as water becomes limiting, transpiration is reduced and plant temperature increases. Canopy temperature is determined based on the water status of the plants and by ambient meteorological conditions. *CWSI* based on the determination of the canopy temperature is derived as: $CWSI=(T_c-T_{cl})/(T_{cu}-T_{cl})$, where $T_c$, $T_{cl}$, and $T_{cu}$ are the canopy temperature, lower limiting canopy temperature, and

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upper limiting canopy temperature, respectively. The lower limiting canopy temperature can be reached when the crop transpires without water shortage. On the other hand, the upper limiting canopy temperature can be reached when plant transpiration is zero. O'Toole et al.[24] conducted a comprehensive comparison of 8 different measurement methods for assessing the plant water status and concluded that *CWSI* based on the determination of the canopy temperature was the best technique, stating that it was a significant advancement in assessing the water status of crop or natural plant communities. Two types of *CWSI* based on canopy temperature have been proposed to estimate the $T_{cl}$, an empirical approach reported by Idso[9] and Idso et al.[10,11] and a theoretical approach reported by Jackson et al.[15,16]. In the empirical method (Idso's *CWSI*), *CWSI* is estimated by determining "non-water-stressed baselines" for crops. In addition, estimation of $T_{cu}$ is necessary. However, the non-water-stressed baselines change not only with the crop variety but also with the seasons[16]. Furthermore, the estimation of the upper limit of temperature is somewhat ambiguous. The third criticism has been that Idso's *CWSI* does not account for radiation and wind speed. In the theoretical method (Jackson's *CWSI*), *CWSI* is estimated based on the net radiation and an aerodynamic resistance factor, in addition to the temperature and vapor pressure terms required by the empirical method. Since these variables are site-specific, it is difficult to collect representative meteorological data for field practice in a small and heterogeneous crop area. Requirement of large uniform fields and local meteorological data is the main problem facing the application of Jackson's *CWSI*. Although Jackson's approach shows how the upper and lower limits can be evaluated, the complexity of the method precludes thorough field tests. Thus, there has been a long search for theoretically sound and simple procedures that would enable to overcome the shortcomings of the above methods.

The objectives of the current studies are: 1) to develop a method to assess $T$ using temperatures and a few meteorological parameters without the requirement of crop correction factors, empirical coefficients, or canopy and aerodynamic resistances, 2) to verify the estimation accuracy of the proposed method by comparison with actual $T$ obtained by a weighing lysimeter, and 3) to apply the developed theory to the estimation of *CWSI* under both field and greenhouse conditions.

## Theoretical development

Assuming that there is an imitation leaf canopy in the plant canopy with a relatively small volume, the temperature, humidity, wind speed, and other environmental parameters of the plant canopy are not significantly modified by the imitation leaf canopy. In other words, the imitation leaf canopy is one part of the plant canopy. It is assumed that temperatures of plant canopy and imitation leaf canopy are represented by temperatures of sunlit leaves and imitation leaves, respectively. Hereafter, we refer to the imitation leaf canopy as the imitation leaf and the temperature of the imitation leaf canopy as imitation leaf temperature. It is assumed that the radiation absorptive and albedo properties of these imitation leaves are similar to those of plant leaves. Transpiration does not occur from imitation leaves and the latent heat flux is zero.

The energy balance of the canopy is represented by the equation[22]:

$$R = G + H + LE \quad \text{......................} (1)$$

where $R_n$ is the net radiation of the canopy, $G$ the heat flux to soil, $H$ the sensible heat flux from canopy to air, and $LE$ the latent heat flux to air. All the units are expressed in W m$^{-2}$. Since these variables can be positive or negative, depending on their direction, positive direction for $R_n$ is toward the soil surface and positive directions for $G$, $H$, and $LE$ are away from the soil surface.

It should be emphasized that we only focus on the energy balance of the canopy by using Eq. (1). The exposed soil portion of the partially covered canopy is separated by using canopy coverage. In the canopy-covered area, the incident radiation is intercepted by the canopy so that the partitioning of energy on the soil surface is relatively negligible[20]. Thus evaporation from the canopy-shadowed soil is generally low and $LE$ is often expressed as canopy transpiration ($T$).

