Agricultural and Forest Meteorology, 35 (1985) 193—203
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

FOLIAGE TEMPERATURE AS A MEANS OF DETECTING STRESS OF COTTON SUBJECTED TO A SHORT-TERM WATER-TABLE GRADIENT

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(Received September 21, 1984; revision accepted February 21, 1985)

ABSTRACT

Reicosky, D.C., Smith, R.C.G. and Meyer, W.S., 1985. Foliage temperature as a means of detecting stress of cotton subjected to a short-term water-table gradient. Agric. For. Meteorol., 35: 193—203.

Quantifying crop stress resulting from both excess and deficit water is essential to higher water use efficiencies under flood irrigation. Our objective was to measure foliage temperature as an indicator of plant stress under various levels of waterlogging. Cotton (*Gossypsium hirsutum*) was grown in a water-table gradient facility and when a complete canopy had developed was subjected to 8 days of flooding. The water table gradient facility ensured that a continuum of water-table conditions ranging from complete inundation to a complete absence in the root zone was established. The foliage temperature, measured around solar noon with a hand-held infrared thermometer, and microclimate data from a nearby weather station were used to calculate evapotranspiration rates. The foliage temperature of plants with more than 60% of their root system inundated increased slightly relative to air temperature after 4 days of flooding although visible symptoms of stress on these same plants were not evident until the eighth day, at which time foliage temperatures were 4 to 6°C above the non-flooded plants. Calculated values of instantaneous evapotranspiration showed a 38% decrease while values of photosynthesis decreased by 86% after 8 days of flooding. These calculations support data from other plant measurements which suggest that the plant stress induced by the flooding was not primarily the result of water deficit. The results show that canopy temperature measurements may be sensitive enough to indicate plant stress which is not primarily induced by water deficits and that a derived crop stress index will indicate the onset and severity of the stress.

INTRODUCTION

There is considerable interest in the use of canopy temperature to detect the onset, and to assess the severity of water deficits in field crops. The method is based on monitoring canopy temperature which results from the

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0168-1923/85/$03.30

interaction of plant transpiration with the evaporative demand of the atmosphere (Jackson, 1982). When the vapor pressure deficit of the air is sufficiently large, the canopy is cooled below ambient temperature. As soil water becomes limiting, transpiration is reduced and the leaf temperature rises. The ability to easily measure canopy temperature by infrared thermometry, and the dominant influence of the vapor pressure deficit of the air on the difference between canopy and ambient temperature led to the development of a crop water stress index by Idso et al. (1977) and Jackson et al. (1977). More recently Idso et al. (1982b) have shown the existence of a significant correlation between the crop water stress index, leaf diffusive resistance and net photosynthesis in cotton.

Previous work using canopy temperatures has mostly characterized crop response to soil water deficit (Jackson, 1982). Little information on canopy temperature is available when other causes of plant stress, such as those associated with excess soil water or plant diseases are encountered. This work was designed to evaluate the utility of cotton foliage temperature as an indicator of crop stress resulting from short-term flooding and to determine the subsequent effects on evapotranspiration and photosynthesis as proposed by Idso et al. (1982a, 1982b).

MATERIALS AND METHODS

A field study was conducted at the Centre for Irrigation Research at Griffith, New South Wales, Australia, during the 1982/83 cropping season to evaluate the effects of short-term flooding on foliage temperatures of cotton (*Gossypsium hirsutum* cv. Deltapine 61). The experiment was conducted in a water-table gradient facility described previously (Reicosky et al., 1985). Briefly, the facility provided for the rapid imposition and removal of a continuously variable water-table depth that ranged from 0.1 m above, to 0.66 m below the soil surface along its 45 m length. Cotton was grown in 0.25 m rows at a population of 18 plants m^{-2} using conventional tillage and herbicide application techniques. The narrow row spacing was employed to ensure complete canopy cover as early as possible in the season to permit use of the infrared thermometer. The crop was watered via a sprinkler irrigation system throughout the growth cycle to prevent drought stress. Fertilizer was applied before sowing and was incorporated into the top 0.1 m of soil at the rate of 130 and 100 kg ha^{-1} for N and P_2O_5 respectively.

