Evaluation of Irrigation Response using AE Method for Management of High-Frequency Irrigation of Hydroponic Miniature-Tomato

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ABSTRACT: AEs in living plants are related to the drought stress which induces the cavitation. The irrigation management is important factor to cultivate the tomato plants under suitable drought stress. In this study, the response to irrigation of miniature-tomato plants was evaluated using AE method. We proposed that the change of AE occurrence rate before and after the irrigation *RD* represented the stress response to the change of the drought stress. The AE measurement of hydroponic miniature-tomato with high-frequency irrigation revealed that the *RD* was influenced by the irrigation schedule. Furthermore, the average value of *RD* was deeply related to the yield and the sugar content of the fruits.

1 INTRODUCTION

AEs in plants are accompanied by cavitation events that occur in xylem elements [1]. Cavitation accompanies ultrasonic AEs, which can be detected by an AE sensor attached to the stem or trunk. Many studies on diagnosis of living tree has been done using AE measurement owing cavitation [2,3]. Qiu and Okushima [4], furthermore, analyzed the relationship between AE and transpiration rate of tomato plant by measurement of AE, leaf temperature and transpiration rate. They found that the influence of the change of transpiration rate on the AE behavior depended on the drought stress level. Takakura et al. also proposed the concept of the speaking plant approach (SPA) to evaluate dynamic responses of plants to changes in their environment and examined developed a chlorophyll fluorescence imaging system for tomato plants cultivated in greenhouses [5]. Such a combination of several sensing techniques, i.e. a spectrum of a leaf, transpiration rate (weight of water in a pot) and AE at stem, was successful to evaluate water or drought stress response of plants to environmental changes. The measurements of the spectrums of leaves and the weight of the pots, however, are not suitable for the practical use in agricultural greenhouse because of high cost and delicate handling. The AE method is widely used for monitoring of industrial structures because the low-cost and robust devices have been developed. Additionally, the stress response of the plants could be evaluated by only AE method if the environmental changes can be detected. The AE and irrigation is good combination to evaluate the stress response of a plant because the irrigation drastically eases the drought stress of the plant while the AE behavior is deeply related to the drought stress.

The authors, therefore, studied the AE behavior of miniature tomato plants to develop a technique for the health monitoring of plants using AE measurement and irrigation control [6]. Consequently, irrigation control of the miniature tomato using the AE change ratio before and after irrigation *RD* (response to drought stress change) was successful for deficit irrigation of the miniature tomato

$$RD = \frac{N_{after} - N_{before}}{N_{before} + N_{after}} \quad (1)$$

where N_{before} and N_{after} represent AE events before and after irrigation, respectively.

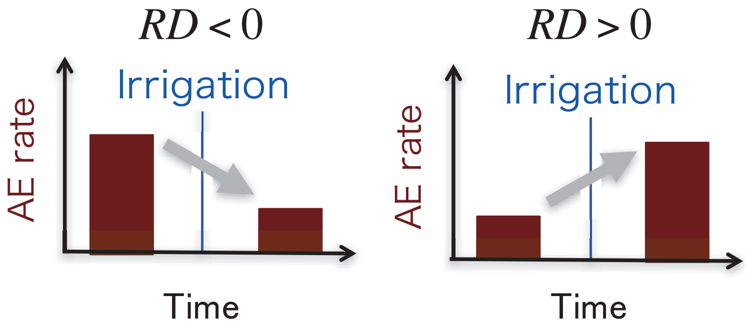


Figure 1: Schematic of evaluation of irrigation response using *RD*.

RD can be treated as the irrigation response of a plant as shown in figure 1. The plant shows a forward response when *RD*<0 because both of the drought stress and AE rate were decreased. In our model, the forward response means that the plant is well irrigated and the drought stress is moderate because the occurrence of cavitation was restrained. In contrast, the backward response (*RD*<0) means that the plant needs water and the drought stress is severe because the irrigation accelerated the occurrence of cavitation. Drought stress significantly influences on the yield and the sugar content of fruits at tomato cultivation. Hence, *RD* could be used for the prediction of yield and sugar content of the fruits because the *RD* is deeply related to the drought stress of tomato plants [7]. In this study, the hydroponic cultivation system for tomato plants with high frequency irrigation was fabricated to investigate the influence of the irrigation condition on the *RD* behavior. The AEs at the stem of tomato plants were continuously detected during cultivation and the response of *RD* against the change of the irrigation time was discussed.

