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Effects of Water Stress on Leaf Temperature and Chlorophyll Fluorescence Parameters in Cotton and Peanut

Shahenshah and Akihiro Isoda

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Abstract: A greenhouse experiment was conducted to study the adaptive mechanism of cotton and peanut under water stress conditions. Five cultivars of cotton and six cultivars of peanut were grown in pots under two water levels; the control and water stress condition, where irrigation water equal to 100% and 50% of the daily transpiration, respectively, was daily applied. Peanut showed a greater increase than cotton in leaf temperature (T_L) and non-photochemical quenching (NPQ) and a greater decrease in water content per unit leaf area (WCLA), chlorophyll content and maximum quantum yield of photosystem II (PSII) (Fv/Fm) in the water stress condition. On the other hand, the water stress lowered the transpiration rate, actual quantum yield of PSII ($\Delta F/F_m$) and leaf area (LA) more in cotton than in peanut. Cotton showed greater reduction in LA along with little reduction in the root dry weight (RDW) leading to high WCLA, while peanut showed increased RDW with little reduction in LA under the water stress condition. It was concluded that photodamage and down regulation in PSII were induced by water stress, coinciding with increases in leaf temperature regulated mainly by transpiration. Peanut showed more severe photodamage in PSII than cotton under the water stress condition.

Key words: Chlorophyll fluorescence, Cotton, Leaf temperature, Peanut, Transpiration, Water stress.

Under conditions of water scarcity, plants are often subjected to a high temperature, which increases their vulnerability to light stress and consequently the photoinhibition (Carpentier, 1996). Supraoptimal leaf temperatures limit carbon dioxide fixation through limitation in activity of photosynthetic enzymes such as Rubisco (Berry and Björkman, 1980; Kobza and Edwards, 1987). When carbon dioxide fixation is limited, the rate of active oxygen formation increases in chloroplasts as excess excitation energy, which would either become manifest as oxidative damages to the plant or would result in activation of defense and repair mechanisms which could prevent such damage from occurring (Smirnoff, 1993). Plants have several mechanisms for avoiding and/or dissipating the excess excitation energy non-destructively. Some plants regulate incident solar radiation on leaf by paraheliotropic leaf movement (Begg and Torsell, 1974; Ehleringer and Forseth, 1980), production of a thicker cuticle (Chatterton et al., 1975; Saneoka and Ogata, 1987) and pubescence on the leaf surface (Wooly, 1964; Johnson, 1975). In addition, most of the plants adapt themselves to water stress by dissipating the excess excitation energy thermally with the down regulation of photosystem II (PSII) activity to protect photosynthetic apparatus from photodamaging effect

under water stress often coinciding with high leaf temperature (T_L) (Bilger and Björkman, 1990; Björkman and Demming-Adams, 1994; Inamullah and Isoda, 2005b).

Previously, it was indicated that cotton protected its photosynthetic apparatus from photodamage by keeping its T_L lower through high transpiring ability than soybean under water stress condition (Inamullah and Isoda, 2005a, b). On the other hand, soybean dissipated the excess excitation energy thermally along with the down regulation of PSII activity supported by paraheliotropic leaf movement. Since these experiments were conducted using only one cultivar of cotton and soybean, the diversity of chlorophyll fluorescence parameters in relation to T_L needs to be studied using the different cultivars and/or species. Murata (1981) reported on the CO_2 assimilation rate and radiation use efficiency in various crops. However, there are few reports on the differences in the photochemical reactions in photosynthesis among species, although there are reports for individual species, such as apple (Massacci and Jones, 1990), coffee (Lima et al., 2002), potato (Jeffries, 1994) and wheat (Havaux and Lannoye, 1985). Studies on the varietal and/or crop differences in photosynthetic characteristics will help to understand not only the relationship among these characteristics and but also

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Abbreviations: $\Delta F/F_m$, actual quantum yield of photosystem II; Fv/Fm, maximum quantum yield of photosystem II; NPQ, non-photochemical quenching; RDW, root dry weight; T_L , leaf temperature; WCLA, water content per unit leaf area.

Table 1. Cotton and peanut cultivars used in the experiment.

Cotton	Peanut
Xinluzao 7	Luhua 11
Xinluzao 10	Huayu 22
Xinluzao 26	Huayu 20
Xinshi K-7	Huayu 16
Kangdi 168	Huayu 14
	Qunyu 101

adaptive mechanisms of each species to water stress comprehensively. In this experiment, we investigated the eco-physiological adaptive mechanism of cotton and peanut cultivars under a water stress condition, especially in chlorophyll fluorescence parameters in relation to changes with T_L .

Materials and Methods

The experiment was conducted in the greenhouse at Faculty of Horticulture, Chiba University, Japan. Five commercial cultivars of cotton and six of peanut in China were used (Table 1). Cotton and peanut seeds were sown on 6 June 2007 in the 1/2000a Wagner pots (height 30 cm and diameter 24 cm) and 1/650a styrofoam boxes (length 43 cm, width 36 cm and height 30 cm), respectively. Two irrigation treatments were used for each crop. The pots and boxes were arranged in a randomized complete block design with four replications in a split plot arrangement. Water levels were allocated to the main plot while cultivars to the subplots. Before pot filling, the soil was sieved using 5×5 mm mesh. Fertilizer (3:10:10% = N:P₂O₅:K₂O) was applied at the rate of 30 kg a⁻¹ before sowing. Five and three seeds per pot were sown to ensure the crop stands for cotton and peanut, respectively. After the establishment of seedlings, all were thinned to a single plant per pot and box.