Once the cotton canopy had reached full cover (82 days after planting) at a height of 0.6 m in this case, the water-table was raised and maintained at the predetermined control level to flood various portions of the plant root zone for a period of 8 days. Canopy temperature was measured using an Everest Interscience* Model No. 110 hand-held infrared thermometer

* Use of a trade or firm name is for reader information only and does not constitute endorsement by USDA-ARS or CSIRO of any commercial product or service.

with the emissivity set at 0.98. The thermometer was held at an angle of about 30° from the horizontal and care was taken that no soil or water was viewed during the measurement. Foliage temperature measurements were made around solar noon and the average of three readings facing south and three facing north at each preselected site representing a range of water-table depths was calculated. Wet- and dry-bulb temperatures were measured with an aspirated Theis psychrometer held at a height of 1.5 m adjacent to the experimental area. These temperature values were used to calculate ambient vapor pressure deficit (AVPD). The dry-bulb temperature was used to calculate the difference between foliage (T_f) and ambient temperatures (T_a). Incoming solar radiant energy was measured using a Li-Cor model LI-200SB pyranometer and a LI-195 meter. During the flooding period, the sky was essentially clear on all days of measurement.

Because of the unknown effects that were likely to be induced by raising the water-table, a well-watered control area was established adjacent to the water-table gradient facility. This was deep tilled and treated in the same manner as the water-table facility and provided a non-stressed control for reference purposes. The control was managed so that the plants would not experience any stress from either too little water or too much water.

THEORY

Waterlogging of the root zone would be expected to cause an increase in canopy temperatures if there was a reduction in latent energy flux from the canopy. This would result in an increased proportion of the intercepted incoming energy ending up in the heat content of the canopy (Monteith, 1973). This effect can be understood by consideration of the energy balance of a canopy surface expressed by the equation

$$R_n = G + H + E \ [\mathrm{Wm^{-2}}] \qquad (1)$$

where R_n = net radiant energy, G = soil heat flux, H = sensible heat flux and E = latent energy flux. The sensible heat flux is proportional to the difference in temperature between foliage (T_f) and air (T_a) given by

$$H = \rho c_p (T_f - T_a)/r_a \ [\mathrm{Wm^{-2}}] \qquad (2)$$

where ρc_p is the volumetric heat capacity (J m^{-3} °C^{-1}) and r_a the aerodynamic resistance (s m^{-1}). From eqs. 1 and 2 the change in E(mm h^{-1}) due to a change in ($T_f - T_a$) can be calculated as

$$E = \frac{(R_n - G) - \rho c_p [(T_f - T_a)/r_a]}{3.6\,\lambda} \qquad (3)$$

where λ is the latent heat of vaporization of water (J g^{-1}) and the constant 3.6 is a factor converting from units of g m^{-2} s^{-1} to mm h^{-1}. Aerodynamic resistance was determined for neutral conditions by the equation (Monteith, 1973)

$$r_a = [\ln(z-d)/z_0]^2/K^2 u(z) \tag{4}$$

where z is the reference height (2 m) above the canopy, d is the zero plane displacement (m), z_0 the surface roughnes height (m), K is von Karman's constant ($K = 0.41$, dimensionless) and $u(z)$ is the windspeed at the reference height (m s^{-1}).

The measured $T_f - T_a$ differentials indicated that varying degrees of stability will exist depending on the bouyancy of the air mass. The aerodynamic resistance corrected for r_a' was calculated by the methd of Monteith (1973) from the equation

$$r_a' = \frac{r_a - n(z-d)g(T_f - T_a)(\ln(z-d)/z_0)^2}{T_k K^2 u(z)^3} \tag{5}$$

where g is the acceleration of gravity (9.8 m s^{-2}) and T_k the absolute temperature at the mean of canopy and air temperatures and n is a constant given a value of 5 (Monteith, 1973). Also, $d = 0.66$ h and $z_0 = 0.13h$, where h is crop height (Monteith, 1973), which was 0.6 m during the flooding event.

