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Remote and Visualized Sensing of Physiological Depression in Crop Plants with Infrared Thermal Imagery

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Abstract
An infrared thermal imagery was measured concurrently with physiological status in stressed and non-stressed maize and wheat canopies. Each thermal image, composed of 512 (H)×240 (V) pixels with a sensitivity of 0.05°C, was obtained with an infrared thermography system from a distance of 5 to 20 m. The stress-induced physiological depression in photosynthesis was accompanied by an increase in the canopy-surface temperature, which was visualized clearly on the pseudo-color thermal images, while no visible changes were observed directly from the distance. The maximum difference in mean surface temperatures of the stressed and non-stressed parts of the canopy was no less than 4.2°C in maize and 3.1°C in wheat. The infrared imagery was effective for detecting physiological depression or for comparing various canopies in their physiological status on a remote and real-time bases.

Discipline: Agro-meteorology
Additional key words: canopy temperature, environmental stress, image analysis, transpiration

Introduction

It is essential to detect environmental stresses as early as possible so that management practices can be instigated to minimize negative effects of such stresses on the growth or yield of crops. Irrigation managements, in particular, require accurate information on crops and soil water status for the efficient water use[2,18]. However, measurements on relevant traits such as leaf water potential of individual leaves are labor-intensive or subject to errors because of limited replications[15,17]. Hence, non-destructive and instantaneous methods are required for assessing efficiently and effectively the physiological status of crop plants in the field. A remote means such as infrared thermometry, in particular, has great advantages, since it is non-destructive, real-time and quantitative[7,11,17]. Remotely sensed canopy temperatures have been used as an input to stress-indices such as canopy- and air-temperature differential, stress-degree-day index, and crop water stress index (CWSI)[1,4,11,12]. Millard et al.[16] attempted to relate temperature data from an airborne thermal scanner with a stress-degree-day index in differentially irrigated wheat, suggesting that further research be necessary to correlate the canopy temperature with physiological parameters. In the previous studies so far undertaken, however, no physiological data have been taken on both stressed and non-stressed crop canopies simultaneously with infrared imagery measurements.

The applicability of infrared thermal imagery was thus examined and confirmed for detecting physiological changes in photosynthesis and transpiration under field conditions[10]. This paper presents a brief account on the results of the examination.

Materials and methods

Infrared thermal images of maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) canopies were obtained by a thermography system (JOEL, JTG 3200)[5]. Several parts of each canopy received a root-reducing treatment which was carried out by cutting a root system with a thin metal plate at the depth of approximately 20 cm. That treatment is expected to simulate some damages or stresses in the root system caused by intertillage, ridging, root rot, and/or water deficit, which might give no apparent changes in plant stands as shown in the photographs of Fig. 2. Treated parts of a canopy were denoted by "stressed" in comparison with the surrounding "non-stressed" part of the canopy. The distance from the thermal camera to the target canopy was 5 m for wheat and 20 m for maize. Physiological status such as photosynthesis was measured with a portable gas analyzer system (ADC) on leaves near the top of each canopy. The field of view and resolution of the thermographic camera was 25° (H) × 23°(V) and 0.05°C, respectively. Each thermal image, composed of 512(H) × 240(V) pixels, was displayed on a monitor and recorded in a video tape every 8 sec.

Results and discussion

Fig. 1 shows the changes in physiological status and canopy-surface temperature in the maize canopy, which temperature was derived from infrared thermal images. Before the treatment, the maize canopy was so uniform that no spatial differences were found in physiological and thermal status and appearance as well. After the treatment, however, the stressed part of the canopy changed greatly in its physiological status. Photosynthesis, transpiration, and stomatal conductance in the stressed canopy were depressed throughout the rest of the day. Those physiological changes were accompanied by an increase in the canopy-surface temperature. The infrared surface temperature in the stressed canopy was kept consistently higher than that in the surrounding non-stressed canopy. The relative increase in leaf temperature was attributed to the depressed transpiration, while the leaf temperature is also influenced by the other factors such as air temperature and humidity. The maximum difference in the mean surface temperatures between the stressed and non-stressed parts of the canopy was no less than 4.2°C. Vertical bars in Fig.1 indicate 95% confidence intervals. Bars in Fig. 1 (d) are too short to appear out of each symbol, although bars in Fig. 1(a)–(c) are fairly long especially in the stressed-canopy. Hence, physiological changes in crop plants can be detected from a distance on a real-time basis with a preferable confidence.