Irrigation treatment was started on 29 July, when cotton was at the square formation stage and peanut was at the flowering stage. Irrigation was applied on daily basis in the evening between 1730 to 1930. In the control and water stress conditions, the irrigation water applied was equal to 100% and 50% of the transpiration, calculated by weighing the pots/boxes with an electronic balance. Evaporation was controlled by covering the soil surface of the pots and boxes with aluminum foil to exclude the effect of evaporation. Water was applied to the pots through small L-shaped PVC pipes (diameter 10 mm) fitted in a small hole in the bottom portion in each pot very near to the base. In the case of styrofoam boxes, water was applied directly to the soil surface near the root zone by taking up the aluminum foil and replacing it again just after the irrigation. Although data were collected for several days, the data collected on 25 August 2007 (the 28th day of water treatment), which was the most suitable sunny weather condition, were used for the chlorophyll

fluorescence parameters and T_L . During data collection, the cotton plants were in the ball formation stage and peanut in the pod filling stage.

Data for T_L and chlorophyll fluorescence parameters were collected on the upper fully expanded leaf. The data regarding T_L , air temperature, air relative humidity and global solar radiation were collected at one-minute intervals from 0600 to 1800 by a data-logger (Eto Denki Inc., Thermodac E, Japan) connected to a personal computer. T_L measuring thermocouples were attached to the abaxial side of leaf/leaflet. Air relative humidity and global solar radiation were measured with a humidity sensor (CHS-UPS, TDK Electronic Co. Ltd, Japan) and global radiation sensor (Model MS-4, Eko Instruments Trading Co., Ltd, Japan), respectively.

Maximum quantum yield of PSII (Fv/Fm, where Fv=Fm-F₀) of the dark adapted leaves and actual quantum yield of PSII ($\Delta F/F'm$, where $\Delta F=F'm-F_t$) of the illuminated leaves were measured using a chlorophyll fluorometer (PAM-2000, Walz, Germany) using a leaf-clip holder (2030-B, Walz, Germany). Fm and F₀ represent the maximum and minimum fluorescence yield of dark-adapted leaves, respectively. F'm represents the maximum fluorescence yield of an illuminated leaf via saturation pulse method, while F_t represents the steady state fluorescence yield, measured at any given time. Fv/Fm was determined before dawn, i.e., before the direct sunlight hit the leaves (around 0300), while data of $\Delta F/F'm$ was collected in the morning (0930–1130), noon (1230–1430) and afternoon (1500–1700). Non-photochemical quenching (NPQ) was calculated as (Fm/F'm)-1 (Bilger and Björkman, 1990).

After the water treatment, all leaf lamina were detached from petioles and weighed to record their fresh weight, which were then dried in an oven for 48 hr at 80°C to take their dry weight. Using the fresh weight (FW) and dry weight (DW) of all the leaves, water content per unit leaf area (WCLA) was calculated according to the following formula;

$$WCLA = (FW - DW) / \text{leaf area}$$

Leaf area (LA) was measured with an automatic area meter (AAM-8, Hayashi Denko Co. Ltd., Japan). Roots were taken out from the pots/boxes and washed gently for root dry weight (RDW). Fine roots were collected by sieving the soil water mixture through a fine mesh screen and weighed after drying in an oven for 48 hr at 80°C.

The data were analyzed using statistical software StatView (SAS, 1999). The significances of differences among cultivars were determined according to Fisher's LSD test. Correlation coefficients were also determined on the selected data using StatView.

Results

1. Transpiration

Figure 1 shows the changes with time in transpiration (transpiration per plant per day) for cotton and peanut

