CSIRO PUBLISHING
www.publish.csiro.au/journals/fpb *Functional Plant Biology*, 2009, **36**, 990–997

An infrared-based coefficient to screen plant environmental stress: concept, test and applications

Guo Yu Qiu[A,D], *Kenji Omasa*[B] *and Sadanori Sase*[C]

[A]School of Environment and Energy, Shenzhen Graduate School, Peking University, Shenzhen 518055, China.
[B]Graduate School of Agricultural and Life Sciences, The University of Tokyo, Tokyo 113-8657, Japan.
[C]National Institute for Rural Engineering, Tsukuba, Ibaraki 305-8609, Japan.
[D]Corresponding author. Email: qiugy@szpku.edu.cn

This paper originates from a presentation at the 1st International Plant Phenomics Symposium, Canberra, Australia, April 2009.

Abstract. By introducing a reference dry leaf (a leaf without transpiration), a formerly proposed plant transpiration transfer coefficient (h_{at}) was applied to detect environmental stress caused by water shortage and high temperature on melon, tomato and lettuce plants under various conditions. Results showed that there were obvious differences between leaf temperature, dry reference leaf temperature and air temperature. The proposed coefficient h_{at} could integrate the three temperatures and quantitatively evaluate the environmental stress of plants. Experimental results showed that the water stress of melon plants under two irrigation treatments was clearly distinguished by using the coefficient. The water stress of a tomato plant as the soil dried under a controlled environmental condition was sensitively detected by using h_{at}. A linear relationship between h_{at} and conventional crop water stress index was revealed with a regression determination coefficient $R^2 = 0.97$. Further, h_{at} was used to detect the heat stress of lettuce plants under high air temperature conditions (28.7°C) with three root temperature treatments (21.5, 25.9 and 29.5°C). The canopy temperature under these treatments was respectively 26.44, 27.15 and 27.46°C and the corresponding h_{at} value was –1.11, –0.74 and –0.59. Heat stress was also sensitively detected using h_{at}. The main advantage of h_{at} is its simplicity for use in infrared applications.

Additional keywords: heat stress, IR, lettuce, melon, plant transpiration transfer coefficient, remote sensing, tomato, transpiration, water stress.

Introduction

The surface temperature of plants varies with evapotranspiration (ET), photosynthesis and environmental factors. Because of this characteristic, plant surface temperature has been used as an indicator of water and environmental stress, and extensive research has been conducted to explore the relationship between plant surface temperature and other factors. Monteith and Szeicz (1962) presented a theoretical discussion of the relationship between surface temperature and stomatal resistance. Carlson *et al*. (1972) found that plant leaf temperature increased as the relative leaf water content and vapour pressure deficit decreased. Ehrler (1973) demonstrated the linear relationship between the leaf–air temperature difference and the vapour pressure deficit. Later, a quantitative expression relating the canopy–air temperature difference to ET, net radiation, soil heat flux and aerodynamic resistance was developed (Monteith 1981; Hatfield 1985). Plant temperatures in these early works were mainly measured by thermocouples.

Beginning in the 1980s, the use of surface temperature as an indicator of water and environmental stress increased due to the development of an infrared (IR) thermometer. For example, it was applied to estimate ET (Garder *et al*. 1981; Hatfield 1983; Jackson *et al*. 1983; Ben-Asher *et al*. 1992; Qiu *et al*. 1996*a*; Qiu and Ben-Asher 2009), photosynthesis (Weyers and Lawson 1997) and crop water stress index (Jackson *et al*. 1981, 1988; Idso 1982; Qiu *et al*. 1996*b*).

From the early 1980s to the early 1990s, the application of surface temperature in plant science dramatically increased due to the development of digital IR imaging techniques. IR imaging was initially applied only under controlled conditions. The approach developed by Omasa *et al*. (1980, 1981*a*, 1981*b*) and Hashimoto *et al*. (1984) were the earliest works to use digital IR imaging in plant science. Later, this technique was gradually improved and applied widely in the detection of stomatal movement, stomatal conductance and photosynthesis (e.g. Hashimoto *et al*. 1990; Omasa 1990; Omasa and Croxdale 1992; Omasa 2002; Omasa and Takayama 2003). Recently, this technique was further applied to screen plant genotypes for drought tolerance (Jones 2009), salinity tolerance (James *et al*. 2008; Sirault *et al*. 2009) and stomatal mutants (Genty 2009). IR imaging has also been applied under field conditions on a plant canopy scale and beyond (Jones 2009) for quantitatively

 10.1071/FP09132 1445-4408/09/110990

detecting environmental stress and guide irrigation or monitoring plant phenotypes (Jones 1999, 2009).