In Eq. (1), the net radiation can be measured or estimated from solar radiation and temperature. Generally $G$ is negligible for the canopy on a daily basis[1,22]. Jackson[13] expressed $H$ by the following equation:

$$H = \frac{\rho C_p (T_c - T_a)}{r_a} \quad \text{..................} (2)$$

where $\rho C_p$ is the volumetric heat capacity (J m$^{-3}$ K$^{-1}$), $T_c$ the canopy temperature (K), $T_a$ the air temperature (K), and $r_a$ the aerodynamic resistance (s m$^{-1}$).

Since the imitation leaf is in the same canopy, the same value of $r_a$ can be used for the imitation leaf[25,26,28]. By assuming that the air temperature at reference height is the same everywhere and $r_a$ of the canopy is approximately equal to the $r_a$ of the imitation leaf, $r_a$ can be expressed by the following equation:

$$r_a = \frac{\rho C_p(T_P - T_a)}{R_{np}} \quad \text{.................} (3)$$

where $T_p$ is the temperature of the imitation leaf surface (K) and $R_{np}$ the net radiation of the imitation leaf (W $m^{-2}$).

Combining Eq. (3) with Eqs. (1) and (2), an equation to estimate transpiration from plant canopy can be derived:

$$LE = R_n - R_{np}\frac{T_c - T_a}{T_p - T_a} \quad \text{.................} (4)$$

On the basis of the above data, the plant transpiration can be estimated by Eq. (4). The necessary input parameters of Eq. (4) are the temperature ($T_c$, $T_a$, and $T_p$) and net radiation ($R_n$ and $R_{np}$).

From the coupling of the energy balance equation to the transfer equations for both sensible and latent heat, assuming that the heat fluxes in soil are negligible, and defining $\Delta$ as the slope of the saturated vapor pressure-temperature relation $(e_c^* - e_a^*)/(T_c - T_a)$, an expression for the temperature difference between the canopy and air can be derived[15,29]:

$$T_c - T_a = \frac{r_a R_n \gamma(1 + (r_c/r_a))}{\rho C_p[\Delta + \gamma(1 + r_c/r_a)]} - \frac{e_a^* + (-e_a)}{\Delta + \gamma(1 + r_c/r_a)} \quad \text{..................................} (5)$$

where $r_c$ is the crop canopy resistance (s $m^{-1}$), $e_c^*$ the saturated vapor pressure (mbar) at $T_c$, $e_a^*$ the saturated air vapor pressure (mbar) at $T_a$, $e_a$ the vapor pressure of air (mbar), and $\gamma$ =0.66 mbar °$C^{-1}$ the psychrometric constant.

Eq. (5) relates the difference between the canopy and air temperature to the vapor pressure deficit of air ($e_a^*$ – $e_a$), the net radiation, and the aerodynamic and crop resistances. Based on Eqs. (3) and (5), *CWSI* related to the canopy temperature will be analyzed.

The temperature of the imitation leaf $T_p$ could be considered to be equivalent to the upper limiting canopy temperature $T_{cu}$. Therefore, the *CWSI* obtained by our approach can be expressed by the equation:

$$CWSI = \frac{T_c - T_{cl}}{T_p - T_{cl}} \quad \text{...................} (6)$$

The lower limiting canopy temperature ($T_{cl}$), determined by setting $r_c$=$r_{cp}$ in Eq. (5) and substituting Eq. (3) into Eq. (5) is:

$$T_{cl} = \frac{R_n(T_p - T_a)}{R_{np}} \cdot \frac{\gamma^*}{\Delta + \gamma^*} - \frac{e_a^* - e_a}{\Delta + \gamma^*} + T_a \quad \text{.....} (7)$$

$$\gamma^* = \gamma\left[1 + \frac{r_{cp}R_{np}}{\rho C_p(T_p - T_a)}\right] \quad \text{............} (8)$$

where $r_{cp}$ is the canopy resistance without water shortage (s $m^{-1}$). The value of $r_{cp}$ is likely to vary with the crops and crop varieties.