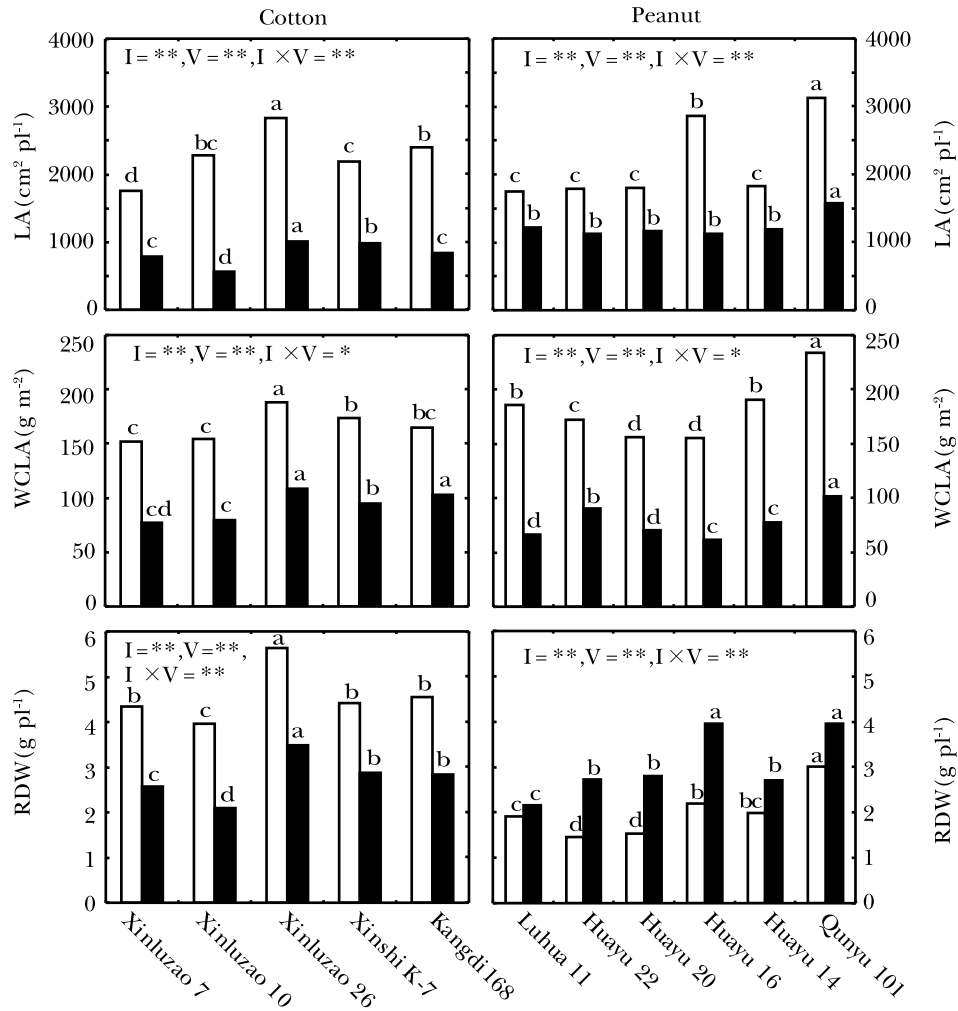


Fig. 2. Leaf area, water content per unit leaf area and root dry weight of cotton and peanut cultivars under the different irrigation treatments.

LA, WCLA and RDW mean leaf area, water content per unit leaf area and root dry weight, respectively. Data are represented as the mean of four replications and were measured at 1800, 25 August 2007.

□, Control; Applied irrigation water equal to the transpiration.

■, Water Stress; Applied irrigation water equal to 50% of transpiration.

Columns representing the same water level with different letters are significantly different at 5% level of probability by Fisher's LSD test. I, V and I×V represent irrigation level, variety and their interaction, respectively. ** and * represent significant differences at 1% and 5% level of probability, respectively.

In both crops, T_L was increased significantly by the water stress. Peanut showed higher T_L than cotton under both conditions. Under the water stress condition, T_L increased by 3.5°C and 4.2°C on the average of cultivars in cotton and peanut, respectively. There were significant varietal differences in T_L in both cotton and peanut. In cotton, Xinluzao 26 maintained T_L lower, while Xinluzao 7 and Xinluzao 10 showed significantly higher T_L than Xinluzao 26 and Kangdi 168 under the water stress condition. In peanut, Luhua 11 showed the highest increase in T_L under the water stress condition.

On the average, cotton had higher SPAD values than peanut under both conditions. The average SPAD value in

cotton under the water stress condition was 12.4% lower than in the control. The water stress reduced significantly SPAD values also in peanut. There was no significant difference between water stress and control in SPAD values in cotton. Among the peanut cultivars, Huayu 20 had a significantly lower SPAD value than the others in the control, while Luhua 11 and Huayu 20 showed lower SPAD values than Huayu 22 and Huayu 16 under the water stress condition.

4. Maximum quantum yield of PSII (Fv/Fm), actual quantum yield of PSII ($\Delta F/F_m$) and non-photochemical quenching (NPQ)

