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Acoustic Emissions in Tomato Plants under Water Stress Conditions

Guo Yu QIU[1], Limi OKUSHIMA[2]*, Sadanori SASE and In-Bok LEE[3]

Department of Agricultural Environment Engineering, National Institute for Rural Engineering (Tsukuba, Ibaraki 305–8609, Japan)

Abstract

Acoustic emissions (*AE*) could be used as an indicator of plant water stress as "speaking plant". The objective of this study was to observe the *AE* of tomato plant and to analyze the relationship between *AE* and plant water consumption associated with transpiration. Three glasshouse experiments were conducted with potted tomato plants. The *AE*, transpiration rate and "the plant transpiration transfer coefficient (h_{at})" as an indicator of plant water stress level were determined with h_{at} being calculated based on sunlit leaf temperature, temperature of an artificial leaf without transpiration (hereafter, referred to as "non-transpiration leaf temperature") and air temperature. The results showed that the daily patterns of the *AE* varied depending on the water stress level, which was indicated by h_{at}. Under mild or moderate water stress ($h_{at} \leqq 0$) conditions, the *AE* increased with the decrease in the amount of soil water but decreased with the decrease in the amount of soil water under severe water stress conditions ($0 < h_{at} \leqq 1$). To analyze the hourly changes in the relationship between *AE* and transpiration, the concept of "change of transpiration rate (*AT*)" was introduced. Under mild or in the absence of water stress conditions ($h_{at} \leqq 0$), *AE* increased linearly with the increase of *AT* with a significant regression coefficient ($r^2 = 0.85$ and slope = 0.61). Then, as the water stress level increased, the r^2 gradually decreased, as well as the slope of the regression line between *AE* and *AT*. When the water stress level increased further, the slope continuously decreased. However, r^2 started to increase gradually. Thus, when the water stress increased to a critical level ($0 < h_{at} \leqq 1$), a significant inverse linear relationship between *AE* and *AT,* with $r^2 = 0.64$ and slope = –0.73 could be observed. On the basis of these results, *AE* tended to be differently affected by *AT* depending on the water stress level.

Discipline: Horticulture
Additional key words: change of transpiration rate, transpiration, transpiration transfer coefficient

Introduction

Irrigation control in agriculture requires the accurate determination of the timing of irrigation and the amount of water to be added. Especially in protected cultivation, in order to increase the sugar content of fruits, the development of a technique to reduce the water supply and impose proper water stress is needed before harvest. Yet, in most of the cases, irrigation practice is controlled either by farmer's experience or by the soil water status.

It has recently been shown that the acoustic emission (*AE*) method could be used as an indicator of the plant water status[5]. *AE* are associated with the phenomenon of cavitation[16] in the plant stem, namely a reduction in the diameter of the conduit resulting from water stress or winter freezing. A cavitation event causes a rapid relaxation of the liquid tension that produces an acoustic emission of energy (sound).

Recently, studies on the relationship between *AE*

Present address:
[1] Institute of Resources Science and China Center of Desert Research, Beijing Normal University (19 Out Xinjiekou Avenue, Beijing, 100875 China)
[2] Department of Program Management and Coordination, National Institute for Rural Engineering (Tsukuba, Ibaraki 305–8609, Japan)
[3] Fundamental Engineering Technology Division, National Agricultural Mechanization Research Institute (Seodun-Dong, Suwon-Shi, 441–100 Korea)
*Corresponding author: fax +81–298–38–7609; e-mail limi@affrc.go.jp
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and water stress have been reported by several researchers. Jones and Pena observed that *AE* increased with the increase of the water stress level in both potted and field apple trees[2]. Using *Picea abies* and Carob (*Ceratonia siliqua*) trees, Borghetti, Raschi and Grace[1] and Lo Gullo and Salleo (1991)[4] observed similar results. Salleo and Lo Gullo found that the *AE* counts increased significantly in water-stressed Carob tree[13]. Using detached leaves, Kikuta et al. compared *AE*, with the field water relationship, and pressure-volume curves of the leaves of 8 different woody species and reported that *AE* increased with the increase in the water stress level[3]. Matthews et al. found that *AE* were significantly higher on the leaves of vines at a lower water content than at higher water contents and a highly significant correlation was obtained from the regression of daily *AE* on the mid-day leaf water potential[5]. These studies indicated that *AE* could be used as an indicator of plant water stress.