Because plant surface temperature can be measured or estimated by remote sensing in combination with other plant and environmental factors, there has been increased use in satellite based remote sensing (Karnieli *et al*. 2001). Moran *et al*. (1994) proposed a surface–air temperature and vegetation index to estimate crop water deficit and Moran *et al*. (1996) combined the Penman-Monteith equation with measurements of surface temperature and reflectance to estimate the ET of semiarid grasslands. Moran *et al*. (1997) also suggested that measurements of soil and crop properties combined with multispectral imagery could produce accurate, real time maps for soil and crops.

On the basis of the above research, remote sensing of surface temperature with IR has become an established technique for the diagnosis of bioenvironmental information and has been widely applied in the fields of plant physiology, ecophysiology, environmental monitoring and agriculture (Jones 1999). Monitored bioenvironmental processes include transpiration, stomatal conductance, metabolic processes, disease and infection (Jones 2004). Since the late 1990s, IR technique has been receiving more attention in applications ranging from micro to macro scales (Suleiman and Crago 2004; Omasa and Aiga 2006). The use of thermal remote sensing, especially when combined with spectral reflectance or even fluorescence measurement, is becoming a powerful and increasingly-used tool to diagnose and monitor the effects of environmental stress on plants (Jones 2009).

However, plant surface temperature can vary both spatially and temporally. For example, leaf surface temperature can vary with transpiration rate, stomatal opening, air temperature, soil water content, wind velocity and albedo (Leigh *et al*. 2006). Thus, temperature variability is a limitation for the real application of IR technique, especially when 'scaling up' to the field level. As summarised by Jones (2009), calibration or normalisation can make it more quantitative. So far, there have been several approaches to normalisation: normalising against air temperature (such as stress degree day, Jackson *et al*. 1977), normalising against calculated wet or dry references (crop water stress index (CWSI), Idso 1982) or actual wet or dry surface (Qiu *et al*. 1996*b*, 2000; Jones 1999) and calculation using meteorological data (air temperature, net radiation, humidity, wind velocity, Leinonen and Jones 2004).

Among these normalising methods, using real dry references has several advantages. Because the dry surface is installed in the same environmental conditions as the actual surface, it responds to environmental variability in a way similar to the real surface. Indeed, in many cases using the actual dry surface is easier for application and maintenance.

Due to these characteristics, the dry reference approach was applied here and further improved by normalising the leaf temperature simultaneously against a dry reference temperature and air temperature (Qiu 1996). Because there were three kinds of temperature included in his approach, Qiu's model was referred as 'three temperatures model (3T model)'. Briefly, the 3T model was proposed by Qiu (1996) and included two components: soil evaporation and plant transpiration. Later, the soil evaporation part was developed to estimate soil evaporation rate (Qiu *et al.* 1998, 1999), soil evaporation stage (Qiu and Ben-Asher 2009) and remote sensing application (Qiu *et al.* 2006). However, progress of plant transpiration part was less developed. In 1996, the transpiration submodel in the 3T model was developed for estimation of plant transpiration rate (Qiu *et al.* 1996*a*) and then extended for estimation of the crop water stress (Qiu *et al.* 1996*b*) under field conditions. Afterward, it was further improved for greenhouse conditions (Qiu *et al.* 2000). Later, comparisons of the 3T model with Penman-Monteith and Bowen ratio methods were conducted (Qiu *et al.* 2002). In 2003, a plant transpiration transfer coefficient (h_{at}) was proposed (Qiu *et al.* 2003).

According to Qiu (1996), a reference leaf canopy (dry leaf canopy without transpiration, hereafter referred to as the reference leaf) in the plant canopy, with a relatively small volume, would experience temperature, humidity, wind speed and other environmental parameters of the plant canopy were not significantly modified by the reference leaf. It was assumed that the radiation absorbance and albedo property of the reference leaf was similar to the other plant leaves. The temperatures of the plant canopy and reference leaf were assumed to be represented by the sunlit temperatures of leaves and reference leaves, respectively. Then, by neglecting the soil heat flux under plant canopy, the energy balance of the plant canopy and reference leaf could be given as:

$$R_n = H + LE \tag{1}$$

$$R_{nf} = H_f \tag{2}$$

where R_n and R_{nf} are the net radiation of the plant canopy and reference leaf, respectively, H and H_f are the sensible heat flux of the plant canopy and reference leaf, respectively, and LE is latent heat (transpiration rate) of the plant canopy, all measured in J m^{-2} s^{-1}.