Fv/Fm was significantly affected by the water stress

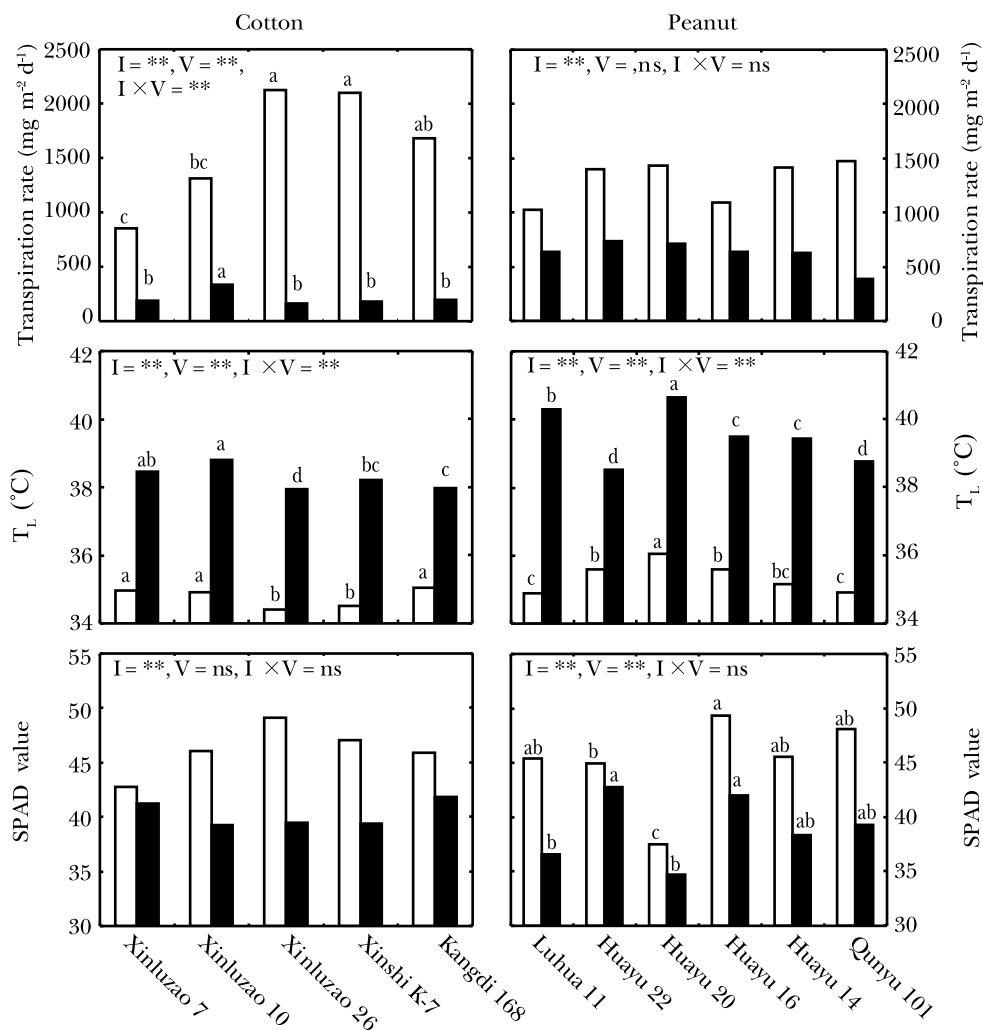


Fig. 3. Transpiration rate, leaf temperature and SPAD value of cotton and peanut cultivars under different irrigation treatments. T_L means leaf temperature. Columns represent means of four replications taken in the morning (0930–1130), noon (1230–1430) and afternoon (1500–1700) on 25 August 2007. □, Control; Applied irrigation water equal to the transpiration. ■, Water Stress (WS); Applied irrigation water equal to 50% of transpiration. Columns representing the same water level with different letters are significantly different at 5% level of probability by Fisher's LSD test. I, V and I×V represent irrigation level, variety and their interaction, respectively. ** and ns represent significant differences at 1% level of probability and non-significant, respectively.

treatment in both cotton and peanut (Fig. 4). Water stress affected the F_v/F_m in peanut more severely than cotton, representing a 12.1% decrease in peanut and 3.0% decrease in cotton. Qunyu 101 had the highest value of F_v/F_m under both water levels and the smallest decrease in F_v/F_m due to the water stress. Luhua 11 and Huayu 20 showed larger decrease in F_v/F_m by 16.0%.

The water stress also affected $\Delta F/F'm$ significantly in both crops, particularly in cotton. Water stress decreased $\Delta F/F'm$ by 44.4% and 31.1% on the average in cotton and peanut, respectively. There was no significant difference in $\Delta F/F'm$ among the cotton cultivars, while significances of varietal differences were observed in peanut. Qunyu 101

had the highest $\Delta F/F'm$ value under both conditions, while Luhua 11 under the control and Huayu 20 under the water stress conditions showed the lowest $\Delta F/F'm$ value.

NPQ was also significantly affected by the water stress treatment in both crops. NPQ was increased by 173% and 176% due to the water stress in cotton and peanut, respectively. In cotton, Xinluzao 26 had the lowest NPQ under both control and water stress conditions, while the highest NPQ was recorded in Kangdi 168 under the control condition and in Xinluzao 7 and Xinluzao 10 under the water stress condition. Xinluzao 26 had lower NPQ values than Kangdi 168 and Xinluzao 7 under the control and water stress conditions. In peanut, Huayu 16,

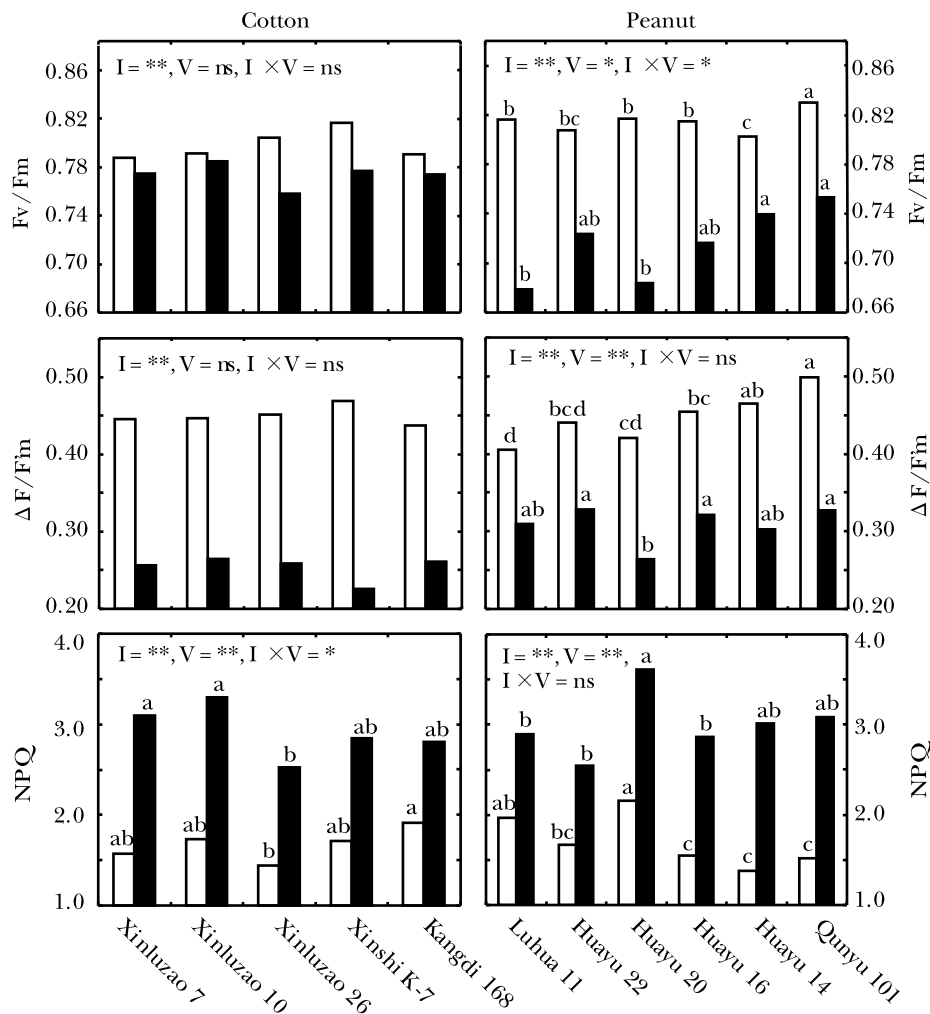


Fig. 4. Maximum quantum yield of PSII, actual quantum yield of PSII and non-photochemical quenching of cotton and peanut cultivars under the different irrigation treatments.

