Early Detection of Water Stress in Tomato Plants
Based on Projected Plant Area

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Early detection of water stress in tomato plants is required for the precise irrigation control to produce high-brix tomato fruits. For this purpose, we have developed a new water stress detection technique based on the projected plant area calculated from digital color images captured by a commercially available, inexpensive, digital still camera. As a first step, the effectiveness of using the projected plant area of tomato plants as a water stress index was confirmed by measuring the projected plant area along with other plant physiological information, e.g. leaf temperature, water potential, transpiration rate, and photosynthetic rate. Next, an image processing algorithm for the automated calculation of the projected plant area from digital color images was established using the discriminant analysis method. Furthermore, the most effective measurement angle of the projected plant area for the early detection of water stress was examined and measurement at an angle of 90° was proved to be the most sensitive to water stress in the tomato plant, i.e. wilting. The features of this technique are the stability of the projected plant area as an index of water stress, the low cost of the measurement equipment, and easy installation of the system. These features suggest that this technique can be introduced to commercial greenhouses to detect water stress in tomato plants and to be used for irrigation control for the production of high-brix tomatoes.

Keywords: digital still camera, high-brix, high sugar content, imaging, irrigation control, stress diagnosis

INTRODUCTION

Presently, the needs of consumers for agricultural products are diversified and specialized. A sweet-tasting tomato, called “fruit tomato,” “high sugar content tomato”, and “high-brix tomato”, is one of the most popular products with a high market demand and a high selling price; high-brix tomatoes from famous producers have reached ¥10,000/kg. Such high-brix tomatoes are produced by keeping the tomato plants under a moderate water stress (drought stress) condition that is often induced by non-irrigation treatment at the farm level. The high-brix tomato producers control irrigation appropriately to keep the tomato plants under the moderate water stress condition by using visual cues and experience, i.e. the producers detect the water stress in plants based on the changes in a plant’s appearance, “wilting”. If we can detect the water stress in tomato plants using objective sensors rather than subjective criteria, irrigation for the high-brix tomato production can be controlled automatically.

Water stress in plants can be detected by measuring leaf water potential, transpiration rate, leaf

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temperature, and photosynthetic rate (Hashimoto et al., 1984; Iwao and Takano, 1988a, 1988b; Nakahara and Inoue, 1997; Jones and Leinonen, 2003). However, for the continuous monitoring of water status of tomato plants for high-brix tomato production, water stress detection must be performed in non-destructive and non-contact ways. Several studies have been done for the detection of water stress in plants by using various sensors and measuring techniques without touching the plant. Oishi and Ishida (1994) and Nishina et al. (2000) detected water stress in tomato plants by measuring the diameter of the stem with a laser ranger (see Fig. 1). Kurata and Yan (1996) reported a correlation between water potential and the inclination of the tomato plant rachis measured by an imaging technique. Furthermore, Foucher et al. (2004) detected water stress in potted *Forsythia* by morphological changes determined with an image analysis technique. However, these measurement techniques require expensive equipment or complex measurement procedures, so that these techniques seem unsuitable for the detection of water stress in tomato plants in a commercial greenhouse.

A water stress detection technique suitable for use in a commercial greenhouse should satisfy the following requirements: (1) the water stress index must be stable, (2) the measurement should be performed by using inexpensive materials, (3) the water stress detection must be done automatically, and (4) water stress should be detected as early as possible. To meet these requirements, we have developed a new technique for detecting water stress in tomato plants based on projected plant area calculated from a digital color image that is captured by a commercially available, inexpensive, digital still camera (Nishina et al., 2004; Nishina et al., 2005). In this review, we introduce several steps to achieve the early detection of water stress in tomato plants with this technique. First, we present the effectiveness of using the projected plant area as an index of water stress, which was examined by measuring the projected plant area along with other plant physiological information: leaf temperature, water potential, transpiration rate, and photosynthetic rate. Second, the automation of the projected plant area calculation is confirmed. Finally, the most effective measurement angle of the projected plant area for the early detection of water stress is discussed.