On the basis of the above data, it is concluded that by introducing the imitation leaf temperature, *CWSI* defined by Eq. (6) can be determined from temperatures (canopy, imitation leaf, and air), net radiation, and the vapor pressure. The aerodynamic resistance is eliminated and accordingly the complexity of application is significantly reduced.

## Verification experiments

*1) Experiment in a sandy field with sorghum crop*

A 1 ha flat field with coarse grain sand (95.8% of sand in the 0.25–2.00 mm range) at the Arid Land Research Center, Tottori University (Tottori, Japan) was used in this study, where a weighing lysimeter had been installed. Sorghum (*Sorghum bicolor* (L) Moench.) crop was grown in the field. A sprinkler irrigation system was employed to irrigate the crop in the sandy soil field. Plant densities, both around and inside the lysimeter, were about 8 plants $m^{-2}$. Measurements were performed from June 20 to August 31, 1994. In this experiment, the imitation leaves were made from green paper by selecting a paper which had nearly the same color as the plant leaf and cutting the paper into the shape of a plant leaf. Then the green paper leaf was inserted in the upper part of the sorghum canopy to avoid shade from the canopy (Fig. 1).

**Fig. 1. Imitation leaf used in sorghum experiment**

Actual evapotranspiration was measured by using a weighing lysimeter. Soil evaporation was measured daily with the microlysimeters. The plant leaf area was measured with a leaf area meter (AAC-400, Hayashi Electric Co., Ltd.) weekly throughout the experimental period to estimate plant coverage and calculate the leaf area index (LAI). Temperatures of the imitation leaf and canopy (sunlit leaf) were measured with Cu-Co thermocouples. Stomatal resistance was measured with LI-1600 Steady State Porometer (Li-Cor. Inc.). Solar radiation and air vapor pressure were obtained from the meteorological station of the Arid Land Research Center, Tottori University. The experimental procedures were also described in detail by Qiu et al.[26,27].

*2) Experiments in a greenhouse with melon crop*

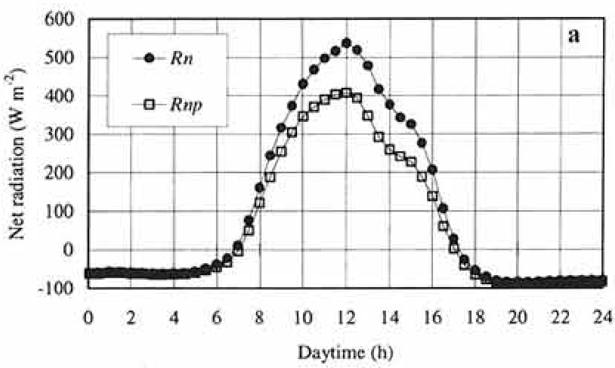
This experiment was conducted from April to July, 1998 in a glasshouse at the National Research Institute of Agricultural Engineering (Tsukuba, Japan). The dimensions of the glasshouse were 60.4 m in length, 14.4 m in width, and 3.9 m in height (ridge). The orientation of the ridge line was South/North. Soil consisted of loam (2.60–2.65 g $cm^{-3}$ specific gravity, 0.7–0.8 g $cm^{-3}$ dry bulk density, and 70% porosity) and the soil surface was covered by a plastic film to prevent evaporation. Melon crop (*Cucumis melo* L.) was used in this experiment in rows 1.5 m apart and the distance between individual plants was 0.8 m. Water was supplied by the drip irrigation method under the film. Two irrigation treatments were arranged. One area was fully irrigated (area A, volumetric water content varied in the range of 0.3–0.4 $m^3m^{-3}$). Another area was not fully irrigated (area B, volumetric water content varied in the range of 0.2–0.3 $m^3m^{-3}$). Radiation, air humidity, and temperatures of the imitation leaf and air were measured by the same method as in the field experiment. Sunlit leaf temperature of melon was measured using an infrared thermometer (THI-500, Tasco Co., Ltd.). Soil water was measured using a TDR soil moisture measurement system (Campbell Scientific Inc.).