2 EXPERIMENTAL PROCEDURES

2.1 *Experimental material*

A miniature tomato (Chika, Takii Seed) was used in this study. The seeds were germinated in a tray and mixed with vermiculite. The plants were placed in a temperature-controlled room where the temperature was set at 24 and 20 ºC for day and night, respectively. The lighting intensity was set to 240 µmol·m-2·s-1 at the base of the shoot; the lighting cycle ran for 12 h each day. Well-grown plants at one month after transplanting the seedlings were examined and measured. All lateral shoots were removed when they appeared during the measurement, and the plants were pinched above the third truss with two true leaves over the truss. The seedlings were planted in a small pot and grown using a hydroponic cultivation system, as shown in Figure 2. Irrigation was done by spraying the nutrient solution to the roots through mist nozzles using a water pump from a tank below the shoots. Root cutting was down at the interval of 10-14 days for a root-zone restriction. The plants were cultivated for 75-88 days while AE measurement.

2.2 *AE measurement*

A high-precision vibration sensor (VS-BV203, NEC TOKIN) was selected as an AE sensor because of reducing cost. A pair of AE sensors were attached to the same stem of a miniature tomato to measure AE owing to cavitation in xylem tissues. The center-to-center distance between each sensor was set to 2-5 cm. The AE sensor was fixed using a stainless-steel hose clamp. AE signals were detected by an oscilloscope (PicoScope 4424, Pico Technology) with a sampling rate of 10 MHz, and the waveforms were recorded using a PC. The thresholds for AE measurement were set to 3 mV for the AE sensor. *RD* was evaluated every hour by following procedures. Firstly, sums of N_{before} and N_{after} up to 1 hour before were calculated when T_{AE} was set to 10 min or T_i/2 if T_i<20 min as shown in Figure 3. Then RD was calculated using sums of N_{before} and N_{after} and equation 1 (*RD* was treated as being lost when N_{before}+N_{after}=0).

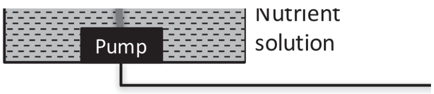


Figure 2: Experimental setup

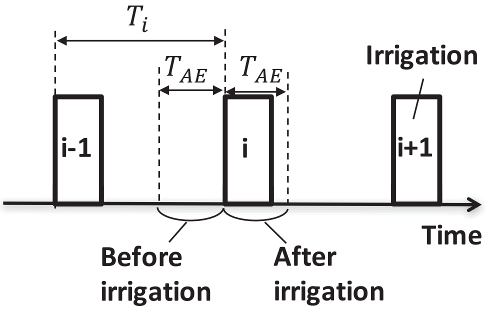


Figure 3: Schematic of definition of T_i and T_{AE}.

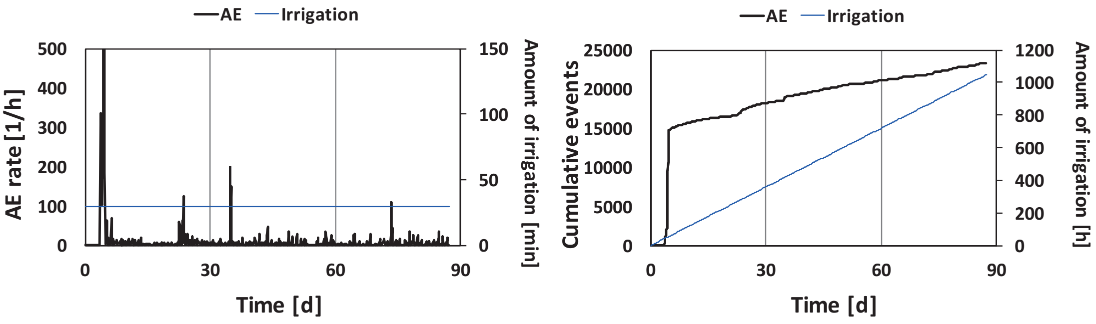
Table 1: Experimental conditions for hydroponic culture