The typical thermal images of a maize canopy and

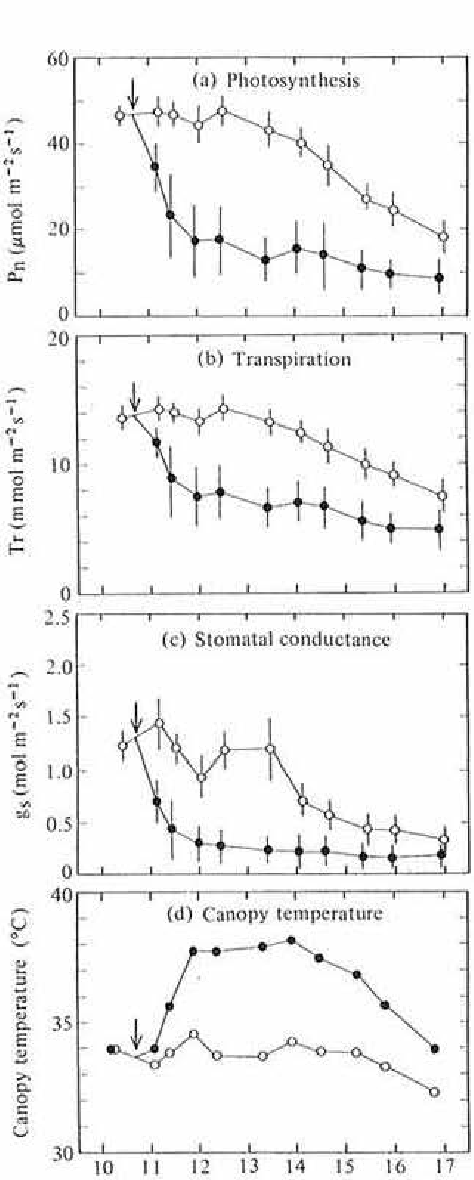
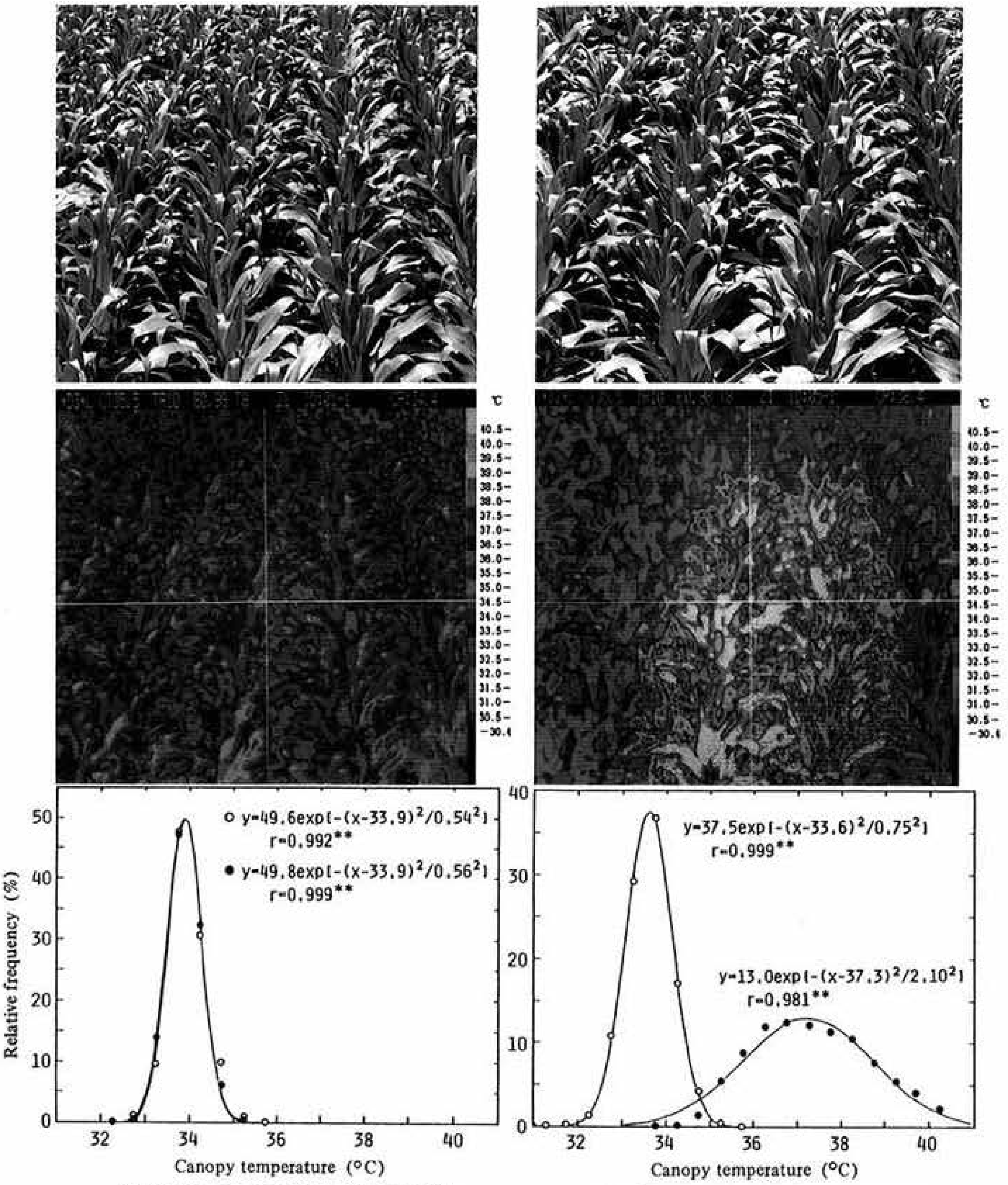