Usually, sensible heat flux is expressed as:

$$H = \rho C_p \frac{T_c - T_a}{r_a} \tag{3}$$

where ρ is the density of air (kg m^{-3}), C_p the heat capacity of air (J kg^{-1}), T_c and T_a are the temperatures of the canopy and air (°C), respectively, and r_a is the aerodynamic resistance (s m^{-1}).

Because the reference leaf is in the same canopy as the plant leaf, the same r_a value could be used for the reference leaf (Qiu 1996). Combining the energy balance equation for plant canopy and reference leaf, we obtained the following equation to estimate plant transpiration (LE):

$$LE = R_n - R_{nf} \frac{T_c - T_a}{T_f - T_a} \tag{4}$$

where T_f is the temperatures of the reference leaf (°C). Equation (4) shows that the parameters included in the 3T model were net radiation and temperature. Generally, net radiation is estimated by the net short wave and long wave radiation, which could, in turn, be estimated by solar radiation, albedo, surface temperature and other parameters (Qiu *et al.* 1996*a*).

In the 3T model, canopy temperature, reference dry leaf temperature and air temperature were the key components used to calculate transpiration. Therefore, a plant's transpiration transfer coefficient (h_{at}) was defined as (Qiu *et al.* 2003):

$$h_{at} = \frac{T_c - T_a}{T_f - T_a} \tag{5}$$

Theoretically, $h_{at} \leq 1$, if $T_c = T_f$, h_{at} assumes its maximum value (h_{at} = 1) and transpiration assumes its minimum value ($LE = 0$). This limit was determined by lack of water for transpiration or by serious environmental stress. However, when h_{at} was at its minimum value, transpiration could reach its maximum value (potential transpiration rate). This limit was determined by the available energy for transpiration under no environmental stress. Therefore, h_{at} could determine the transpiration rate from zero to potential transpiration rate. A lower value of h_{at} corresponded to a higher transpiration rate and low environmental stress. A plant suffering environmental stress would have a higher h_{at} value than that of a non-suffering one.

By checking Eqn (5), we found that it could quantitatively determine plant environmental stress and was easier for application. This kind of technique could promote the application of IR technique in plant function monitoring if we can make full use of it. The objective of this study was to test and apply h_{at} for the monitoring of plant water and heat stress under various conditions.

Materials and methods

Three experiments were conducted to test and apply the proposed coefficient at the National Institute for Rural Engineering in Tsukuba, Japan, one in a greenhouse and two in growth chambers. In this study, the reference leaf was made from green paper. The procedures to prepare the reference leaf were: (i) choosing the green paper, which should be as similar in colour to the plant leaf as possible; (ii) cutting the paper into the shape of the plant leaf; and (iii) installing the paper leaf into the upper part of the plant canopy. The reference paper was not be shaded by nearby leaves. Before and during each experiment, equipment was carefully calibrated.

Experiment 1: Controlled soil water in a greenhouse with melon crop

This experiment was conducted from April to July (1998) in a glasshouse (Fig. 1*a*). The dimensions of the glasshouse were 60.4 m in length, 14.4 m in width and 3.9 m in height at the ridge. Two irrigation treatments were arranged. One was fully irrigated (area A, volumetric water content was varied in the range of 0.3–0.4 $m^3 m^{-3}$). Another was not fully irrigated (area B, volumetric water content was varied in the range of 0.2–0.3 $m^3 m^{-3}$). The melon crop (*Cucumis melo* L.) was planted in rows 1.5 m apart and the distance between individual plants was 0.8 m. Water was supplied by drip irrigation under the plastic film. The soil surface was covered with a plastic film to prevent evaporation. The temperature of the reference leaf was continuously measured with Cu-Co thermocouples and air temperature was continuously measured with shielded-ventilated Cu-Co thermocouples. Canopy temperatures of the plants in each treatment were continuously measured with an infrared thermometer (THI-500, Tasco Co. Ltd, Japan).Temperature imaging was measured with a thermal camera (TH3100, NEC San-ei Co. Ltd, Japan) and soil moisture in each treatment area was measured with a TDR soil moisture measurement system (Campbell Scientific Inc., USA). All data were sampled at 5-s intervals and recorded every 10 min. Radiation and air humidity data were recorded in a nearby meteorological station.