Fv/Fm, $\Delta F/F'm$ and NPQ mean maximum quantum yield of PSII, actual quantum yield of PSII and non-photochemical quenching, respectively. Columns represent four replications taken in the morning (0930–1130), noon (1230–1430) and afternoon (1500–1700) on 25 August 2007 (except Fv/Fm). Fv/Fm data were recorded before dawn (0300–0430).

□, Control; Applied irrigation water equal to the transpiration

■, Water Stress; Applied irrigation water equal to 50% of transpiration

Columns representing the same water level with different letters are significantly different at 5% level of probability by Fisher's LSD test. I, V and I×V represent irrigation level, variety and their interaction, respectively. **, * and ns represent significant differences at 1% and 5% level of probability and non-significant, respectively.

Huayu 14 and Qunyu 101 had significantly lower NPQ under the control, while the highest NPQ was recorded in Huayu 20 under both conditions.

5. Correlations of $\Delta F/F'm$ with Fv/Fm and NPQ and correlations of T_L with Fv/Fm, $\Delta F/F'm$ and NPQ

$\Delta F/F'm$ was affected by Fv/Fm in both crops (Fig. 5), indicating some photodamage in PSII would occur in both crops, especially in peanut. Varietal differences in $\Delta F/F'm$ in peanut in the control and water stress conditions were not dependent on Fv/Fm, while this relationship was significant only in the control in cotton. A highly

significant and negative correlation was observed between $\Delta F/F'm$ and NPQ in both crops under the control and water stress conditions. This suggested that the down regulation of PSII activities would decrease $\Delta F/F'm$. Varietal differences in $\Delta F/F'm$ in both crops were also dependent on NPQ beside the water stress condition in cotton.

A highly significant negative correlation was observed between T_L and Fv/Fm in cotton and peanut (Fig. 6), suggesting higher photodamage in the photosynthetic apparatus of peanut due to increase in T_L . The correlation of T_L with $\Delta F/F'm$ was negative in both crops in the morning,

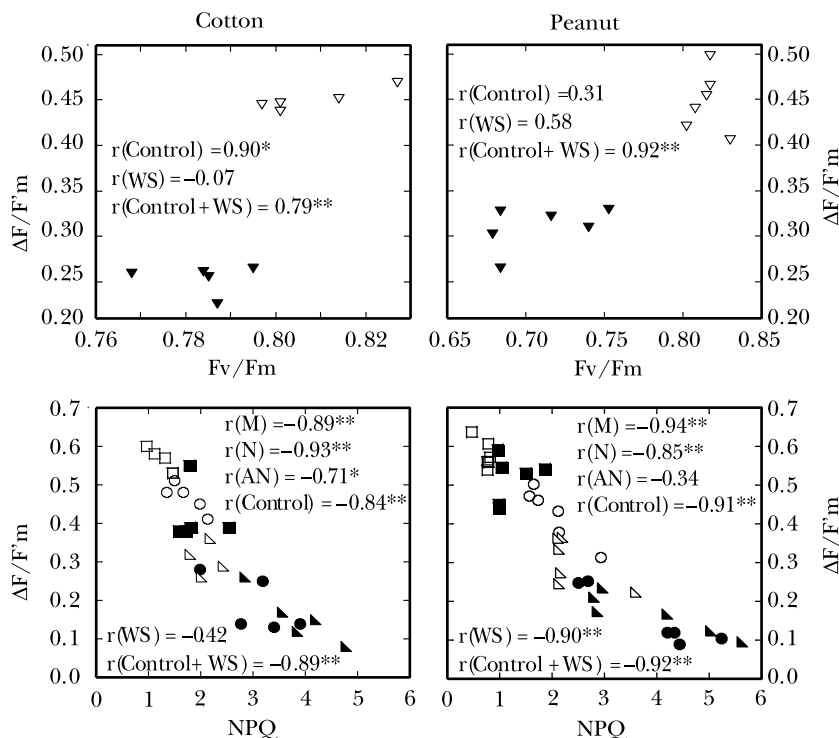


Fig. 5. Correlation of actual quantum yield of PSII with maximum quantum yield of PSII and non-photochemical quenching in cotton and peanut under the different irrigation treatments.

Fv/Fm, $\Delta F/F'm$ and NPQ mean maximum quantum yield of PSII, actual quantum yield of PSII and non-photochemical quenching, respectively. Data were taken before dawn (0300–0430) for Fv/Fm, morning (0930–1130), noon (1230–1430) and afternoon (1500–1700) for $\Delta F/F'm$ and NPQ on 25 August 2007.

▽ EM-Control ○ M-Control △ N-Control □ AN-Control
 ▼ EM-WS ● M-WS ▲ N-WS ■ AN-WS

EM, M, N and AN stand for before dawn, morning, noon and afternoon, while control and WS mean applied irrigation water equal to 100% and 50% of the transpiration, respectively. ** and * represent significance of the differences at 1% and 5% level of probability, respectively.

noon and afternoon. The correlation of T_L with NPQ was positive in both crops except in the afternoon in peanut.

6. Factors related with SPAD, transpiration and WCLA

SPAD value had highly significant positive and negative correlations with Fv/Fm and T_L on the average, respectively, in both crops (Table 2). This suggested the damage of PSII through the decrease in chlorophyll content, which was affected by high T_L under the water stress condition. The varietal differences in Fv/Fm, however, did not depend on SPAD value.