Irrigation Condition	Section Name	Irrigation Interval	Each Irrigation time	EC of fertilizer	Cultivation Period
Constant	C	30 min	15 min	0.2 - 0.6 mS/cm	81 d
Fluctuated	F1		10 s- 20 min		85 d
	F2	3-30 min	15 s		75 d

Irrigation control was carried out by a PC and a relay circuit as shown in figure 2. Constant and fluctuated section were selected for the irrigation condition of the plants. For the constant section, the irrigation interval and time were fixed to 30 and 15 min, respectively. For the fluctuated section, the irrigation time or interval was fluctuated using a fuzzy control. The concept of the irrigation control was to cultivate the tough plants against change of drought stress, i.e. RD=0. Then the program was designated to increase and decrease the irrigation frequency when RD>0 and RD<0, respectively. Unfortunately, the fuzzy control in this study did not work properly for several causes (electrical troubles, computer freezing up and bugs of the program) although the fuzzy control was programmed to change the parameter according to the value of RD. The irrigation condition was treated as being randomly changed for the fluctuated section in this study. The irrigation condition was listed in table 1. The irrigation time and interval time were changed for F1 and F2, respectively.

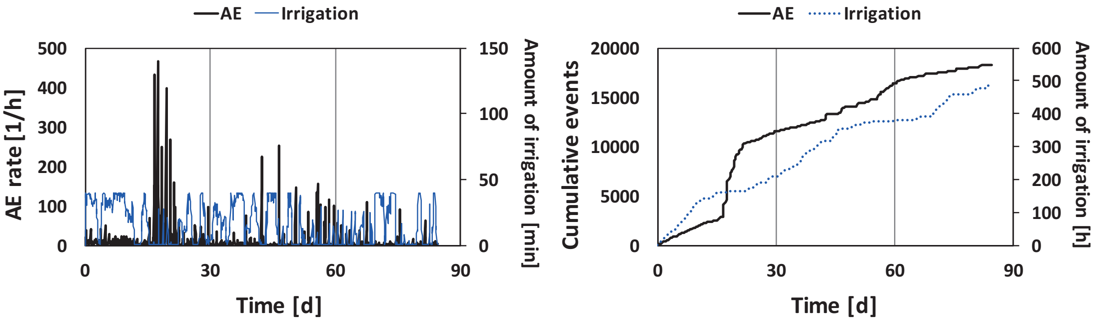
3 RESULTS AND DISCUSSION

Figure 4 to 6 show the behaviors of AE occurrence rate and irrigation time of C, F1 and F2 section. In fluctuated sections F1 and F2, the relationship between the AE occurrence rate and the amount of irrigation time was not recognized though the both were largely fluctuated. Hourly behavior of RD of F1 was significantly scattered as shown in figure 7 because the number of the detected AE was not enough to calculate the precise value of RD. Then, an average value of RD $\overline{RD}$ and a sum of the irrigation time ITT were calculated by separating for each period T for the entire measurement period. Figure 8 shows the behaviors of $\overline{RD}$ and ITT of F1 section when T=24 h. The $\overline{RD}$ showed slight similar behavior with the ITT (same rising peaks at 44, 70 and 80 d were observed).