Fig. 1. Changes in physiological status in a maize canopy (a)–(c), and in mean surface temperature by infrared thermometry (d)
Arrows in the figures indicate the timing of stress-treatment, which was carried out by cutting a root system at the soil-depth of 20 cm.
Vertical bars in the figures indicate 95% confidence intervals. Bars in the figure (d) are too short to appear out of each symbol.



(a) Before stress-treatment [Time=10:27]
Physiological status were:
○: P_n=46.5 Tr=13.6 g_s=1.25
●: P_n=46.9 Tr=13.5 g_s=1.21

(b) After stress-treatment [Time=12:20]
Physiological status were:
○: P_n=47.7 Tr=14.3 g_s=1.19
●: P_n=17.8 Tr= 7.8 g_s=0.28

○ : Non-stressed canopy ● : Stressed canopy

Fig. 2. Infrared thermal images of a maize canopy before (a) and after (b) the stress-treatment
Upper: Natural color photographs, Middle: Thermal images, Lower: Temperature-frequency distributions both in stressed and non-stressed canopies.
The total pixel number for each distribution curve was 3,025.
P_n: Photosynthesis (μmol $m^{-2} s^{-1}$), Tr: Transpiration (mmol $m^{-2} s^{-1}$),
g_s: Stomatal conductance (mol $m^{-2} s^{-1}$).
** Significant at 1% level.

their temperature-frequency distributions are shown in Fig. 2 with their natural-color photographs and concurrent physiological parameters. Little visual and thermal differences were found over the entire canopy before the treatment, as shown in Fig. 2(a). Fig. 2(b), however, shows an obvious difference in the surface temperature between the stressed and non-stressed parts of the canopy at the time about 2 hr after the treatment. The mid-right part of the view-field is the stressed part and surrounding parts are the non-stressed parts of the canopy. A square area (3,025 pixels) was selected each from the stressed and non-stressed parts of a thermal image for calculating the temperature-frequency distribution. The frequency-distribution curve of the stressed part shifted greatly from that of the non-stressed part of the canopy, which was visualized clearly on the pseudo-color thermal image. The stressed part is indicated with bright colors in the thermal image, while the non-stressed or healthy part with cool colors. No visible differences, however, were observed directly from the distance between the stressed and non-stressed parts of the canopy as shown in the natural-color photographs.

The similar result was obtained on wheat canopies (Fig. 3). The temperature-distribution curve in the stressed part of the canopy shifted gradually toward right after the stress-treatment from that in the non-stressed part, while both curves almost overlapped before the treatment. The spatial difference in canopy temperature was visualized clearly on the pseudo-color thermal image. Physiological activities such as photosynthesis decreased in accordance with increase in surface temperature. The difference in mean temperatures of each part of the canopy reached 3.1°C, although little visible differences were found between the stressed and non-stressed parts of the canopy from the distance.