Transpiration rate (transpiration per unit leaf area) affected the differences in T_L between the control and water stress conditions in both crops (Table 3). However, varietal differences in T_L in both crops were not significantly correlated with transpiration rate in both the control and water stress conditions. RDW had significant effects on differences between treatments in both transpiration and WCLA in cotton. In peanut, negative

and no significant relations of RDW with transpiration rate and WCLA, respectively, were found. The varietal differences in transpiration rate and WCLA in both crops were not correlated largely with RDW in both the control and water stress conditions except those in WCLA of cotton, suggesting that the volume of root would not affect varietal differences in transpiration and WCLA.

Discussion

Water uptake was reported to be maximized by increasing root depth and/or water loss minimized by reducing LA, stomatal control and/or paraheliotropic leaf movement (Ludlow, 1989; Bressan, 2002). Several reports have showed that water stress decreased the stomatal aperture, stomatal conductance and transpiration rate (Shimshi, 1963; Li et al., 2004; Inamullah and Isoda, 2005a). In this experiment, the water stress decreased the transpiration rate in both crops (Fig. 1, Fig. 3) with the concurrent decrease in WCLA (Fig. 2). Between crops, a

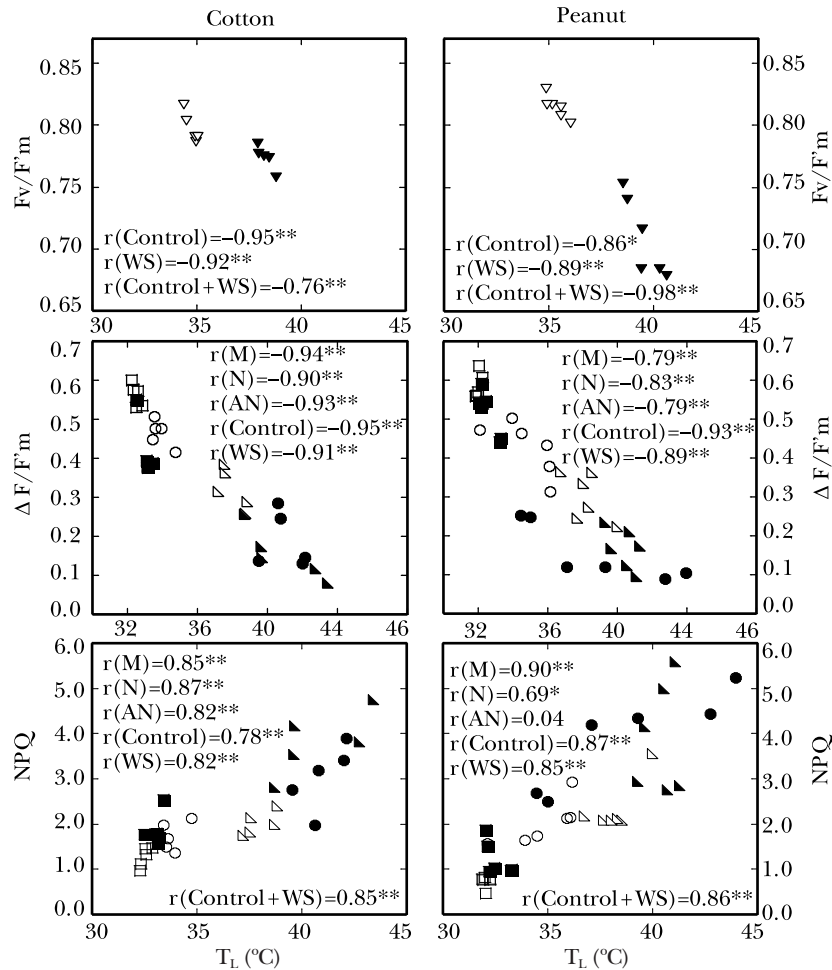


Fig. 6. Correlation of leaf temperature with maximum quantum yield of PSII, actual quantum yield of PSII and non-photochemical quenching in cotton and peanut cultivars under the different irrigation treatments.

T_L, Fv/Fm, ΔF/Fm and NPQ mean leaf temperature, maximum quantum yield of PSII, actual quantum yield of PSII and non-photochemical quenching, respectively. Data were taken before dawn (0300–0430) for Fv/Fm, morning (0930–1130), noon (1230–1430) and afternoon (1500–1700) for T_L, ΔF/Fm, and NPQ on 25 August 2007. T_L with Fv/Fm are means of measurements taken in the morning, noon and afternoon.

▽ EM-Control ○ M-Control ▽ N-Control □ AN-Control
 ▼ EM-WS ● M-WS ▴ N-WS ■ AN-WS

EM, M, N and AN stand for before dawn, morning, noon and afternoon, while Control and WS mean applied irrigation water equal to 100% and 50% of the transpiration, respectively. ** and * represent significance of the differences at 1% and 5% level of probability, respectively.

different reaction to water stress was observed in WCLA, LA and RDW. Peanut showed a greater increase in RDW (Fig. 2), which could maintain a higher LA and transpiration ability than cotton under the water stress condition (Fig. 2). However, RDW in peanut did not show close correlations with transpiration and WCLA (Table 3). The larger root system in peanut under the water stress condition might therefore not be effective for absorbing water. Isoda et al. (1996), and Isoda and Wang (2002) reported that peanut and cotton kept T_L lower by the paraheliotropic leaf

movement and high transpiring ability, respectively. In addition, drastic reduction in LA in cotton resulted in maintenance of high WCLA and reduction in areas exposed to incident solar radiations, leading to lower T_L under the water stress condition as compared with peanut.