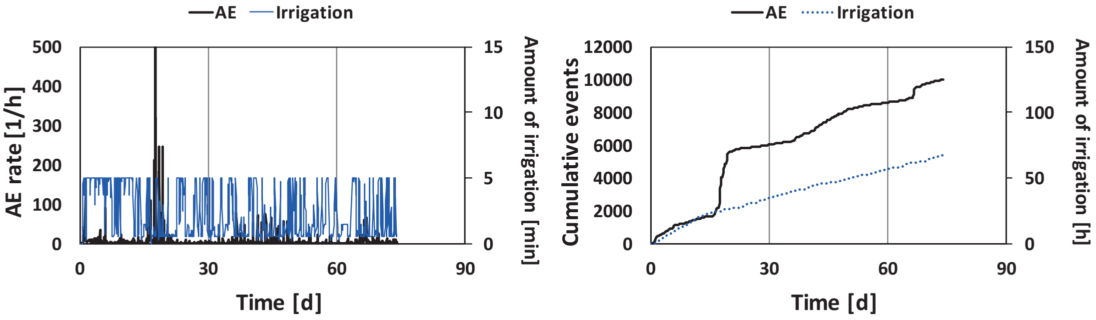
(a) (b)

Figure 4: AE behavior and irrigation fluctuation for C section



(a) (b)

Figure 5: AE behavior and irrigation fluctuation for F1 section



(a) (b)

Figure 6: AE behavior and irrigation fluctuation for F2 section

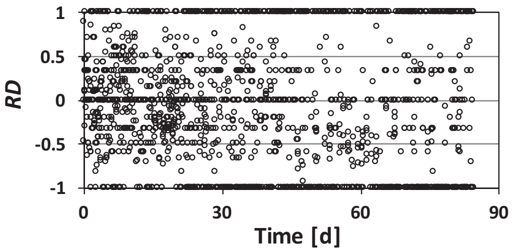


Figure 7: RD behavior for F1 section

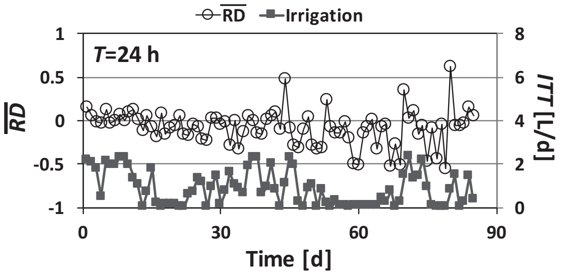
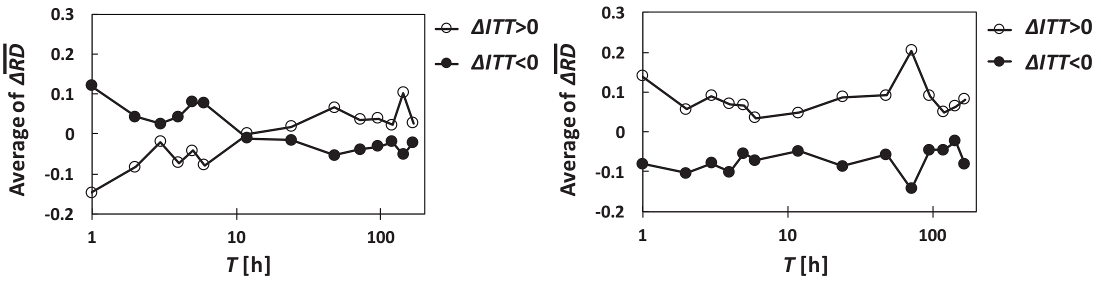


Figure 8: Behavior of $\overline{RD}$ and *ITT* at T=24 h for F1 section



(a) (b)

Figure 9: Relationship between *T* and the average of $\Delta\overline{RD}$ when *ITT* was increased ($\Delta ITT>0$) and decreased ($\Delta ITT<0$) at (a) F1 and (b) F2 section.

To identify the influence of the irrigation change on the *RD*, the change of $\overline{RD}$ against the fluctuation of irrigation time was investigated when T was varied from 1 to 168 h. Firstly, the differential value of $\overline{RD}$ and ITT from the previous period in each section $\Delta \overline{RD}$ and ΔITT was calculated. Then, the average values of $\Delta \overline{RD}$ for $\Delta ITT>0$ and $\Delta ITT<0$ were derived, respectively to find the trend of $\Delta \overline{RD}$ against the fluctuation of ITT. The behaviors of the average value of $\overline{RD}$ when $\Delta ITT>0$ and $\Delta ITT<0$ in F1 and F2 sections were shown in figure 9.