## Results and discussion

*1) Transpiration*

Fig. 2 depicts the daily variations of net radiation and temperatures of greenhouse melon. The canopy temperature and net radiation in Fig. 2 are the average values of area A and area B. During sunshine time, the $R_n$ value was higher than that of $R_{np}$. The maximum value of $R_n$ was close to 550 W $m^{-2}$ and the maximum value of $R_{np}$ was close to 400 W $m^{-2}$. The difference between the values could be as large as 150 W $m^{-2}$ (Fig. 2a). Fig. 2b shows the diurnal changes in the measured $T_p$, $T_c$, and $T_a$. The variation of temperature was affected by the radiation and other weather conditions. The maximum and minimum values of radiation and temperature appeared at the same time. Besides these common characteristics, $T_p$, $T_c$, and $T_a$ also displayed specific features. $T_p$ was always higher than $T_c$ and $T_a$ during the daytime. The temperature difference between $T_p$ and $T_c$ could be as large as 20°C in the daytime. During the night, the values of $T_p$ and $T_c$ were identical. All the data of the other days over the experimental period showed similar results. Since the soil surface was not fully covered by the melon canopy, solar radiation could be directly absorbed by soil. Moreover, the plastic film used as a cover prevented evaporation from soil and the soil surface temperature could be as high as 50°C. Therefore, the absorbed solar energy directly affected the air temperature through sensible heat transfer and $T_a$ was higher than $T_c$. However, as reported by other researchers, $T_c$ could sometimes be higher or lower than the $T_a$ under field conditions[13,26,27]. These distribution features of the 3 temperatures enabled to detect crop transpiration and water stress.

In this study, by using the imitation leaves made from green paper, satisfactory results were obtained. However, if the paper were to be wetted due to rainfall or irrigation, the results may be affected. Therefore, further



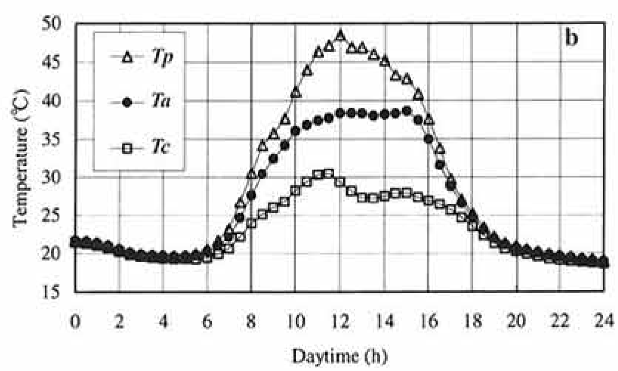




**Fig. 2. Daily variations of net radiation and temperatures of greenhouse melon**

a: Net radiation. b: Temperature.