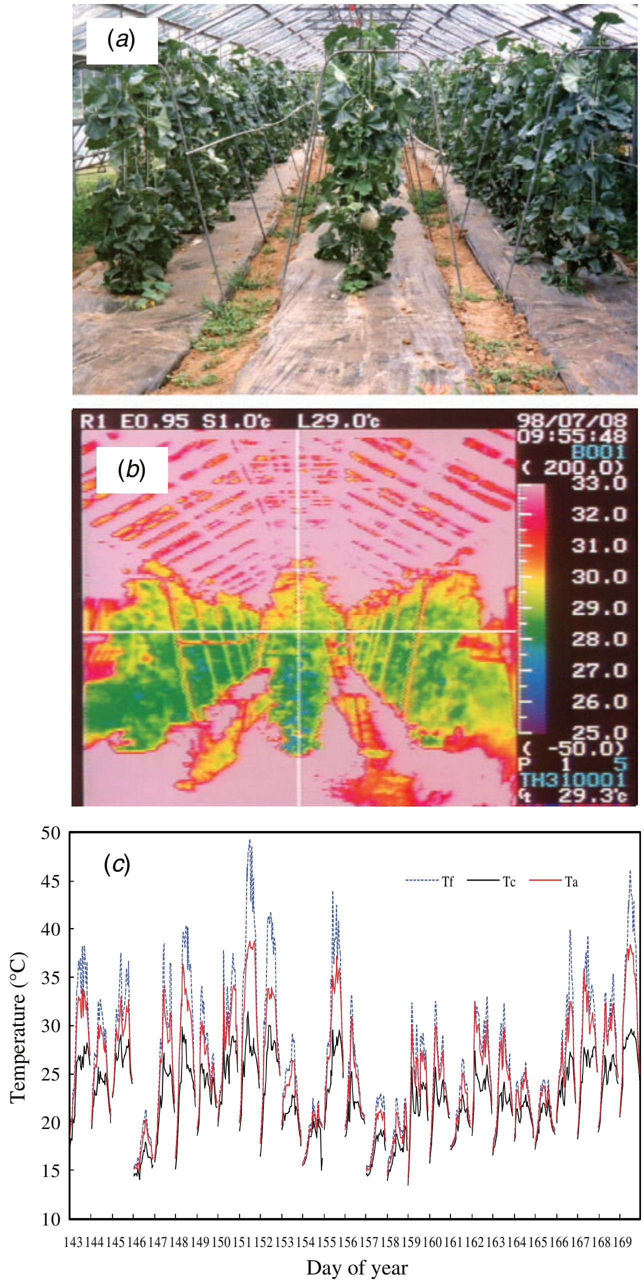

Fig. 1. Glasshouse experiment with melon plants. (*a*) The experiment arrangement and (*b*) the corresponding thermal image on 8 July 1998. (*c*) Variation of the three temperatures in day of year (DOY) 143–169, where T_c is the temperature of the melon leaf, T_f is the temperature of the dry reference leaf and T_a is the temperature of the air.

Experiment 2: Well-controlled experiment in a growth chamber with tomato crop

This experiment was conducted in May 1997 in a growth chamber. The growth chamber had a floor area of 7.3 m^2 and was equipped with lighting and air conditioning. Air temperature was set at 31°C and relative humidity was set at 60%. Lighting hours were 0500–1700 hours and light intensity was 157 W m^{-2}. One tomato plant (*Lycopersicon esculentum* Mill.) was planted in a pot filled with soil, 0.30 m in height and 0.26 m in diameter. The pot was sealed with an aluminium film to prevent soil evaporation. In this experiment, soil water content gradually decreased from a well watered condition to dry condition. Other environmental conditions were kept constant. The temperatures of the canopy and the reference leaf were measured with Cu-Co thermocouples and air temperature was measured with shielded Cu-Co thermocouples (sampled at 5-s intervals and recorded every 10 min). Canopy temperature and reference leaf temperature were also measured with a thermograph (JTG-3210, JEOL Co. Ltd, Tokyo, Japan). Plant transpiration was measured by weighing the pot with an SG32000 balance (Mettler Toledo Inc. Greifensee, Switzerland) and data were recorded every 10 min.

Experiment 3: Hydroponic lettuce in a growth chamber with heat stress

This experiment was conducted in September–October 1997. An environmental chamber with a floor area of 7.3 m^2 was used in this experiment. The chamber was equipped with lighting, air conditioning and a nutrient solution circulating system. Three growing containers, each measuring 0.75 × 2.0 m, were installed on movable benches. Styrofoam boards with holes for supporting plants were placed on the containers. Nutrient solution was circulated via a separate solution reservoir fitted in each container, which allowed for the control of the solution's temperature. Seedlings of butterhead lettuce (*Luctuca sativa* L. cv. 'Okayama Sarada') were transplanted into the growing containers 10 days after germination. Throughout the experimental period air temperature was maintained at 28.7°C during light periods (12 h) and 25°C during dark periods (12 h). Relative humidity was 70% throughout the experimental period. Twelve 400-W BOC lamps were used, producing a light intensity of 400 μmol m^{-2} s^{-1}. The only difference between the operating systems for each container was the temperature of the nutrient solution (root temperature). Temperatures in the three reservoirs were 21.5, 25.9 and 29.5°C, respectively. Temperatures of the canopy (three replications for each treatment), reference leaf, air and nutrient solution were measured with Cu-Co thermocouples at 5-s intervals and recorded every 10 min. Canopy temperature was also measured with a thermograph (JTG-3210, JEOL Co. Ltd) and an infrared thermometer (IR-0506C, Minolta Camera Co. Ltd, Japan).