In spite of the above studies, limited information for practical use of *AE* for irrigation and water stress management in protected cultivation is available, because most of the reports dealt with woody species, although most of the common crops in protected cultivation are herbaceous species. Additionally, to apply *AE* for automated irrigation control in protected cultivation, more detailed experimental studies on the relationship between *AE* and water stress as well as between *AE* and the plant water consumption associated with transpiration are required. Tyree et al. reported that cavitation events commonly occurred in corn grown under field conditions[15]. Okushima et al. monitored the *AE* of melon plant in relation to transpiration and concluded that *AE* could possibly become an index of crop water stress[6]. Compared with tree plants, *AE* in herbaceous plants were fewer and weaker.

The objectives of this study were to observe *AE* of tomato plants growing under different water stress conditions and investigate the relationship between *AE* and transpiration under different levels of plant water status.

Materials and methods

Measurements and experimental procedures

Three separate glasshouse experiments were conducted at the National Institute for Rural Engineering in Japan. Fig. 1 shows a schematic representation of the set up of the instruments used for measuring *AE* and plant transpiration. One potted tomato plant (*Lycopersicum esculentum* Mill) var. 'Momotaro' was used in each experiment. The pot which was 0.30 m in height and 0.26 m in diameter was filled with commercial growing medium (Metro-Mix 350). The transpiration rate was measured by weighing the pots with a SG32000 balance (Mettler Toledo Inc.) at 10 min intervals and the data were recorded with a computer. Sunlit leaf temperature, the temperature of a leaf made of green paper in which transpiration does not occur (hereafter referred to as "non-transpiration leaf temperature"), and air temperature were measured with C-C thermocouples at 5 sec intervals and recorded every 10 min with a 21X data logger (Campbell Scientific Inc.). Soil evaporation was assumed to be negligible as the soil surface was covered with an aluminum film.

AE sensor, attached to the plant lower stem, was a broadband ultrasonic *AE* transducer (AE-900S-WB, NF Kairo Sekkei Block Co., Ltd.), which had a high frequency band in the range from 100 to 1000 kHz. In Experiments 1 and 3, the *AE* signals were recorded with a 60 dB amplifier (9501, NF Kairo Sekkei Block Co., Ltd.). In Experiment 2, the *AE* signals were recorded with a Music System consisting of a 9604 local processor and a 9913 amplifier (NF Kairo Sekkei Block Co., Ltd.), which could amplify the *AE* signal to 80 dB. For this reason, more *AE* counts were recorded in Experiment 2 than in Experiments 1 and 3.

Experiment 1 was carried out in June 1997. In this experiment, irrigation was applied at 17:00 on June 9 and on June 13. Therefore, the period of June 10–13 could be considered to correspond to one cycle of water stress. In all the 3 experiments, to avoid the effect of plant growth on *AE*, the duration of each water stress cycle was relatively short and new leaves and buds were removed before the start of each water stress cycle. Experiment 2 was carried out in January and February 1998. In this experiment, data recorded during 2 water stress cycles

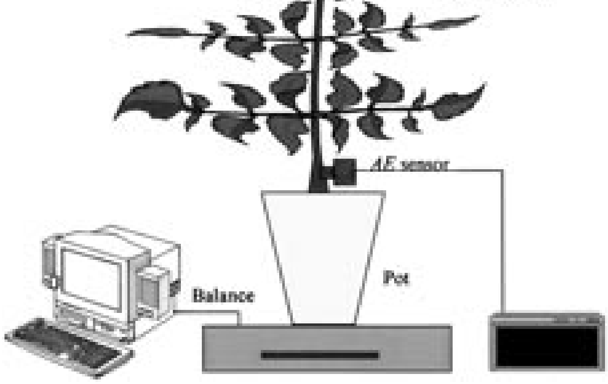

Fig. 1. Schematic representation (not to scale) of the instruments set up for detecting acoustic emissions (*AE*) and transpiration of tomato plant

(January 31 to February 5) were used for analysis. Experiment 3 was conducted in May and June 1999. In this experiment, data recorded during 2 water stress cycles (May 24 to June 2) were used for analysis.

Two new concepts

In this study, the "plant transpiration transfer coefficient (h_{at})" was used as an indicator of plant water stress. Qiu et al.[7–12] proposed this concept and its definition, history, and properties are briefly summarized here.