Net radiant energy R_n was calculated from measured incoming solar radiant energy by the equation of Stanhill et al. (1966) and soil heat flux was assumed to be 10% of the R_n (McIlroy, 1972). Wind run was measured at a standard meteorological station 300 m from the experimental site. The validity of E predictions made from $T_f - T_a$ measurements was tested by using daily class A pan measurements of evaporation and from these data reverse the method of Jackson et al. (1983) to calculate the instantaneous rate at solar noon. For crops that were non-stressed for water, the results indicated that $T_f - T_a$ measurements accounted for 88% of the variation in E. Attempts to confirm accuracy under severely stressed conditions were inconclusive due to the problem of small plot size and edge effects (Smith et al., 1985).

Assuming that $T_f - T_a$ measurements accurately reflect differences in E due to induced root zone limitations imposed by varying water-table heights, then further insight into underlying processes can be gained by using a further development of eqs. 1 and 2 (Jackson, 1982) which expresses E as

$$E = \frac{\Delta R_n + \rho c_p (e_a^* - e_a)/r_a}{\Delta + \gamma(1 + r_c/r_a)} \quad [\mathrm{W\ m^{-2}}] \tag{6}$$

where Δ is the slope of the saturation vapor pressure curve (Pa C^{-1}), γ is the psychrometric constant (Pa C^{-1}) and r_c is the canopy resistance to vapor flux (s m^{-1}). From this equation, values of r_c can be calculated to reflect changes in stomatal resistance.

To interpret the effect of the flooding on the canopy temperature, we followed the method of Jackson et al. (1983), Jackson (1982) and Idso et al. (1982a) in developing a stress index. In order to avoid confusion with the Crop Water Stress Index (CWSI) defined by them for studying crop response to soil water deficits, we define a more general Crop Stress Index (CSI) that encompasses plant stress as a result of short-term flooding. The CSI is mathematically the same as CWSI and this is calculated as the ratio of the measured temperature difference $(T_f - T_a)$ to that of the non-stressed plants at the same AVPD. The upper and lower limits of the $(T_f - T_a)$ vs. AVPD relationship are determined experimentally. The lower limit was determined from measurement on the non-stressed plants in the control area and plotted as a function of the AVPD. The upper limit was determined from a non-transpiring cotton canopy and was found to vary between 3.0 and 4.0°C (Smith et al., 1985). To obtain this non-transpiring canopy, plants in 1 m^2 were excised at ground level and placed in lengths of PVC tube (20 mm ID) inserted in the soil next to the cut stump. Canopy temperatures were measured periodically until the leaves were nearly dry. While this value of the upper limit was obtained from a small number of measurements, it was obtained on a canopy of similar architecture adjacent to the experimental plots. The value so obtained is similar to values for other crops (Jackson et al., 1981; Idso et al., 1982a; Jackson, 1982) and is reasonably close to that found for cotton by Idso et al. (1982b).

RESULTS AND DISCUSSION

Midday microclimate data collected in association with the canopy temperature during the flooding event is shown in Fig. 1 as a function of days after flooding. The sky was essentially clear at solar noon with solar radiant energy varying from 1040 to 1170 W m^{-2}. The maximum radiant energy value 7 days after flooding was associated with a clear cool day as a frontal weather system moved through the area. The highest daily air temperature of 36.5°C occurred 5 days after flooding while the lowest maximum of 24.0°C occurred on day one. The midday AVPD generally follows the air temperature. The range in AVPD was 2.1 to 5.0 kPa during the flooding period.

Foliage temperature (T_f) minus the air temperature (T_a) as measured on non-stressed cotton is plotted as a function of AVPD in Fig. 2. The value of $T_f - T_a$ approaches 0 at an AVPD of about 2.1 kPa and then declines linearly as AVPD increases. Our data generally parallels that of Idso et al. (1982b) with nearly the same slope but with a slightly different intercept. The theory underlying this relationship (Jackson, 1982) indicates that the difference in the two data sets could be accounted for by higher levels of net radiant energy. In addition, there may have been some difference due to experimental technique, since we viewed the cotton canopy only from two directions, while Idso et al. (1982b) viewed their canopy from four directions. Errors in the measurement of ambient wet- and dry-bulb temperature could also cause the difference but we were unable to find evidence of any such errors. Despite the difference, our data confirm the general theoretical expectations and in reality are only slightly different from previously published data (Idso et al., 1982b; Howell et al., 1984).