Results

Variation patterns of the three temperatures

Figure 1 shows the experimental arrangement with melon crop (Fig. 1*a*), the corresponding thermal imaging (Fig. 1*b*) and variations of the three temperatures of the greenhouse melon during the main observation period (Fig. 1*c*). Canopy temperature was the average of area A and area B. T_f was higher than T_c and T_a during the daytime. On clear days (e.g. day of year (DOY) 151, 152, 155 and 169), the temperature difference between T_f and T_c could be as much as 20°C. T_a was generally higher than T_c. This was because the soil surface was not fully covered by the canopy, so solar radiation could be directly absorbed by the soil. Moreover, the plastic film covering the soil prevented evaporation from the 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 increased the air temperature. However, as reported previously, T_c could sometimes be higher or lower than T_a, depending on field condition (Qiu 1996). These results showed that there were obvious differences among leaf temperature, reference leaf temperature and air temperature. It is possible to simultaneously use the dry reference temperature and air temperature to normalise the observed leaf temperature.

Detecting water stress

There were two conventional ways to express CWSI. One was by using leaf temperature, such as CWSI = $(T_c - T_{cl})/(T_{cu} - T_{cl})$, where T_{cu} and T_{cl} were the upper limiting and lower limiting canopy temperatures, respectively (Jackson *et al*. 1981). The other was by using transpiration rate, such as CWSI = $1 - LE/LE_p$, where LE_p was the potential transpiration rate (Qiu *et al*. 1996*b*). Although water stress could be evaluated using the conventional temperature-based CWSI, the necessity of solar radiation and humidity in estimating the upper or lower limiting canopy temperatures (Idso 1982; Jackson *et al*. 1988) is a limitation in remote sensing application. In the proposed h_{at}, only temperature is included, since it is relatively easier for use remote sensing applications. The reliability of h_{at} for monitoring plant water stress is discussed below.

To monitor plant water stress, the data in Experiment 2 were analysed. Irrigation was conducted on the night of 23 May and then the data measured during the following 3-day-period were used. Figure 2 shows the comparisons between h_{at} and LE/LE_p (Fig. 2*a*) and between h_{at} and CWSI = $1 - LE/LE_p$ (Fig. 2*b*) of tomato plant. During the 3-day drying period, radiation, air temperature and humidity were kept constant and the only variable environmental factor was the decrease in soil water content due to plant transpiration.

In this experiment, the reference leaf temperature was around 44°C and the air temperature was around 35°C. As a result of water stress, the transpiration rate decreased from 120–140 g h^{-1} on 24 May to 80–120 g h^{-1} on 25 May and 30–70 g h^{-1} on 26 May. The corresponding plant surface temperature increased from 33, 34–39 and 39–43°C, respectively. The ratio of LE/LE_p was 1.0 from 24 May to the early morning of 25 May, indicating that there was no water stress for tomato plant. The corresponding values of h_{at} were –0.2– 0. Water stress began to show in the early morning of 24 May and then gradually increased. During the same period the ratio of LE/LE_p gradually decreased from 1.0 to 0.2 and the values of h_{at} gradually increased from 0 to 0.75

Figure 2*a* shows that h_{at} sensitively reflected the changes in the LE/LE_p ratio. It may also well related to CWSI = $1 - LE/LE_p$. Therefore, a comparison of h_{at} and CWSI = $1 - LE/LE_p$ is made and the results are shown in Fig. 2*b*. As h_{at} gradually increased