By introducing the non-transpiration leaf temperature (T_p), a model to estimate plant transpiration was developed:

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

where T is the transpiration rate (MJ m^{-2} per unit time), R_n and R_{np} are the net radiation of sunlit leaf and non-transpiration leaf (MJ m^{-2} per unit time) and T_c, T_a and T_p are the sunlit leaf temperature, the air temperature, and the non-transpiration leaf temperature, respectively. Unit of temperature was expressed in ºC. For convenience, Eq. (1) will be referred to as Qiu's model. Comparison of the transpiration measured with a weighing lysimeter[7,10] and the transpiration simulated by the model ENWATBAL[11], confirmed that the use of Qiu's model was an accurate and simple means to estimate transpiration. Afterwards, Qiu's model was further extended for estimating soil evaporation by introducing the dry soil surface temperature[12], and a soil evaporation transfer coefficient was defined[8]. The proposed soil evaporation transfer coefficient could be easily measured and was sufficiently stable to adequately estimate soil evaporation. Finally, the concept of h_{at} was proposed as follows:

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

Theoretically, $h_{at} \leqq 1$. If $T_c = T_p$, the maximum value of h_{at} is assumed to be ($h_{at} = 1$) and transpiration showed the minimum value (zero). This limit was determined by the lack of water for transpiration. On the other hand, when h_{at} showed the minimum value, the transpiration could reach a maximum value (potential transpiration rate). This limit was determined by the available energy for transpiration. In this study, h_{at} was adopted as daily value. The temperatures were averaged during the daytime in a day.

To better understand the relationship between *AE* and transpiration, the concept of "change of transpiration rate (*AT*)" was introduced. In this study, the unit of *AT* was g h^{-2}. The values of *AT* could be positive, zero, or negative. $AT > 0$ indicated that the transpiration rate

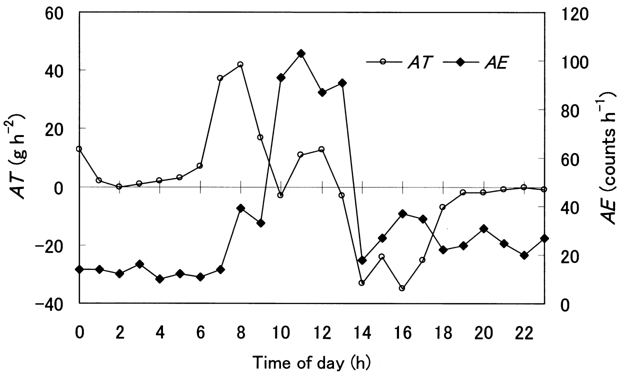

Fig. 2. Variations of *AE* and changes in the transpiration rate (*AT*) of tomato plant on a non-cloudy day

During the period of 05:00–09:00, *AT* was continuously larger than zero (Feb. 2, 1998, Experiment 2).