In agreement with previous reports (Krause, 1988; Björkman and Demming-Adams, 1994; Chow, 1994; Carpentier, 1996; Maxwell and Johnson, 2000), we found that the high T_L induced by the water stress had negative effects on the efficiencies of PSII. T_L was correlated

negatively with F_v/F_m and $\Delta F/F'm$, and positively with NPQ with high significance (Fig. 6). Significant down-regulation of PSII activities with the increase in thermal dissipation of excess excitation energy under the water stress condition indicated that a larger proportion of the PSII reaction center was still functionally intact in cotton as compared with peanut (Fig. 4). Increase in T_L might have activated the xanthophyll pigments cycle to safely dissipate the excess excitation energy as heat (increase in NPQ) along with down regulation of PSII activity (decrease in $\Delta F/F'm$) (Yamamoto, 1979; Frank et al., 1994; Bilger et al., 1995). There was little down regulation of PSII activity under the water stress condition in peanut (Fig. 4). In turn, severe photodamage might occur in peanut since F_v/F_m was affected more in peanut than in cotton. In addition, we also observed that the water stress significantly reduced the chlorophyll content in both species (Fig. 3), which in turn affected the F_v/F_m as significantly positive

correlation between them (Table 2). Although direct effects of high T_L on destruction of chlorophyll were not clear in this experiment, it is suggested that a high T_L would affect destruction of chlorophyll indirectly through the series of physiological and photochemical reactions, i.e., limitation of carbon dioxide fixation resulted from inactivation of photosynthetic enzymes, then increase of active oxygen induced by excess excitation energy (Berry and Björkman, 1980; Kobza and Edwards, 1987; Smirnov, 1993).

Both the down regulation and photodamage in PSII appear to be affected by the increase in T_L (Fig. 6). Transpiring ability, which has been reported as a key factor in drought tolerance (Kramer, 1983; Isoda and Wang, 2002; Li et al., 2004; Wang et al., 2004), affected T_L also in this experiment (Table 3). Cochard et al. (2002) reported that stomatal conductance is the main mechanism of regulating transpiration. It was also suggested that the water extracting ability of roots would concern stomatal conductance resulting in transpiring ability (Inamullah and Isoda, 2005a). The relationship between transpiring ability (transpiration per unit leaf area) and RDW was not obvious in peanut as compared with cotton (Table 3). It was therefore assumed that other factors beside the water absorbing ability of roots, such as stomatal conductance or hydraulic conductance from root to leaf, would markedly affect the transpiring ability in peanut, although the water absorbing ability of roots depends not only on root volume but also hydraulic conductance from soil to root. As varietal differences, however, T_L was not significantly correlated with transpiring ability in either the control and WS treatments especially in peanut (Table 3). It was therefore suggested that factors other than transpiring ability, such as heliotropic leaf movement, might be related with varietal differences in the regulation of T_L in cotton (Wang et al., 2004) and peanut (Isoda et al., 1996). In addition, in both crops, T_L might not be regulated completely by transpiration under severe water stress. Further

Table 2. Relations of SPAD value to maximum quantum yield of PSII and leaf temperature at the end of the treatment.

Crop				
Treatment	n	F_v/F_m	T_L	
Cotton (Control + WS)				
Control	5	0.65	-0.77	
WS	5	0.01	-0.29	
Peanut (Control + WS)				
Control	6	0.14	-0.62	
WS	6	0.55	-0.83	

F_v/F_m and T_L mean maximum quantum yield of PSII and leaf temperature, respectively.

Control; applied water equal to the transpiration.

WS; water stress, applied irrigation water equal to 50% of the transpiration.

** indicates 1% level of significance.

Table 3. Relationships between leaf temperature and transpiration, transpiration and root dry weight, and water content per unit leaf area and root dry weight at the end of the treatment.

Crop					
Treatment	n	T_L -Transpiration rate	Transpiration rate-RDW	WCLA-RDW	
Cotton (Control + WS)					
Control	5	-0.77	0.60	0.88*	
WS	5	0.81	-0.83	0.86	
Peanut (Control + WS)					
Control	6	-0.21	0.07	0.78	
WS	6	0.34	-0.44	0.26	

T_L , RDW and WCLA mean leaf temperature, root dry weight and water content per unit leaf area, respectively.

Control; Applied water equal to the transpiration.

WS; Water stress, applied irrigation water equal to 50% of the transpiration.

*, ** indicates 5% and 1% level of significance, respectively.

investigation is needed to identify the detailed varietal differences in the regulation of T_L under severe water stress. It was concluded that photodamage and down regulation in PSII were induced by water stress, coinciding with increases in leaf temperature that were regulated mainly by transpiration. Peanut showed more severe photodamage in PSII than cotton under the water stress condition.