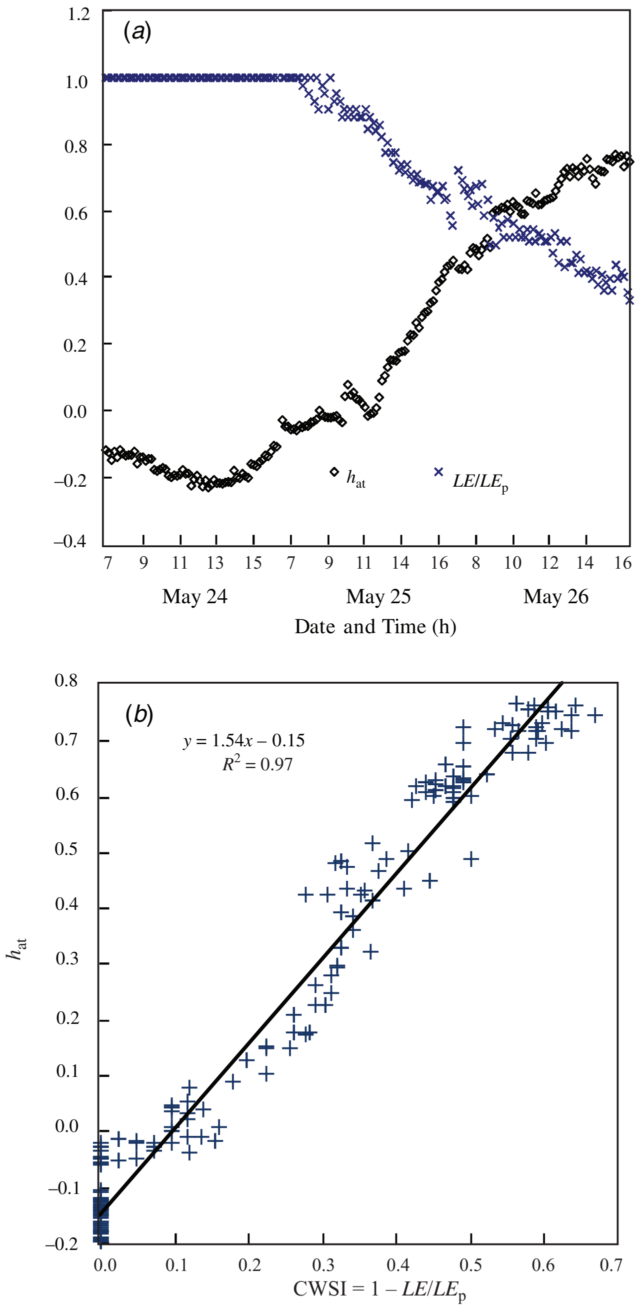

Fig. 2. A comparison of h_{at} with (*a*) the ratio of LE/LE_p and (*b*) CWSI = 1 – LE/LE_p of tomato plant during a 3-day drying process. Data were measured in Experiment 2.

from –0.1 to 0.75, the corresponding CWSI increased from 0 to 0.7. A linear relationship between them was revealed with a regression determination coefficient $R^2 = 0.97$

These results show that h_{at} values could give a quantitative evaluation of plant water stress. During the first day after irrigation (May 24) h_{at} was low (–0.1 to –0.2), while the transpiration rate was high and CWSI was zero. Lower values of h_{at} indicate no water stress. Starting at 1300 hours on the second day (25 May), h_{at} began to increase gradually and approached 0.4 at 1700 hours. The corresponding CWSI was ~0.35–0.40, indicating slight to medium water stress. Our other observations showed that a h_{at} value ranging from 0.4–0.5, usually indicated medium water stress (data not shown). At the end of the third day (26 May) h_{at} and CWSI had increased to 0.8 and 0.65, respectively, indicating severe water stress.

These results show that h_{at} could reasonably indicate plant water stress in a well-controlled environment. It was then further applied to the greenhouse melon, which was not as well controlled as the tomato plant used in Experiment 2. Results showed that, during the 18-days of observation, for areas A and B, the average volumetric water contents were 0.36 and 0.27 $m^3 m^{-3}$, the average transpiration rate were 4.18 and 3.65 mm day^{-1} and the average h_{at} values were –2.56 and –2.08, respectively. The differences in soil water content were clearly reflected by the difference in h_{at} value. To show this difference more clearly, cumulative values of soil water content, transpiration rate and h_{at} were plotted in Fig. 3. This shows that the soil water content and the transpiration rate in area A were higher than in area B (Fig. 3*a*, *b*) and that the corresponding h_{at} value in area B was higher than that in area A (Fig. 3*c*). The difference in soil water content was again clearly reflected in the difference in h_{at}.

In this experiment, despite the decrease in soil water content due to transpiration, the soil water content remained relatively high over the experimental period ($\geq 0.25\ m^3 m^{-3}$). Therefore, the melon plants experienced little or no water stress. This observation was also confirmed by the low h_{at} values because all of them were less than –1.0. These results again suggested that, under little or no water stress conditions, h_{at} had a lower value and fluctuated with changes in weather conditions.