The $\Delta \overline{RD}$ showed the reverse polarity to the ΔITT when T<12 h in F1 section while the polarity of $\Delta \overline{RD}$ coincided with that of ΔITT regardless of T in F2 section. The cavitation rate (AE rate) is decreased usually after the irrigation when the drought stress is eased because the amount of the irrigation is increased. Hence, a well-irrigated plant should demonstrate negative value of $\Delta \overline{RD}$ when $\Delta ITT>0$ in short period as shown in F1 section. Furthermore, the average values of the irrigation time of C, F1 and F2 sections were 709, 347 and 54 min/d, respectively. F2 section, therefore, suffered the severe deficit irrigation. These results suggest that the plants of F2 suffered severe drought stress and eventually the behavior of $\Delta \overline{RD}$ was different between F1 and F2 in short term.

On the other hand, figure 9 also indicate that there is the positive relation between the *RD* and the amount of irrigation in long period for both of F1 and F2. Such a tendency might be related to the growth of the examined plants because the increase of the amount of irrigation (fertilizer) should promote the plant's growth following the increase of transpiration rate which increases the cavitation vulnerability.

The $\Delta \overline{RD}$ was related to the yield YD and the average sugar contend AS of the fruits after experiment as shown in figure 10. The *YD* was decreased compared with F1 section while *AS* was not changed as shown in figure 10. Consequently, these results suggest that $\overline{RD}$ could be controlled by the irrigation control if the polarity of $\Delta \overline{RD}$ against ΔITT was inverted in short period as observed in F1 section. Furthermore, the control of $\overline{RD}$ can be expected to optimize of *YD* and *AS* of tomato plants. The effect of irrigation control using RD on the improvement of yield and sugar content of fruits in tomato cultivation, therefore, will be studied in future works.

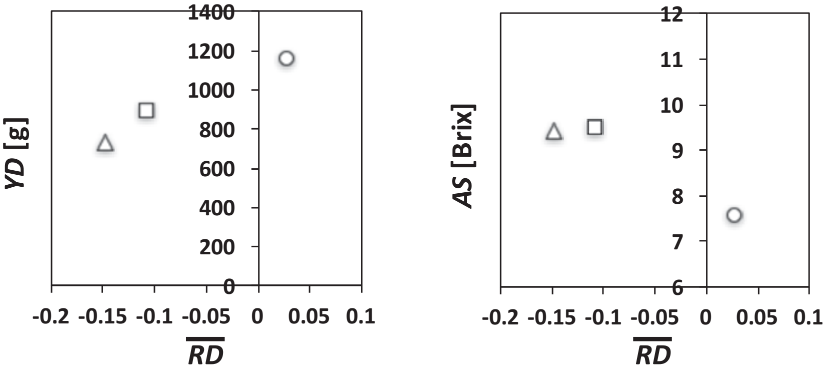


Figure 10: Influence of $\overline{RD}$ on yield (*YD*) and average sugar content (*AS*) of fruits when T is whole measurement period. Circles, squares and triangle represent C, F1 and F2, respectively.

4 CONCLUSTIONS

This study investigated the influence of the irrigation condition on the behavior of the AE change ratio before and after irrigation *RD* as the irrigation response of a tomato plant. The hydroponic cultivation system for tomato plants with high frequency irrigation was fabricated and the AEs at the stem of tomato plants was continuously were detected during cultivation. The daily average value of $\overline{RD}$ was slightly related to the irrigation time though the hourly value of RD was largely scattered. The change of $\overline{RD}$ showed the same polarity to the fluctuation of irrigation time when calculating period T was longer than 12 h when the irrigation time was fluctuated (F1 and F2 sections). On the other hand, The change of $\overline{RD}$ showed the different tendency between the F1 and F2 sections while the yield of the fruits of F2 was decreased compared with F1. Consequently, *RD* could be controlled by fluctuating the irrigation condition unless the plants suffers severe deficit-irrigation and might be useful parameter to optimize the yield and sugar content of the fruits of tomato plants.

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