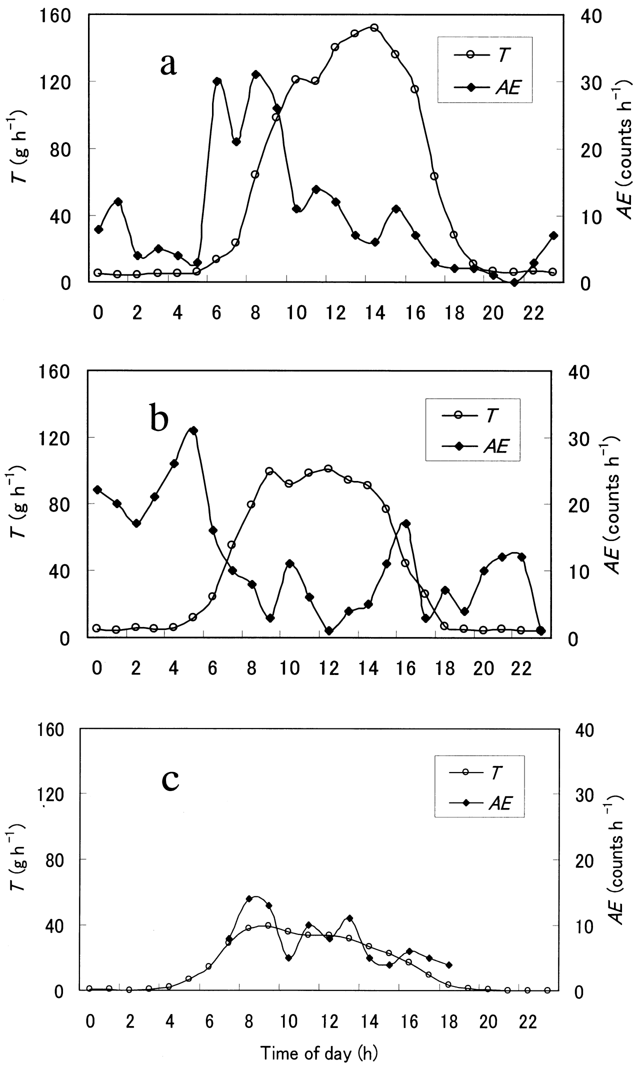

Fig. 3. Relationship between *AE* and transpiration rate (*T*) of tomato plant under different water stress conditions

a: No./mild water stress (June 10, 1997, Experiment 1), b: Moderate water stress (June 13, 1997, Experiment 1), c: Severe water stress (May 23, 1999, Experiment 3).

increased. $AT = 0$ indicated that the transpiration rate did not change, while $AT < 0$ indicated that the transpiration rate decreased. On a non-cloudy day, usually AT was close to zero in the night, larger than zero in the morning and smaller than zero in the afternoon (Fig. 2). The AT value was larger than zero when the water moving state was very active.

Results

Hourly variations of *AE* and transpiration rate

Fig. 3a shows the hourly variations of *AE* and transpiration rate (T) of tomato plants on the first day after irrigation. *AE* obviously started to increase at 06:00, which corresponded to the time when the solar radiation started to increase. *AE* increased up to 30 counts h^{-1} during the period of 06:00–09:00 as T increased from 1 to 100 g h^{-1}. These results indicated that, in the absence of or under mild water stress conditions, *AE* increased significantly at the time when T decreased, namely $AT > 0$.

Fig. 3b shows the hourly variations of *AE* and T on the second day after irrigation. *AE* remained at a high level during the period of 00:00–06:00 and reached a maximum value of 30 counts h^{-1} at 06:00. *AE* decreased to 5–10 counts h^{-1} in the daytime after this peak. However, T showed a different distribution from that of *AE*. From 00:00 to 06:00, T remained at a lower level of 5 g h^{-1}. T started to increase at 06:00 and reached a maximum value of 100 g h^{-2} at 09:00. The difference in the curves of *AE* and T showed that, under moderate water stress conditions, the peak of *AE* counts appeared earlier than the peak of T.

Fig. 3c shows the hourly variations of *AE* and T on the third day after irrigation, which corresponded to severe water stress conditions. *AE* remained low and decreased in the daytime. All the *AE* readings were in the range of 5–15 counts h^{-1}. The maximum value of *AE* was 15 counts h^{-1} at 09:00 and then *AE* decreased gradually to 5 counts h^{-1} although during the nighttime, *AE* data could not be used for analysis because of the high background noise. T also remained low and the maximum value was around 40 g h^{-1}. Under severe water stress conditions on the third day, tomato plants experienced a water shortage, resulting in wilted leaves.

These results show that the hourly variations of *AE* did not always correspond to those of T.

Daily variations of *AE* under different levels of plant water stress

The use of h_{at} enabled to compare different levels of plant water stress. Fig. 4 shows the daily relationship between *AE* and plant water stress during 5 water stress