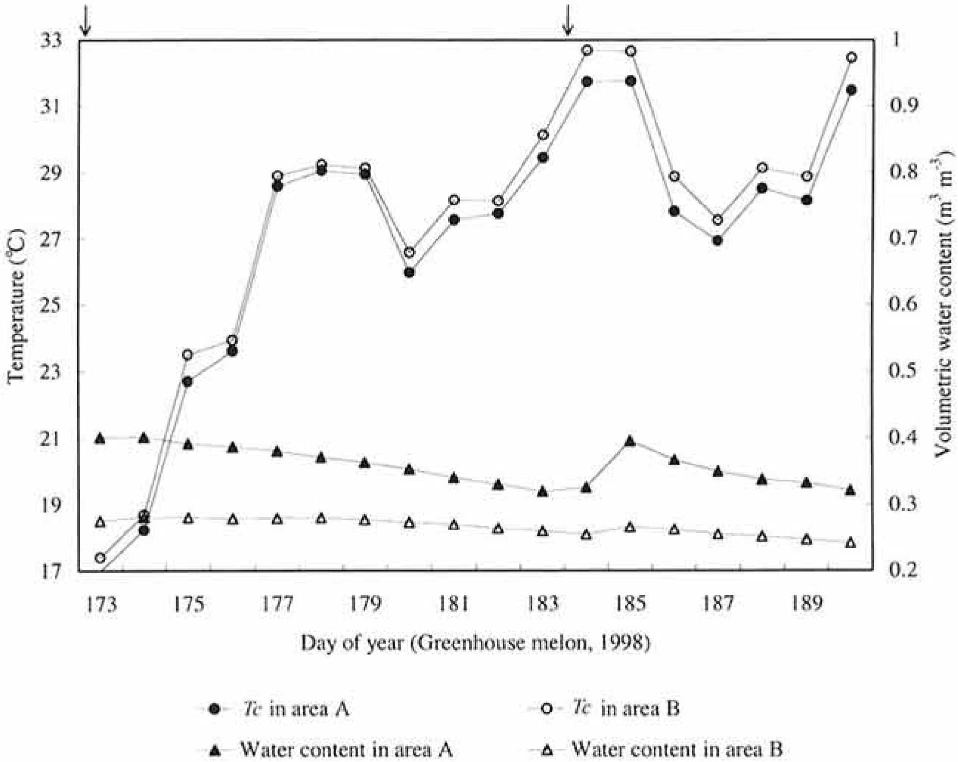



**Fig. 3. Distribution of greenhouse melon canopy temperatures in 2 different irrigation areas**
Arrows indicate the irrigation time.

studies should be carried out to select different materials to replace the green paper.

Fig. 3 shows the distribution of melon canopy temperatures in 2 different irrigation areas. During the experimental period, the soil water content varied in the ranges of 0.3–0.4 $m^3m^{-3}$ in area A and 0.2–0.3 $m^3m^{-3}$ in area B. Though daytime average canopy temperatures in both areas varied in the ranges of 17–33°C, in area A, since the soil water content was higher, the canopy temperature was consistently lower than in area B. The temperature difference between the 2 areas was usually less than 1°C. However, maximum difference could be as much as 1°C. These results suggest that the canopy temperature is a good indicator of the soil water status.

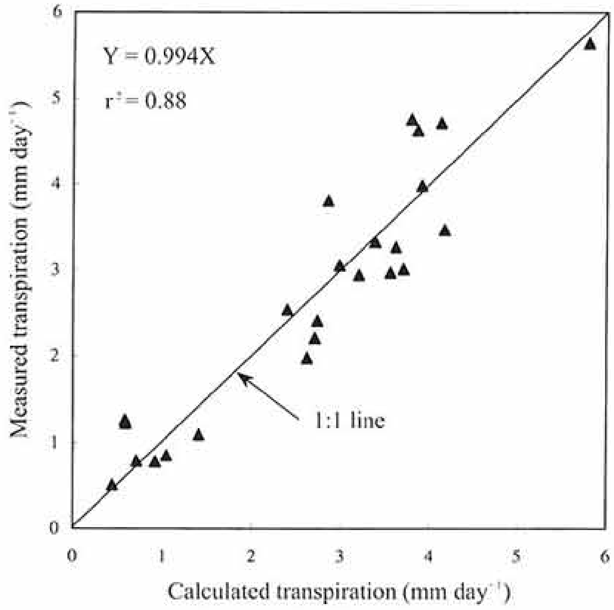



**Fig. 4. Relation between calculated and lysimeter-meaured transpiration of field sorghum**

Fig. 4 shows the daily transpiration of sorghum under field conditions. Daily estimated transpiration (*T*) was obtained by *ET-E*, where *ET* was the evapotranspiration measured with the weighing lysimeter and *E* the soil evaporation measured with the microlysimeters. The calculated daily *T* was obtained from Eq. (4). Fig. 4 shows that calculated *T* agreed well with the estimated *T*. The maximum difference between calculated and estimated transpiration was less than 1 mm $day^{-1}$. The transpiration differences on most of the days were within 0.5 mm $day^{-1}$. The regression analysis showed that the estimated *T* was closely correlated with the calculated *T*. The regression coefficient was $r^2$=0.88. Crop transpiration can thus be accurately calculated by the proposed method.