The infrared thermal imagery is, thus, highly effective in detecting physiological depression or comparing various canopies in their physiological status, since the micro-meteorological conditions over a canopy are approximately the same. The similar results were obtained in water-stressed soybean and rice canopies as well as in a diseased cabbage canopy (Inoue, unpublished). This fact implies that the infrared imagery could be applicable for detecting various kinds of enviornmental stresses. On the basis of those experimental results, a remote sensing

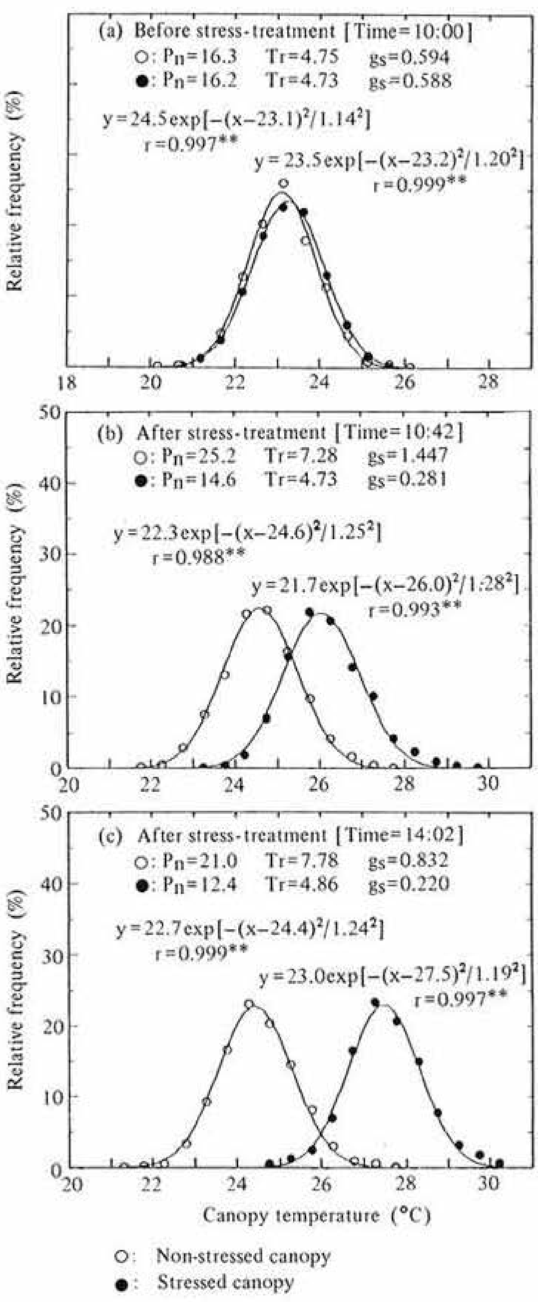


Fig. 3. Temperature-frequency distributions obtained from infrared thermal imagery for stressed and non-stressed wheat canopies

Abbreviations and units are the same as those in Fig. 2.

The total pixel number for each distribution curve was 2,800.

** Significant at 1% level.

method has also been presented for estimating leaf transpiration and stomatal resistance using the infrared temperature as an input to a biophysical model[6,9].

In regard to the use of infrared thermometers, care should be taken to avoid the complication of the soil background, especially when sparse vegetation is being measured. This is because most temperature-based stress indices assume that only vegetation temperatures are measured. Several empirical or theoretical methods are proposed for extracting the foliage temperature from the measurement on an incomplete crop cover[3,14]. A thermographic method, however, can provide temperature data from vast numbers of points (e.g., 122,880 pixels with the present system) on a canopy or the most probable average for the specified area. Those data would enable to extract the leaf temperature alone from a thermal imagery of a sparse crop, since soil- or head-temperatures could be distinguished separately from leaf temperatures[8].

The sensitivity of sensors mounted on a satellite which can observe agricultural fields from the height of 800 km is around 0.1°C. Such high sensitivity indicates that the temperature data from satellites could provide some useful information on the physiological status of field crops. Jackson et al.[13], for instance, demonstrated that remote sensing techniques using temperature data from an aircraft were applicable for estimating the evapotranspiration from agricultural fields. Thus, the abovestated results provide a basis not only for the crop diagnostics on the ground-level but also for the long-distance or wide-area remote sensing of environmental stresses in the field.

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