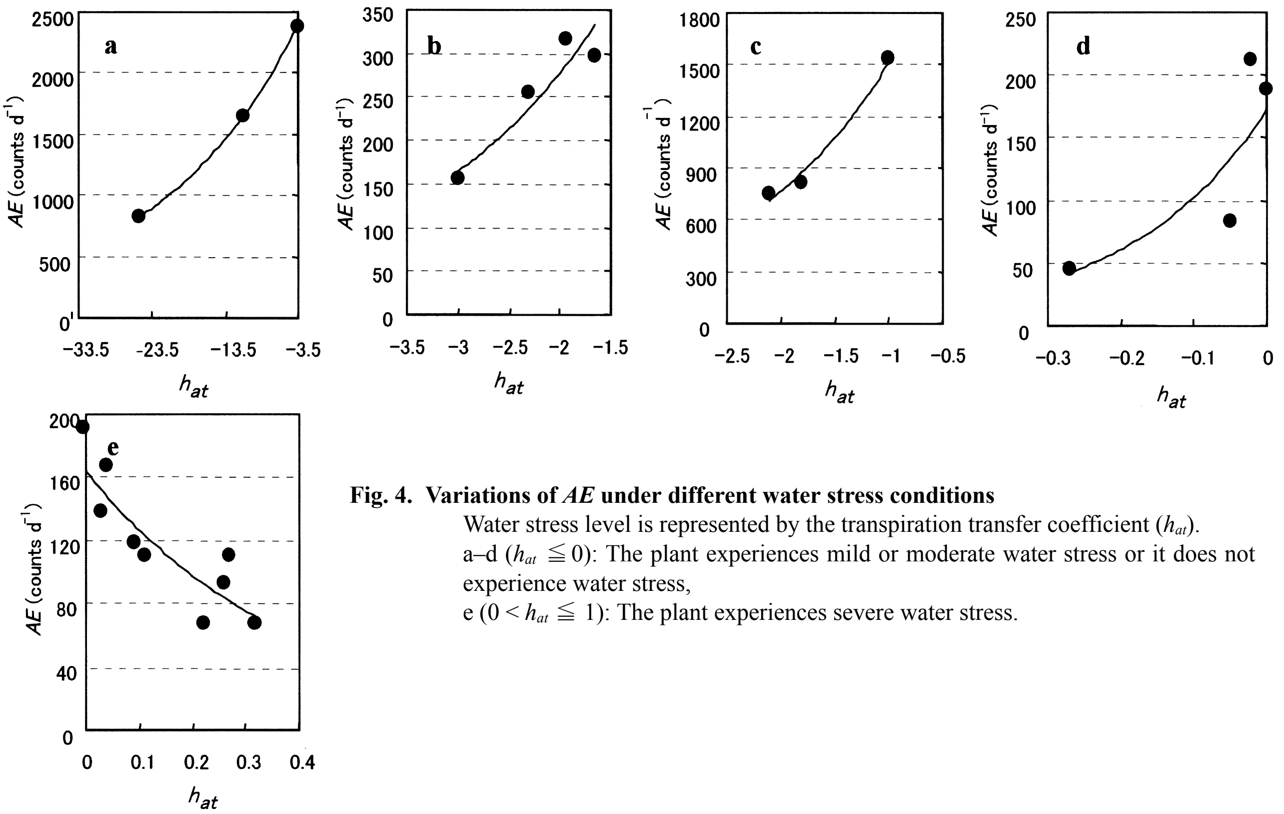

Fig. 4. Variations of *AE* under different water stress conditions

Water stress level is represented by the transpiration transfer coefficient (h_{at}).

a–d ($h_{at} \leqq 0$): The plant experiences mild or moderate water stress or it does not experience water stress,

e ($0 < h_{at} \leqq 1$): The plant experiences severe water stress.