Detecting heat stress

Increasing global warming may cause heat stress for many plant species. This will be especially true if water stress and heat stress occur simultaneously. In this study, we used h_{at} to detect heat stress on a lettuce crop. Lettuce is traditionally grown in cool climates and the optimal day time temperature for lettuce is 24°C (Thompson *et al.* 1998). Under high temperatures conditions, growth is stunted, the leaves may be bitter and the seed stalk forms and elongates rapidly.

In this study, we designed an experiment (Experiment 3) to detect the heat stress by using h_{at}. The lettuce crop was continuously exposed to high air temperature (28.7°C, ~4.5°C higher than lettuce's optimal temperature) and three different root temperature conditions (21.5, 25.9 and 29.5°C, respectively). Figure 4*a* shows the reference dry temperature, air temperature and canopy temperature for the three root temperature treatments. Although lettuce plants were exposed to the same air temperatures, the differences in canopy temperature were detected by thermal imaging by the differences in root temperature. Over the experimental period, the average canopy temperatures were 26.44, 27.15 and 27.46°C for root temperature treatment of 21.5, 25.9 and 29.5°C, respectively. The difference in average root temperature between them was 4°C and the difference in canopy temperature was ~0.5°C. In the low root temperature (21.5°C) treatment, the canopy of the lettuce suffered heat stress but the roots did not suffer heat stress. In the medium root temperature (25.9°C) and the high root temperature (29.5°C)

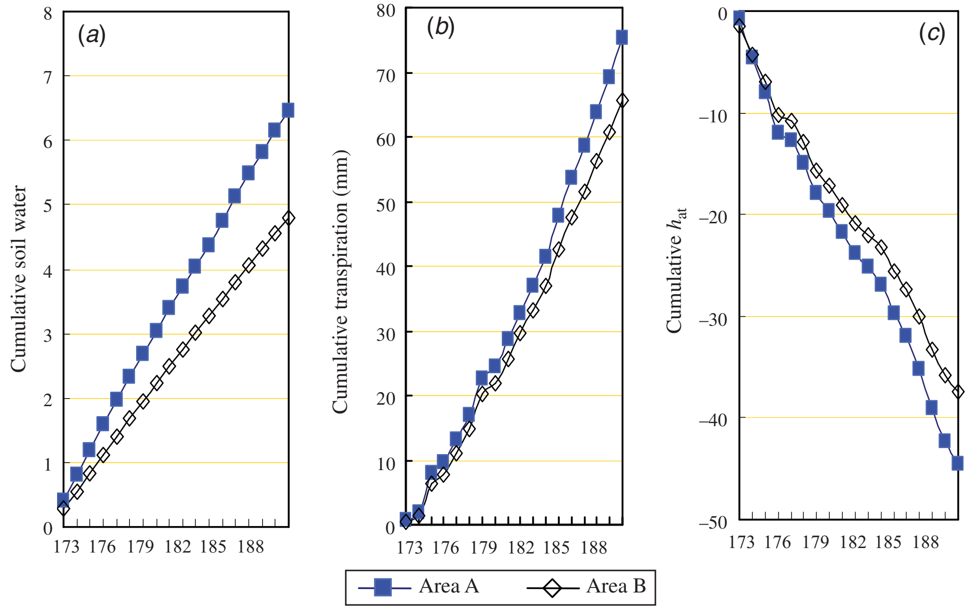

Fig. 3. Comparison of (*a*) cumulative volumetric soil water content, (*b*) transpiration rate and (*c*) h_{at} of the melon crop grown in a greenhouse in June–July 1998 (Experiment 1). Area A received more water than area B. The transpiration rate was calculated using Eqn (1). The numbers of the horizontal axis were the days of the year.

treatments, the lettuce plants suffered heat stress in both the roots and canopy. However, the stress level was different due to different root temperature and this difference was detected by using h_{at} (Fig. 4*b*). In the low root temperature (21.5°C) treatment, the lettuce suffered less heat stress and had an average h_{at} value of –1.11, which was about –0.3 lower than the medium temperature treatment. In the medium root temperature (25.9°C) treatment, average h_{at} value was –0.74, which was between those of the low and high root temperature treatments. The high root temperature (29.5°C) treatment had the highest h_{at} values (averaged value was –0.59), which indicates that the lettuce crops in this treatment suffered more heat stress.