**PROJECTED AREA OF A TOMATO PLANT FROM A LATERAL VIEWPOINT AS AN INDEX OF WATER STRESS**

Figure 2 shows a typical set of color images of a tomato plant (*Lycopersicon esculentum* Mill. cv. ‘House momotaro’) (A) and the projected area of that tomato plant in Fig. 2-A (B). The color image (Fig. 2-A) was captured with a digital still camera (model D100; 3008 × 2000 pixels, Nikon Corporation, Tokyo, Japan) from a lateral viewpoint. The projected area, i.e. the black area shown in Fig. 2-B, was determined manually using image processing software (Adobe Photoshop 6.0, Adobe Systems, San Jose, USA) (Nishina et al., 2004). Then, the number of the pixels within the projected area was used as the relative projected area of the tomato plant in this experiment. The tomato plant was grown in a greenhouse for 8 weeks from November 10 and watered daily with

![Fig. 1](image-url)  
**Fig. 1** Diurnal change in the stem diameter of the upper part of tomato plant. The upward arrow indicates irrigation event (Nishina et al., 2000).
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Fig. 2  A color image of tomato plant taken by digital photograph (A) and the projected area of the tomato plant (Black area of B). The projected area was determined manually with image processing software.

Fig. 5  Digital color image of tomato plant captured by digital still camera in lateral view (A), color (hue) histogram of the digital color image of A (B), changes in interclass variance of the color histogram of B (C) and the plant area extracted by using threshold (hue=146°) indicated by a double arrow and dotted line in B and C (D).

A nutrient solution (the electrical conductivity of the nutrient solution was changed from 1.2 to 2.0 mS cm⁻¹ depending on the growing stage) before starting the non-irrigation treatment. The tomato plant was 1.3 m high and 0.4 m wide. Figure 3 shows the changes in the projected area ratio (A), transpiration rate (B), leaf temperature (C), leaf water potential (D), and photosynthetic rate (E) during non-irrigation treatment for three continuous sunny days in January, when solar radiation reached 0.6 kW m⁻² at noon. The non-irrigation treatment was performed in a greenhouse in which the air temperature and relative humidity were approximately 23°C and 40% during the days and about 13°C and 60% at nights during the treatment period. The projected area ratio (PROᵣ) (Fig. 3-A) was derived by the following equation:

\[
PROᵣ = \frac{PROᵣ}{PROᵢ}
\]

in which PROᵢ is the initial value of the projected area of the tomato plant at the beginning of this experiment and PROᵣ is the measured projected area at each measuring time point during the
Fig. 3  A typical time course of projected area ratio (A), transpiration rate (B), leaf temperature (C), leaf water potential (D) and photosynthetic rate (E). The time course was measured during three continuous sunny days in January. The upward arrow indicates irrigation events.

experiment. Hence, PRO$_x$ ranges from 0 to infinity (Nishina et al., 2004). Transpiration rate (Fig. 3-B) was measured by a weighing method with a high precision electric balance (model GP-20K, A & D Company, Limited, Tokyo, Japan). Leaf temperature (Fig. 3-C) was measured with a thermograph (model TH3102; 8 to 13 $\mu$m, NEC San-ei Instruments, Ltd., Tokyo, Japan) having a temperature resolution of 0.1$^\circ$C. Leaf water potential was measured with a pressure chamber (model 600, PMS Instruments Company, Albany, USA). The photosynthetic rate of the leaves was measured with a portable photosynthesis measuring system (model LI-6400, LI-COR, Lincoln, USA).

During the initial two days of the non-irrigation treatment, no significant difference between the control and the non-irrigation-treated tomato plants was observed. At 11:00 on the third day, the projected area ratio of the non-irrigation-treated plant began to decrease compared with the control (Fig. 3-A). At the same time, a decrease in transpiration rate and an increase in leaf temperature were observed in the non-irrigation-treated plant (Fig. 3-B and C). At 15:00 on the third day, the wilting of the non-irrigation-treated plant reached a critical level; the plant was then irrigated, which is indicated by an upward arrow in Fig. 3-A. At that time, the projected area ratio of the
non-irrigation-treated plant reached 0.7. Just before the irrigation, slight decreases in leaf water potential and photosynthetic rate were also observed in the non-irrigation-treated plant (Fig. 3-D and E). This result suggests that the projected area of tomato plants may be used as an effective index of water stress (Nishina et al., 2004).