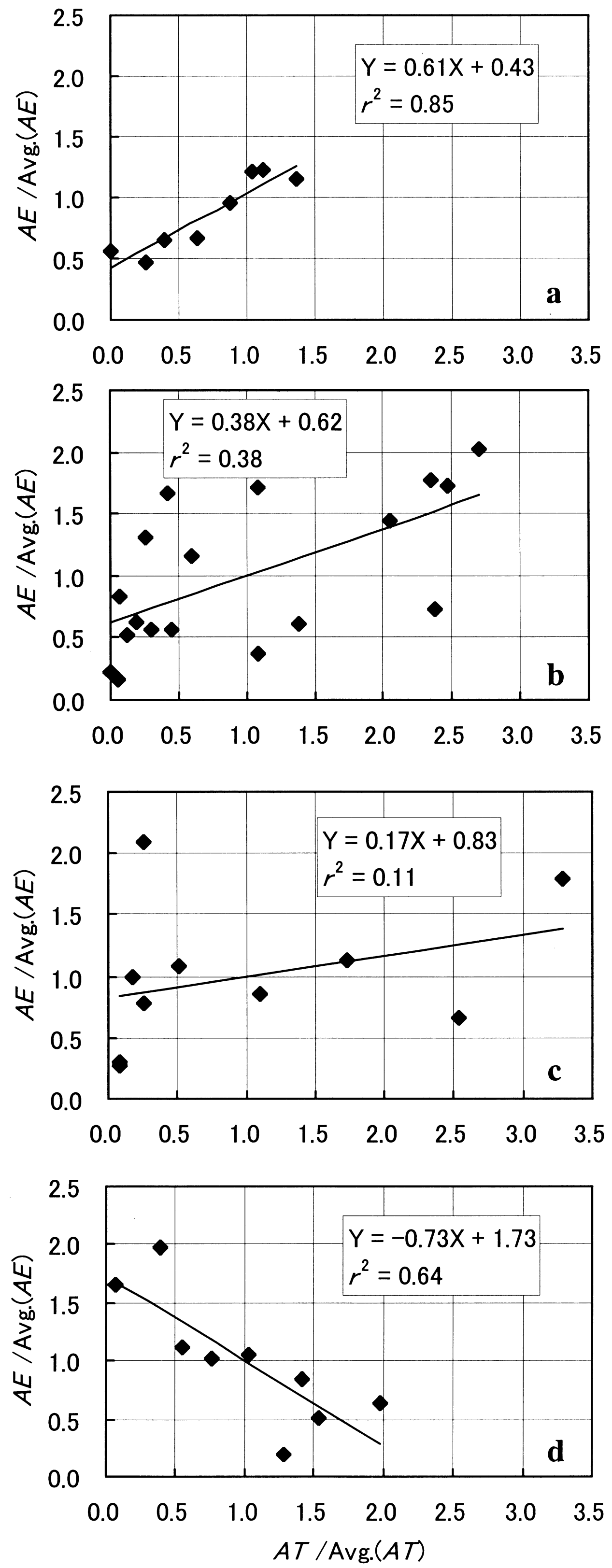

Fig. 5. Relationship between *AE* and change in the transpiration rate (*AT*) of tomato plant under different water stress conditions

a: No./mild water stress, b–c: Moderate water stress, d: Severe water stress.

cycles (h_{at} varied from –33.5 to 0.4).

Figs. 4a– 4d show the relationship between *AE* and the h_{at} under the $h_{at} \leqq 0$ condition. The daily maximum value of *AE* increased with increasing h_{at}. For example, in Fig. 4a, the *AE* and h_{at} values were 818 counts d^{-1} and –25.3 on the first day after irrigation, 1,642 counts d^{-1} and –11.1 on the second day after irrigation and 2,378 counts d^{-1} and –3.6 on the third day after irrigation. Similar results are presented in Figs. 4b–4d. These results were in agreement with the findings of other researchers[1–5, 14].

On the other hand, as shown in Fig. 4e, *AE* decreased with increasing h_{at} under severe water stress conditions ($0 < h_{at} \leqq 1$). The daily maximum *AE* counts and the corresponding h_{at} values were 200 counts d^{-1} and 0. The *AE* and h_{at} values were 50 counts d^{-1} and 0.4 (maximum value).

These results showed that the daily maximum *AE* counts varied depending on the level of the plant water status. Especially, the fact that daily maximum *AE* counts decreased with increasing plant water stress under severe water stress conditions had not been reported elsewhere. It might thus be dangerous to control the water supply by using only daily *AE* counts.

Furthermore, in the hourly values of *AE* and h_{at}, a similar relationship to the daily relationship could not be observed. Further investigations should be carried out for hourly control of the water supply.

Relationship between hourly *AE* and *AT*

Fig. 3a shows that the increase in *AE* followed the increase of the transpiration rate as long as the transpiration rate was continuously increasing. Therefore, the hourly relationship between *AE* and *AT* under the condition ($AT > 0$) was analyzed in this study.

Fig. 5 shows the hourly relationship between *AE* and *AT* (> 0) under different water stress levels. The data of *AE* and *AT* in Fig. 5 were normalized by dividing the values with the average values in each experiment, because the recorded values in each experiment were considerably different due to the plant water status, environmental characteristics, and measuring methods. Figs. 5a–5d show that plant water stress gradually increased. Fig. 5a shows the situation under mild conditions or in the absence of water stress conditions. *AE* increased with the increase of *AT* and a significant linear relationship with a regression coefficient r^2 = 0.85 and slope = 0.61 was observed between *AE* and *AT*. As water stress increased (Fig. 5b), the significance and the slope of the regression line between *AE* and *AT* decreased (r^2 = 0.38 and slope = 0.38). When the water stress further increased (Fig. 5c), the significance and the slope of the regression line between *AE* and *AT* still decreased (r^2 = 0.11, slope =

0.17). As shown in Fig. 5d, under severe water stress conditions, *AE* decreased with increasing *AT*. A significant inverse linear relationship (slope = –0.73) with the regression coefficient $r^2 = 0.64$ was observed. Under this condition, tomato plants experienced water stress and part of the leaves wilted. In this case the significant inverse linear relationship between *AE* and *AT* could be used as an indicator of critical water supply. Additionally, it might be possible to continue to impose water stress upon the plants by monitoring the slope value although the regression coefficient was low.