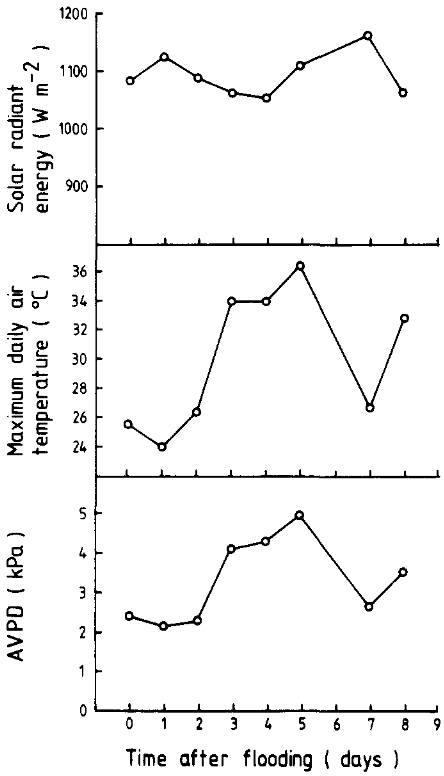

Fig. 1. Summary of the midday microclimate data collected in association with the canopy temperature during the flooding event (17 to 25 January 1983).

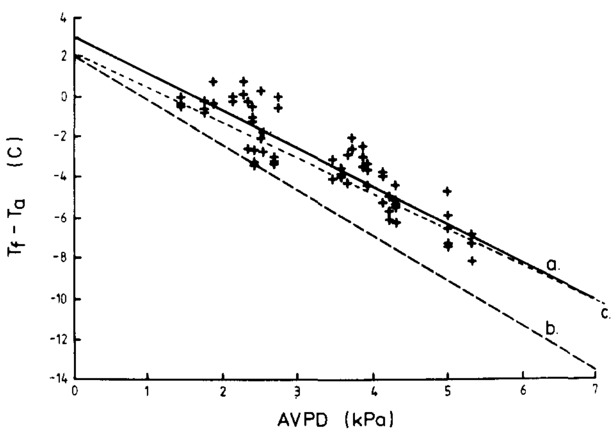

Fig. 2. The difference between foliage temperature (T_f) and ambient temperature (T_a) versus AVPD for nonstressed cotton. Line (a) is the line fitted to the observed data while line (b) is that determined by Idso et al. (1982b) and line (c) is that determined by Howell et al. (1984).

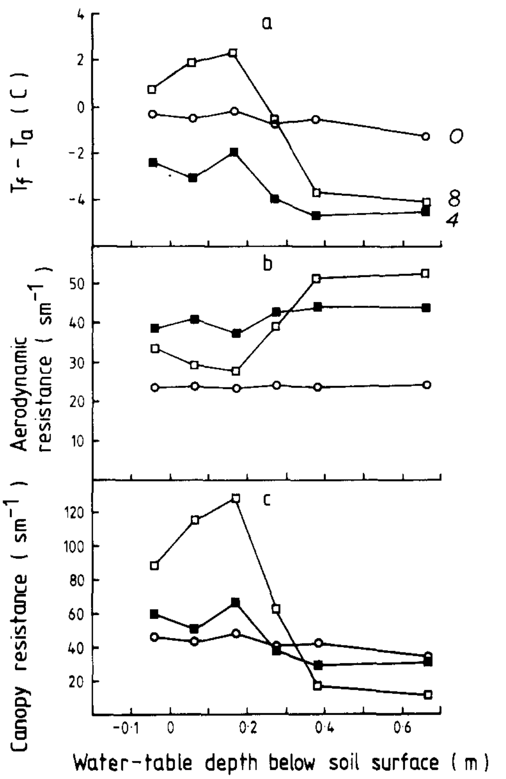

Fig. 3. The measured $T_f - T_a$ differential (a), calculated aerodynamic resistance (b) and canopy resistance (c) as a function of the water-table depth 0, 4 and 8 days after flooding began.