Fig. 5 shows a comparison of calculated *T* under different irrigation treatments of melon under greenhouse conditions. During the experimental period, calculated *T*

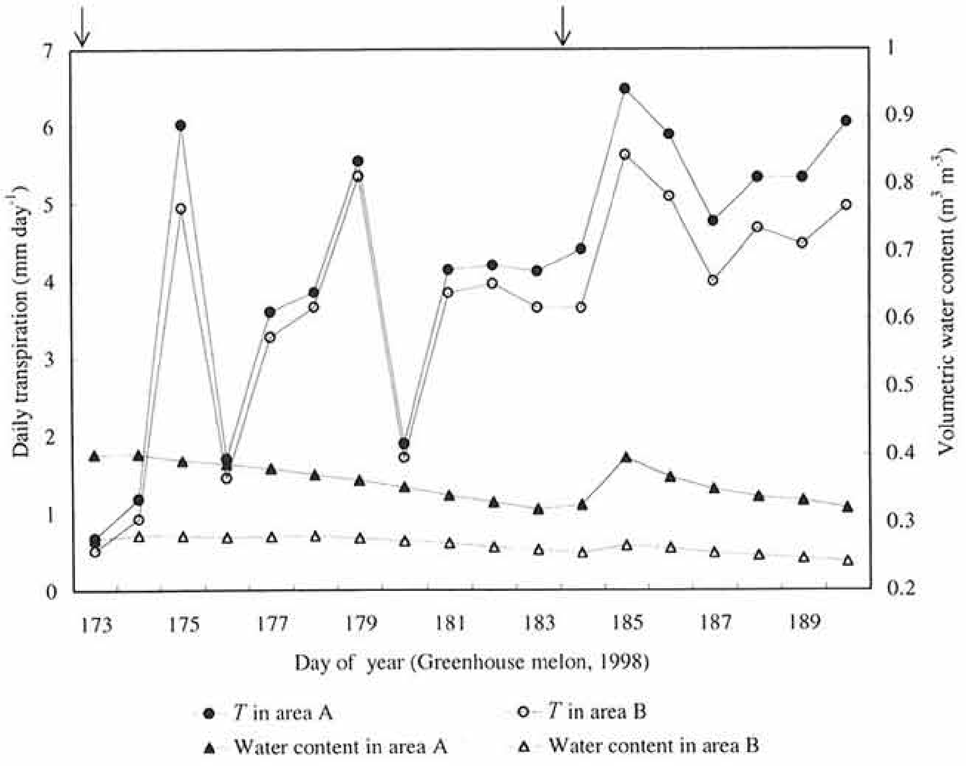



**Fig. 5. Calculated daily transpiration of greenhouse melon in 2 different irrigation areas**

Arrows indicate the irrigation time.

in both irrigation areas varied with the changes of the weather conditions. On clear days, the $T$ value could be as high as 5–6 mm day$^{-1}$, while on cloudy days the $T$ value could be as low as 1–2 mm day$^{-1}$. However, $T$ in area A was consistently higher than in area B, the difference being as large as 1 mm day$^{-1}$. Cumulative $T$ was near 75 mm in area A and 65 mm in area B.

On the basis of the above data, it can be concluded that the proposed method gives a reasonable estimation of crop transpiration under field and greenhouse conditions.

*2) Crop water stress*

(1) Upper limiting canopy temperature

In Jackson's method, upper limiting canopy temperature ($T_{cu}$) is expressed by the equation:

$$T_{cu} = \frac{r_a R_n}{\rho C_p} + T_a \quad \text{......................} (9)$$

In the proposed method, $T_{cu}$ is equal to $T_p$. Fig. 6 shows that the measured $T_p$ agreed with $T_{cu}$ calculated by Eq. (9). Due to the assumption that the canopy resistance was infinite, $T_{cu}$ was slightly larger than $T_p$ in the high temperature ranges. The regression coefficient between $T_p$ and $T_{cu}$ was $r^2$=0.997.