Discussion

Root-zone temperature changes which cause stress to plant communities is very important to global warming researchers. Global warming could reduce soil evaporation rate by decreasing water content of the surface soil. Conversely, it could increase plant transpiration rate due to more vigorous development of the root system (Weng and Luo 2008). A suitable way to detect transpiration rate change under root warming condition was highly desired (Y. Luo, pers. comm.). The proposed h_{at} could provide a solution to this challenge. Results of this study show that h_{at} could effectively detect the changes caused by root temperature differences. To date, we have not been able to determine the relative contribution of water stress and heat stress when both of them occurred simultaneously, although we could determine the heat stress under controlled water conditions. More research into this topic will be necessary for a better understanding that global warming may cause through ecosystem changes.

In this study, we examined an alternative index to the more commonly used 'crop water stress index'. This index replaced the

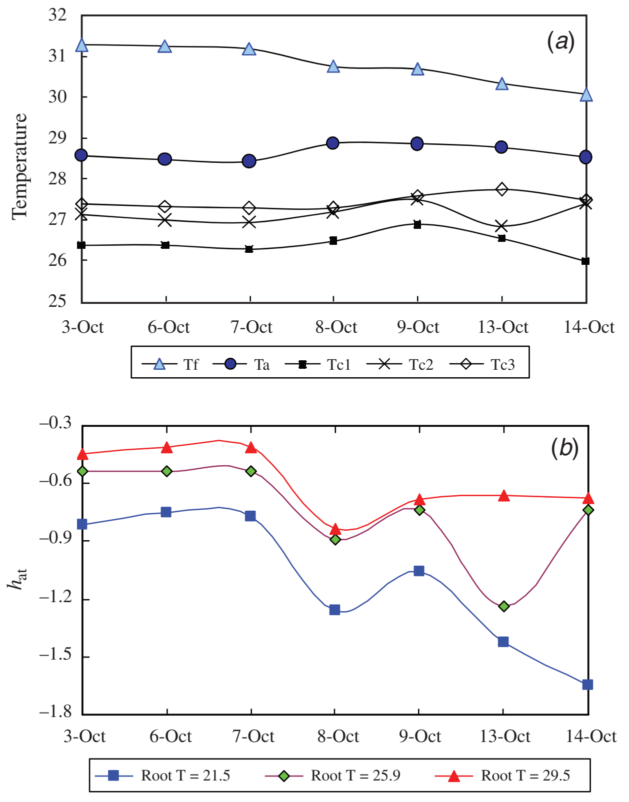

Fig. 4. Variations in (*a*) temperatures and (*b*) h_{at} values of hydroponic lettuce under high air temperature conditions ($T_a = 28.7$°C) for three root zone temperature (Root T) treatments. T_{c1}, T_{c2} and T_{c3} are canopy temperatures for different root temperature treatments, corresponding to root temperature of 21.5, 25.9 and 29.5°C, respectively. The experiment was conducted in 1997 in a growth chamber (Experiment 3).

use of a wet reference surface with air temperature measurement. The most important advantage of this index was that it is easy to measure, especially for remote sensing applications. The application of this index by using thermal imaging showed that it could be used to screening large numbers of plants.

Because air temperature was included, this index was more closely related with transpiration than stomatal conductance. For this reason, although it was valuable for detecting the physiological results of water deficits and heat stress, as indicated by Jones (2007), this kind of index may not be very useful in mechanistic studies aiming to understand the process. This point was clearly shown in the heat stress experiment in which we observed significant differences in canopy temperature for different root temperature treatments. The corresponding h_{at} values also showed obvious differences. These results showed the heat stress levels, but we could not explain its mechanism by using h_{at}. Additional measurements are necessary to fully understand the included mechanism.

Although we did not provide a direct comparison of h_{at} with stomatal conductance, surface temperature and crop water stress index could be closely related with stomatal conductance under certain conditions, as shown by Grant *et al*. (2007). In general, h_{at} is a valuable index for various applications if we pay attention to its limitations.

Conclusions

Three different temperature measurements were included in the proposed h_{at}: leaf temperature, reference dry leaf temperature and air temperature. Generally, there were obvious differences among them. The difference between the dry reference and leaf could be as much as 20°C. The proposed index could integrate these differences and quantitatively evaluate the environmental stress to the plant. From semi-controlled glasshouse to well-controlled chamber conditions, our results showed that water stress and heat stress of plants could be effectively detected by using h_{at}. Despite the fact that it was closely related to transpiration rate rather than stomatal conductance, the proposed index was valuable for plant stress detection, especially for remote sensing application, because it was easier to measure than other indices.

Acknowledgement

This study was jointly supported by the National Basic Research Program of China (2009CB421308), National Natural Science Foundation of China (40771037), Ministry of Education, Cultural, Sports, Science and Technology-Japan and the University of Tokyo.

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Manuscript received 3 June 2009, accepted 5 September 2009