References

- Begg, J.E. and Torsell, B.W.R. 1974. Diaphanostic and parahelionastic leaf movements in *Stylosanthes humilis* HBK. *R. Soc. New Zealand Bull.* 12: 277-283.
- Berry, J.O. and Björkman, O. 1980. Photosynthetic temperature response and adaptation to temperature in higher plants. *Ann. Rev. Plant Physiol.* 31: 491-543.
- Bilger, W. and Björkman, O. 1990. Role of the xanthophyll cycle in photoprotection elucidated by measurements of light-induced absorbance changes, fluorescence and photosynthesis in leaves of *Hedera canariensis*. *Photosynth. Res.* 25: 173-185.
- Bilger, W., Schreiber, U. and Bock, M. 1995. Determination of the quantum efficiency of photosystem II and of non-photochemical quenching of chlorophyll fluorescence in the field. *Oecologia* 102: 425-432.
- Björkman, O. and Demming-Adams, B. 1994. Regulation of photosynthetic light energy capture, conversion, and dissipation in leaves of higher plants. In E.D. Schulze and M.M. Caldwell, eds. *Ecophysiology of Photosynthesis*. Ecological Studies 100. Springer, Berlin, Heidelberg, New York. 14-47.
- Bressan, R.A. 2002. Stress Physiology. In L. Taiz and E. Zeiger, eds. *Plant Physiology*, 3rd edition ed. Sinauer Associates, Inc., Sunderland, Massachusetts. 591-623.
- Carpentier, C. 1996. Influence of high light intensity on photosynthesis: Photoinhibition and energy dissipation. In M. Pessarakli, ed., *Handbook of Photosynthesis*. Marcel Dekker, New York. 443-450.
- Chatterton, N.J., Hanna, W. W., Powell, J.B. and Lee, D. R. 1975. Photosynthesis and transpiration of bloom and bloomless sorghum. *Can. J. Plant Sci.* 55: 641-643.
- Chow, W.S. 1994. Photoprotection and photoinhibition. In E. E. Bittar and J. Barber, eds., *Advances in Molecular and Cell Biology, Molecular Processes of Photosynthesis*, Vol. X. JAI Press Inc., Greenwich. 151-196.
- Cochard, H., Coll, L., Roux, X.L. and Ameligo, T. 2002. Unraveling the effects of plants hydraulics on stomatal closure during water stress in walnut. *Plant Physiol.* 128: 282-290.
- Ehleringer, J. and Forseth, I.N. 1980. Solar tracking by plants. *Science* 210: 1094-1098.
- Frank, H.A., Cua, A., Chynwat, V., Young, A., Gosztola, D. and Wasielewski, M.R. 1994. Photophysics of the carotenoids associated with the xanthophyll cycle in photosynthesis. *Photosynth. Res.* 41: 389-395.
- Havaux, M. and Lannoye, R. 1985. Drought resistance of hardy wheat cultivars measured by a rapid chlorophyll fluorescence test. *J. Agric. Sci.* 104: 501-504.
- Inamullah and Isoda, A. 2005a. Adaptive responses of soybean and cotton to water stress. I. Transpiration changes in relation to stomatal area and stomatal conductance. *Plant Prod. Sci.* 8: 16-26.
- Inamullah and Isoda, A. 2005b. Adaptive responses of soybean and cotton to water stress. II. Changes in CO_2 assimilation rate, chlorophyll fluorescence and photochemical reflectance index in relation to leaf temperature. *Plant Prod. Sci.* 8: 131-138.
- Isoda, A., Aboagy, L. M., Nojima, H. and Takasaki, Y. 1996. Effects of leaf movement on radiation interception in field grown leguminous crops. IV. Relation to leaf temperature and transpiration among peanut cultivars. *Jpn. J. Crop Sci.* 65: 700-706.
- Isoda, A. and Wang, P. 2002. Leaf temperature and transpiration of field grown cotton and soybean under arid and humid conditions. *Plant Prod. Sci.* 5: 224-228.
- Jefferies, R.A. 1994. Drought and chlorophyll fluorescence in field-grown potato (*Solanum tuberosum*). *Physiol. Plant.* 90: 93-97.
- Johnson, H.B. 1975. Plant pubescence : An ecological perspective. *Bot. Rev.* 41: 233-258.
- Kobza, J. and Edwards, G.E. 1987. Influences of temperature on photosynthetic carbon metabolism in wheat. *Plant Physiol.* 83: 69-74.
- Kramer, P.J. 1983. *Water relations of plants*. Academic Press, Inc., New York. 291-341.
- Krause, G.H. 1988. Photoinhibition of photosynthesis. An evaluation of damaging and protective mechanisms. *Physiol. Plant.* 74: 566-574.
- Li, F., Kang, S. and Zhang, J. 2004. Interactive effects of elevated CO_2 , nitrogen and drought on leaf area, stomatal conductance and evapotranspiration of wheat. *Agric. Water Manage.* 67: 221-233.
- Lima, A.L.S., Damatta, F.M., Pinheiro, H.A., Totola, M.R. and Loureiro, M.E. 2002. Photochemical responses and oxidative stress in two clones of *Coffea canephora* under water deficit conditions. *Environ. Exp. Bot.* 47: 239-247.
- Ludlow, M.M. 1989. Strategies of response to water stress. In K.H. Kreeb, et al., eds.- *Structural and Functional Responses to Environmental Stresses: Water Shortage*. SBP Academic, Hague. 269-281.
- Massacci, A. and Jones, H.G. 1990. Use of simultaneous analysis of gas-exchange and chlorophyll fluorescence quenching for analyzing the effects of water stress on photosynthesis in apple leaves. *Trees* 4: 1-8.
- Maxwell, K. and Johnson, G.N. 2000. Chlorophyll fluorescence - a practical guide. *J. Exp. Bot.* 51: 659-668.
- Murata, Y. 1981. Dependence of potential productivity and efficiency for solar energy utilization on leaf photosynthetic capacity in crop species. *Jpn. J. Crop Sci.* 50: 223-232.
- Saneoka, H. and Ogata, S. 1987. Relationship between water use efficiency and cuticular wax deposition in warm season forage crops grown under water deficit condition. *Soil Sci. Plant Nutr.* 33: 439-448.
- Shimshi, D. 1963. Effect of soil moisture and phenyl-mercuric acetate upon stomatal aperture, transpiration, and photosynthesis. *Plant Physiol.* 38: 713-721.
- Smirnoff, N. 1993. The role of active oxygen in the response of plants to water deficits and desiccation. *New Phytol.* 125: 27-58.
- Wang, C., Isoda, A., Li, Z. and Wang, P. 2004. Transpiration and leaf movement of cotton cultivars grown in the field under arid conditions. *Plant Prod. Sci.* 7: 266-270.
- Wooly, J.T. 1964. Water relations of soybean leaf hairs. *Agron. J.* 56: 569-571.
- Yamamoto, H.Y. 1979. Biochemistry of the violaxanthin cycle in higher plants. *Pure Appl. Chem.* 51: 639-648.