Discussion

Our results showed that *AE* of tomato plant could be readily measured. However, compared with woody plants, *AE* in tomato plants were fewer and weaker. Measurement of *AE* in herbaceous plants tended to be more easily affected by the background noise. Further improvement of *AE* measurements in herbaceous plants is required.

Hourly variations of *AE* showed that (Fig. 3) under mild or in the absence of water stress conditions, when *T* started to increase with solar radiation in the morning, a significant increase in *AE* could be observed. However, this relation between *AE* and *T* was not observed under moderate or severe water stress conditions, presumably because even under mild or in the absence of water stress conditions, there is often a time lag between the transpiration and water supply from the root as long as the transpiration rate increases, which leads to cavitation. Afterwards, conduits with cavitation may be soon replenished with liquid water since there is enough water available in the root system. This process (cavitation and replenishment) may be repeated and consequently *AE* increase with the increase of the transpiration rate. It was assumed that under moderate or severe water stress conditions, *AE* do not increase with the increase of the transpiration rate, because the root system cannot absorb enough water to replenish the conduits with cavitation. These findings indicate that (1) the changes in the characteristics of *AE* depending on water stress conditions may be used as an alarm to apply water for irrigation; (2) *AE* may be affected by the change in the transpiration rate. This hypothesis was further tested as follows.

The daily maximum value of *AE* increased with the increase of the water stress level under mild or moderate water stress conditions ($h_{at} \leqq 0$). In this study, the maximum values of h_{at} were –1.7 and –1.0 in Experiments 1 and 2, respectively. In these 2 experiments, tomato plants grew well in the absence of severe water stress. The relationship between *AE* and h_{at} shown in Fig. 5e, however, was different from the relationship in these 2 experiments. In Experiment 3, the maximum value of h_{at} was larger than 0.3. As mentioned above, $0 < h_{at} \leqq 1$ indicates that the tomato plants experienced severe water stress. This may account for the fact that other researchers did not observe this phenomenon because, in their experiments, the plants were not subjected to severe water stress unlike in Experiment 3. This daily relationship between *AE* and plant water stress is useful for analyzing the mechanism of *AE*, but only the daily value of *AE* may not be sufficient to become an indicator of water supply.

To further test the hypothesis that *AE* are affected by the changes in the transpiration rate, the relationship between *AE* and *AT* was analyzed assuming that *AT* was continuously larger than zero. Generally, this condition can only be satisfied in the morning hours of a non-cloudy day. The results are as follows: (1) Under mild or in the absence of water stress conditions, it was found that *AE* decreased with increasing *AT*. There was a significant linear relationship between *AE* and *AT*, with a high regression coefficient and the value of the slope of the regression line was large; (2) When the water stress level increased, the value of the slope of the regression line between *AE* and *AT* gradually decreased. The significance of the regression relationship between *AE* and *AT* also gradually decreased; (3) When the water stress further increased, although the value of the slope of the regression line continuously decreased, the significance of the regression line started to increase. Finally, after the water stress increased to a severe level, an inverse linear relationship with a significant regression coefficient could be observed between *AE* and *AT*. Under these conditions, the plants experienced water stress and irrigation was absolutely necessary. Therefore, a significant inverse linear relationship between *AE* and *AT* could be used as an indicator of critical water supply. Additionally, adjustment of the water supply to keep a selected slope of *AE* and *AT* could be performed to impose a proper water stress upon the plant. It might be possible to make tomato fruits sweeter. To apply the technique of proper water stress control, however, some problems still remain to be solved because of the low regression coefficient when the value of the slope of the regression line was medium. Furthermore, the relationship between *AE* and *AT* can be applied only under $AT > 0$ conditions. Probably, in the morning as long as $AT > 0$, the amount of water supply could be controlled depending on any model using the slope, and in the afternoon when *AT* becomes <0, the amount of water might be determined based on the balance of water consumption associated with transpiration.

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