(2) Comparison with Jackson's *CWSI*

In addition to $T_c$ and $T_p$ (or $T_{cu}$), $T_{cl}$ is also required to evaluate *CWSI* by the proposed method and Jackson's method. As shown in Eq. (8), the canopy resistance with-

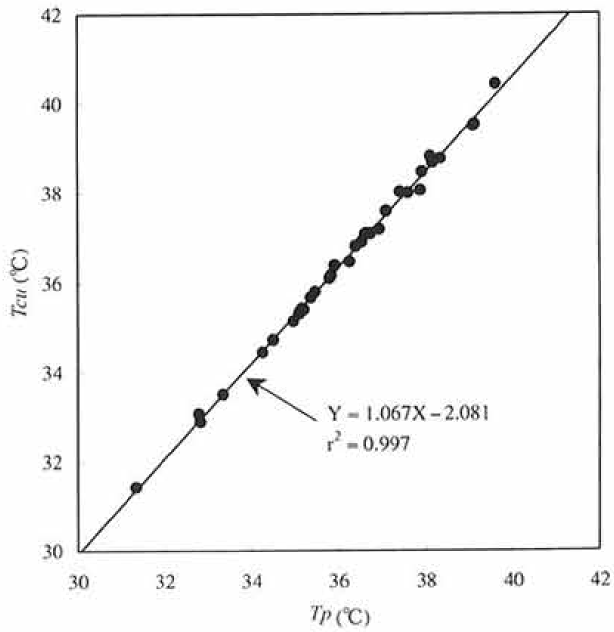



**Fig. 6. Comparison of the measured $T_p$ and the calculated $T_{cu}$ of field sorghum**

out water shortage $r_{cp}$ is required to estimate $T_{cl}$. Values of $r_{cp}$ can be estimated by the following empirical equation[1,27]:

$$r_{cp} = \frac{r_{sp}}{LAI} \quad \text{.......................... (10)}$$

where $r_{sp}$ (s $m^{-1}$) is the stomatal resistance without water shortage and $LAI$ is the leaf area index. During the early period of the field experiment, sorghum was well irrigated. From 520 measured values of stomatal resistance, 10 minimum values were selected to represent $r_{sp}$. The average value of these 10 data was 41.6 s $m^{-1}$. Therefore, the equation $r_{cp}=r_{sp}/LAI=41.6/LAI$ was used to estimate *CWSI* in this study. Fig. 7 shows that the *CWSI* determined by the proposed and Jackson's methods agreed well, with a regression coefficient $r^2$=0.997. Since Jackson's method is sound in theory, the agreement of the 2 methods indicates that *CWSI* by the proposed method is suitable for detecting crop water stress.

(3) Relations with soil water status

Fig. 8 shows a comparison of *CWSI* in the 2 different irrigation areas of greenhouse melon. During the experimental period, the soil water content in area A varied in the ranges of 0.3–0.4 $m^3m^{-3}$, values about 0.1 $m^3m^{-3}$ higher than the values in area B. Meanwhile, *CWSI* in area A was consistently lower than the *CWSI* in area B, with a difference as large as 0.1. Compared with the soil