The $T_f - T_a$ difference, aerodynamic resistance (r_a) and the canopy resistance (r_c) are plotted as a function of water-table depth in Fig. 3. Days zero, 4 and 8 after flooding were selected to illustrate the time trends at the various water-table depths. The magnitude of $T_f - T_a$ for the non-stressed plants over the deeper water table was related to the AVPD on selected days (see Fig. 1). Four days after flooding, the $T_f - T_a$ difference in the zone of high water table started to exceed experimental error and thus indicate the first signs of plant stress as measured with the infrared thermometer. Eight days after flooding, the plants growing in the area which was inundated were exhibiting wilt symptoms and had substantially different canopy temperatures. Up to day 7, there had been no visible signs of stress. Leaf growth measurements started to reflect an effect of flooding after about 4 days (Reicosky et al., 1985). Thus both leaf growth and canopy temperature measurements indicated that by the time visible wilt symptoms were evident, the plants were severely stressed.

The effect of 8 days of flooding on increasing canopy temperatures and so making the $T_f - T_a$ difference more positive resulted in the predicted aerodynamic resistance (r_a) decreasing from about 50 to 30 s m^{-1} (Fig. 3b). The reduction in r_a results from predicted effects of $T_f - T_a$ on bouyancy. As $T_f - T_a$ becomes more positive the air mass next to the canopy becomes more stable which then results in a reduced resistance to vapor loss in the boundary layers. Effects of water-table heights on canopy resistance (r_c) shown in Fig. 3c are mediated mainly through predicted effects on stomatal resistance. With time, flooding caused a predicted increase in r_c from 20 sm^{-1} for non-stressed plants to as much as 80 to 130 sm^{-1} for plants which were visibly wilted. Thus, the resultant effects of the stress indicated by the $T_f - T_a$ difference becoming more positive are moderated by a decrease in r_a opposing the increase in r_c. The result of these factors in the calculation of E using eq. 3 is summarized in Fig. 4. The magnitude of E was not affected as long as $T_f - T_a$ was constant and only a small amount 4 days after flooding. However, as $T_f - T_a$ became more positive, the predicted value of E was reduced from 0.98 mm h^{-1} in the non-stressed plants to about 0.71 mm h^{-1} where the plants were affected by the high water-table 8 days after flooding began. This represents a 38% decrease in E. A slight increase in E was noted where there was free water covering the soil surface. While the canopy structure was essentially the same along the water-table gradient facility, and no water or soil was viewed by the infrared thermometer, the measured values of T_f may have been influenced by the presence of a free water surface under the canopy. The nature of this influence is not clear, but it may be associated with higher vapor densities within the canopy which covers a free water surface.

The crop stress index (CSI) as a function of water-table height for the same 3 days during the flooding is shown in Fig. 5. As expected, the CSI parallels the $T_f - T_a$ differences showing the maximum stress when visible wilt symptoms were present 8 days after flooding began. At this time, the CSI reflected the other measurements of plant water status which showed lower stomatal conductance and lower leaf water potentials of some plants (Reicosky et al., 1985). By combining these values of CSI and using the methods of Idso et al. (1982b), the effect of water-table height on apparent photosynthesis of the crop was calculated. This calculation assumes that the stress indicated by the infrared thermometer results has the same qualitative effect on photosynthesis irrespective of whether it is caused by too little or by too much water. The calculations indicate that apparent photosynthesis could have been reduced by up to 86% after 8 days of flooding when compared to the non-stressed plants.

The CSI indicates a greater reduction in E than was predicted from eq. 3. One cause of this discrepancy probably results from the upper limit used for $T_f - T_a$ when $E = 0$. Under nontranspiring conditions ($E = 0$) eq. 3 rearranges to

$$r_a = \rho c_p (T_f - T_a)/(R_n - G) \qquad (7)$$

From this revised equation, substituting $T_f - T_a = 4.0°C$ at $E = 0$ gives an r_a