AUTOMATION OF THE PROJECTED AREA MEASUREMENT WITH THE DISCRIMINANT ANALYSIS METHOD

Figure 4 shows a schematic of the discriminant analysis for the determination of threshold value (k). The discriminant analysis automatically determines a threshold value (k), which divides a bimodal histogram into two groups (Classes 1 and 2, shown in Fig. 4) with maximizing of the interclass variance \[ \sigma^2(k) \] of the two groups (Fig. 4). The interclass variance is calculated with the following equation:

\[
\sigma^2(k) = \omega_1 (\mu_1 - \mu_2)^2 + \omega_2 (\mu_2 - \mu_1)^2
\]

in which \( k \) is threshold value for dividing the bimodal histogram into two groups (Class 1 and Class 2), \( \mu_1 \) is an average of Class 1, \( \mu_2 \) is an average of Class 2, \( \mu_1 \) is an average of the whole histogram, \( \omega_1 \) is the ratio of the frequency of Class 1 to the frequency of the whole histogram, and \( \omega_2 \) is the ratio of the frequency of Class 2 to the frequency of the whole histogram (Tori, 1996). The color (hue) histogram of a digital color image of a tomato plant with a blue background shows such a bimodal histogram, so we used the discriminant analysis method for automatic determination of the plant area within a digital color image (Nishina et al., 2005).

Figure 5 shows a digital color image of a tomato plant with a blue background captured by a digital still camera (model DSC-P73; 2304 × 1728 pixels, Sony Corporation, Tokyo, Japan) at a lateral view (A), a color (hue) histogram of that digital color image (B), changes in the interclass variance of that color histogram (C), and the plant area extracted by using a threshold (hue = 146°), which was automatically determined by the discriminant analysis described above and which is indicated by a two-headed arrow and dotted line (D). A clear bimodal distribution of hues of the digital color image can be recognized in the color histogram. The interclass variance of the color histogram shows a single-peaked pattern (Fig. 5-C). Therefore, the threshold value, i.e. hue = 146°, can be determined automatically (Fig. 5-B and C). Using the threshold value, the plant area represented in green was clearly extracted (Fig. 5-D) and the pixel number within the plant area could be used as a relative value of the projected plant area to diagnose the water stress in the tomato plant (Nishina et al., 2005). This series of image processing procedures was created using Microsoft Visual Basic 6.0 image processing software (Microsoft Corporation, Tokyo, Japan).

EXAMINATION OF THE IMAGING ANGLES SUITABLE FOR EARLY DETECTION OF WATER STRESS IN TOMATO PLANTS

For the irrigation control, water stress in tomato plants should be detected as early as possible. In this section, the most effective measurement angle of projected plant area for the early detection of water stress is examined. Figure 6 shows a schematic diagram of digital color imaging with four

![Diagram](image-url)
digital still cameras (model DSC-P73; 2304 × 1728 pixels, Sony Corporation, Tokyo, Japan) at four different angles with respect to the horizontal plane: 0°, 30°, 60°, and 90°. The cameras were fixed on the platforms and color images of a tomato plant with a blue background were captured at hourly intervals. The tomato plant (Lycopersicon esculentum Mill. cv. ‘House momotaro’) used in this experiment was 8 weeks old and had a height of 1.5 m and a width of 0.4 m. Water stress in the tomato plant was induced by non-irrigation treatment. This experiment was performed in a greenhouse (air temperature and relative humidity were approximately 20°C and 40% during the days and about 13°C and 60% at nights) over four consecutive sunny days in January 2005, i.e. solar radiation reached 0.6 kW m⁻² at noon.

Figure 7 shows the changes in the transpiration rate (A), leaf temperature (B), and projected area ratio (C) during the non-irrigation treatment. The control plant was watered daily and kept in a well-watered condition. Furthermore, Fig. 8 shows the images of the projected areas of the non-irrigation-treated plant measured at angles of 0° and 90°; these images were obtained at the time points indicated as downward arrows with the lower case letters (a to d) in Fig. 7-C. The value in parentheses in Fig. 8 represents the projected area ratio at the time.