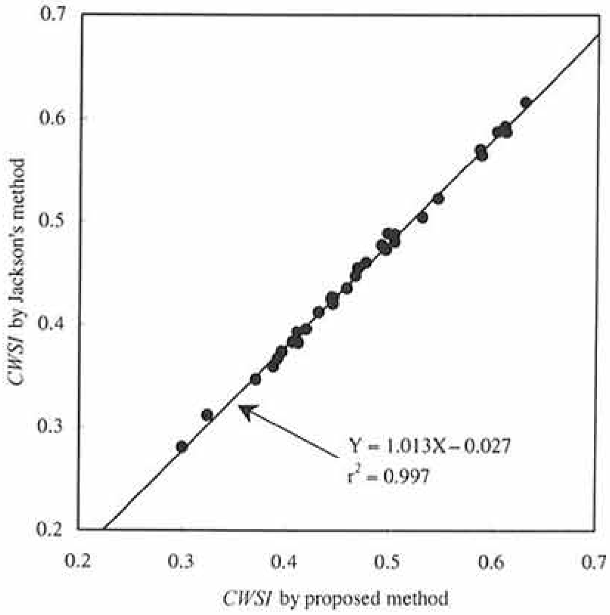



**Fig. 7. Comparison of *CWSI* estimated by the proposed method and *CWSI* by Jackson's method for field sorghum**

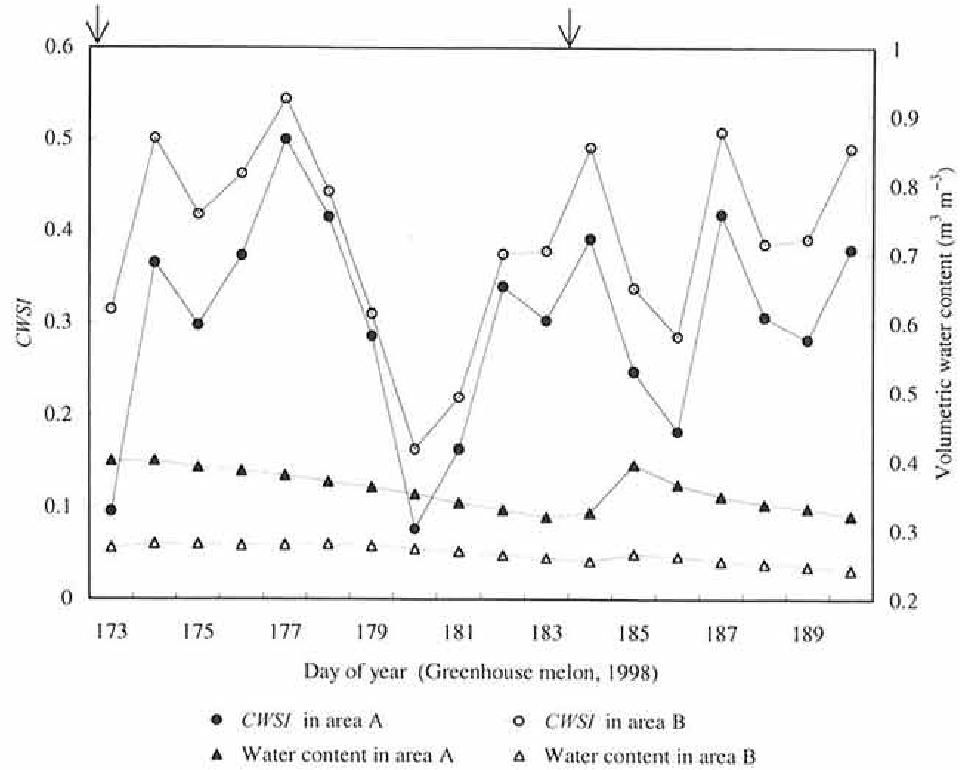



**Fig. 8. Distribution of the calculated *CWSI* of greenhouse melon in 2 different irrigation areas**

Arrows indicate the irrigation time.

water content, fluctuations of the *CWSI* curves were larger than the fluctuations of the soil water content curves. This phenomenon revealed not only that *CWSI* was mainly affected by the weather conditions at a relatively high water content but also that the use of temperature-related *CWSI* enables to predict plant water stress earlier than the soil water-based method. Our results agreed with those of Qiu et al.[27] and Stanghellini and Lorenzi[29] who showed that canopy temperature-based crop water stress index methods are more likely to be suitable for early detection of water shortage than soil water-based methods.

## Summary

A new method for estimating crop transpiration and *CWSI* by using a temperature-related approach was developed and verified in this study. In the proposed method, 3 temperatures (sunlit leaf temperature, imitation leaf temperature, and air temperature) and a few meteorological variables (net radiation and humidity) were required. The imitation leaf referred to an artificial leaf without transpiration. The major advantage of the proposed method is that plant correction factors, empirical coefficients, and canopy and aerodynamic resistances are not required for calculating the plant transpiration and *CWSI*.

Experiments in a sandy field with sorghum crop (*Sorghum bicolor* (L) Moench.) and in a greenhouse with muskmelon crop (*Cucumis melo* L.) were conducted to verify the proposed method. Results were compared with the amount of transpiration determined by using a weighing lysimeter and microlysimeters, soil water status determined by TDR, and *CWSI* estimated by Jackson's method. The calculated transpiration by the proposed method was consistent with the results obtained by using a weighing lysimeter and microlysimeters, with a regression coefficient $r^2$=0.88. Values of *CWSI* calculated by the proposed method were in agreement with the Jackson's *CWSI*, with a regression coefficient $r^2$=0.997. These results indicate that the proposed method can be applied to estimate crop transpiration and water stress index under both field and greenhouse conditions.

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(Received for publication, February 25, 1999)