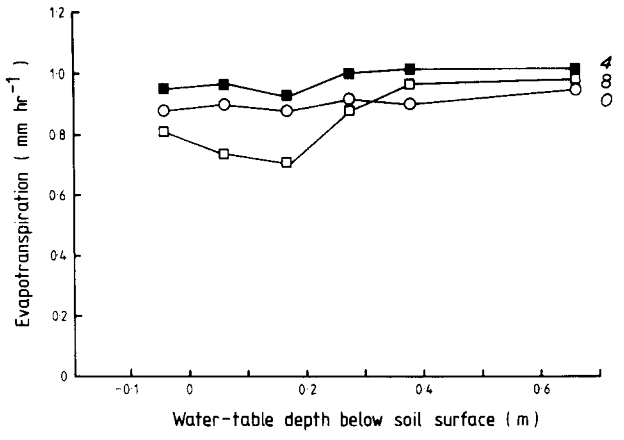

Fig. 4. The effect of water-table depth on calculated values of the rate of evapotranspiration (E) at 0, 4 and 8 days after flooding began.

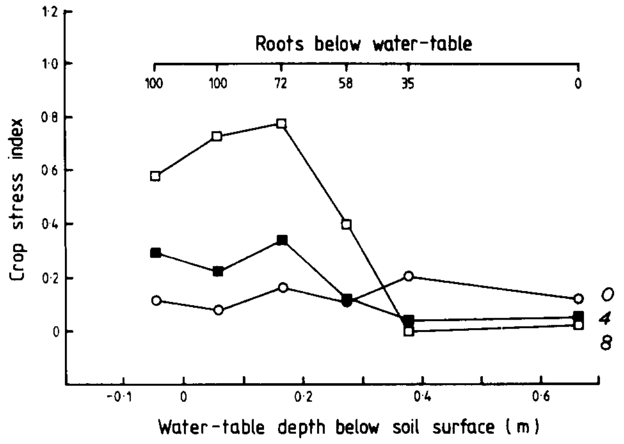

Fig. 5. The crop stress index (CSI) as affected by water-table depth 0, 4 and 8 days after flooding.

value of about 7.0 s m^{-1} (Smith et al., 1985), whereas the r_a calculated by the aerodynamic method (eq. 5) varied between 30 and 50 s m^{-1}. Comparison with other published data (Monteith, 1973) would suggest that the higher values are correct and that the value of $(T_f - T_a) = 4.0°C$ derived from measured values at $E = 0$ is the result of influences induced when using small plots and the effects of buoyancy.

The proportion of the root system which needed to be inundated to cause an effect on the plants was of interest. Four days after flooding, the CSI showed a small increase where plants had 70% of their root system below the level of the water-table (Reicosky et al., 1985). Eight days after the flooding began, plants with more than 60% of their root system submerged appeared to be stressed. Acknowledging that saturated conditions occur above the level of the water-table as the result of capillary action, the results indicate that a relatively large portion of the root system must experience poor aeration before plant stress is evident. This discussion presumes equal effectiveness for all roots as a function of depth. The higher root densities near the surface may mediate the plant response.

The decrease (38%) in calculated evapotranspiration between stressed and unstressed plants in the sloping plot concurs with the findings from the plant water measurements (Reicosky et al., 1985). Their results suggest that plant response to this period of inundation was not initially mediated through the effects on plant water status but that partial stomatal closure may have come from nitrogen deficiencies. Again, the larger calculated reduction in photosynthesis (86%) is consistent with this premise.

CONCLUSION

This work demonstrates that foliage temperature can indicate plant stress which is induced by intermittent waterlogging in the same manner as plant stress induced by water deficits. The method appears to be sensitive in detecting the onset of stress since small changes in the $T_f - T_a$ difference were apparent before visible wilt symptoms appeared. Cotton plants with 60% of their root system inundated had midday foliage temperatures that increased slightly relative to air temperatures after 4 days of flooding and had foliage temperatures as much as 4 to 6°C above non-stressed plants after 8 days of flooding. Calculated values of evapotranspiration and photosynthesis based on foliage temperatures showed the expected decreases as a result of stress from waterlogging. The method has theoretical foundation and appears to have potential to follow the development of stress as the result of irrigation management practices which cause transient waterlogging in the root-zone. The method requires appropriate microclimate data and will be limited, however, to the situations where the crop has a complete canopy cover.

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