During the initial two days of the non-irrigation treatment, no significant difference between the control and the non-irrigation-treated tomato plants was observed at every measuring angle. A small difference in transpiration rate between the control and the non-irrigation-treated plants did not seem due to water stress because the leaf temperatures of these two plants were almost the same. At that time, the values of the projected area ratio remained at more than 0.95. Figure 8-a also shows that the non-irrigation-treated tomato plant was in a well-watered condition and the appearance was healthy.

At 11:00 on the third day, the projected area ratios measured at angles of 60° and 90° started to decrease. Especially, the projected area ratio measured at 90° showed a rapid decline and reached to 0.7 within 1 h (Fig.7-C). At the time, an increase in leaf temperature and a decrease in transpiration rate were observed in the non-irrigation-treated plant (Fig. 7-A and B). These phenomena mean that water stress had begun to occur in the non-irrigated plant at the time (Jones et al., 2003). On the other hand, the projected area ratios measured at angles of 0° and 30° did not show any changes and remained at a constant value, approximately 1 (Fig. 7-C). At that time, the changes in appearance were not easy to detect visually and a very little change could be recognized by comparing images of Fig. 8-a and b measured at an angle of 0° (Fig. 8-b).

In the morning on the fourth day, obvious differences between the control and the non-irrigation-treated plants were observed in the leaf temperature and the transpiration rate. The leaf

![Fig. 6](image_url) Schematic diagram of digital color imaging with four digital still cameras indicated circles at four different angles.
Fig. 7  Time course of leaf temperature (A), transpiration rate (B) and projected areas measured at different angles (C) during the experimental period. The downward arrows and lower case letters indicate representative time points for which projection images are shown in Fig. 8.

temperature of the non-irrigation-treated plant was significantly higher than that of the control (Fig. 7-A) and the transpiration rate of the non-irrigation-treated plant reached its minimum level (Fig. 7-B). These observations meant that the non-irrigation-treated plant was exposed to the significant water stress (Jones et al., 2003). At that time, the projected area ratios measured at angles of 60° and 90° showed significant low values: 0.62 for 60° and 0.45 for 90° (Fig. 7-C). However, the projected area measured at an angle of 0° was 0.99 (Fig. 7-C), although significant wilting could be easily seen in the non-irrigation-treated plant (Fig. 8-c). At noon on the fourth day, the wilting of the non-irrigation-treated plant reached a critical level (Fig. 8-d) and the plant was then irrigated (represented as a downward arrow labeled “d” in Fig. 7-C). At that time, all projected area ratios decreased to less than 0.8 (Fig. 7-C). Particularly, the decrease in the projected area ratio measured at an angle of 90° was remarkable and the value reached to 0.22 at the time of irrigation (Fig. 7-C). After irrigation, the leaf temperature of the non-irrigation-treated plant decreased to the control level and the projected area ratios increased quickly (Fig. 7-A and C).

This experiment proved that the most effective measuring angle of projected plant area for the early detection of water stress in tomato plants is 90° relative to the horizontal plane because the projected area measured at a higher angle, 60° and 90° in this experiment, declined quickly as the plant wilted slightly, while the projected area measured at lower angles, 0° and 30° in this experiment, did not show any changes with slight water stress (Nishina et al., 2005). This finding seems to be due to the wilting process of tomato plants. The wilting process of tomato plant can be classified into two stages. In the first stage of wilting, the leaves hang down, although the wilting of the leaflets is not significant (see Fig. 8-b). Afterward, the leaves hang down more and the wilting of the leaflets becomes increasingly prominent in the second stage (Fig. 8-d).
CONCLUSION

In this article, we introduced a new water stress detection technique by monitoring the projected area of a tomato plant. This technique has the following merits: (1) the projected area of a tomato plant is a very stable indicator that would not be affected by temporary changes in environmental factors, (2) the projected area can be measured continuously and automatically with an inexpensive, commercially available, digital still camera, and (3) this technique is able to detect water stress in tomato plants at an early stage by measuring at an angle of 90° with respect to the horizontal plane. These merits suggest that this technique can be introduced to commercial greenhouses to detect water stress in tomato plants and used for irrigation control for the production of high-brix tomatoes. We are presently developing an irrigation control system based on this water stress detection technique and trying to produce high-brix tomatoes in a commercial greenhouse.

REFERENCES

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