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BARD

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Evaluation of Infrared Thermometry to Assess Cotton Water Use with Emphasis on Irrigation Scheduling

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Abstract

Infrared thermometers (IRT) have become cheap and easy to use field instruments. In this study, the relation of the surface temperature they measure to plant water stress and soil water depletion has been evaluated theoretically by resolving the energy balance and experimentally in cotton field studies. The theoretical analysis revealed that the sampling of the foliage temperature distribution depends upon the sighting angle of the IRT. In Texas, the experiment established that the IRT, sighted at 60° from zenith, read a temperature systematically below that obtained by resolving the energy balance at the sensible heat sink of the canopy-air interface. The experiment in Israel was designed to induce water stress by withholding irrigation. It showed that cotton must endure considerable desiccation before its water stress can be diagnosed by IRT, especially if the atmospheric humidity is high. IRT appeared more appropriate for comparative measurements than for absolute detection of water stress. The spatial average operated by IRT masks the stress induced high temperatures experienced, according to the theory, by a small percentage of the cotton foliage. Such information could be revealed by thermal imagery.

Objectives of proposal

Results from a previous BARD project (Project I-399-81 Final Report) demonstrated how meteorological data and canopy resistances could be combined to estimate water deficit stress in cotton. However, spatial variability of water infiltration due either to soil heterogeneity or to imperfect water distribution equipment may cause large variability of water stress in the field. One means of assessing this variability is by remotely sensing canopy temperature (T_c).

The goal of this research was to partition the physiological and meteorological determinants of canopy temperatures such that T_c could be used to consistently evaluate the level of crop water stress and schedule irrigation. The following objectives were proposed for this study:

1. Determine the effect of canopy structure, growth stage, and level of soil water deficit stress on aerodynamic and canopy resistance to water vapor transport for cotton, derived from hand held infrared thermometer (IRT) measurements of canopy temperature and energy balance measurements.
2. Translate meteorological inputs and IRT measurements into water use rates.
3. Scale canopy temperature variability as a function of spatial variation of soil water levels.

The work in the U.S. and Israel were directly in line with the original objectives. The U.S. work documented how resistances vary with different levels of leaf area and soil water, the accuracy of resistances calculated using IRT measurements of T_c , and the accuracy of LE estimates made using T_c measurements. In Israel, the work demonstrated the variability of T_c which can be found within a canopy. These results are critical in evaluating the utility of IRTs for field-estimates of LE and thus for use in irrigation scheduling.

Scientific reports

This final report is comprised of six self-contained scientific reports. Their salient findings and mutual linkages are described below. The supportive nature of their findings is summarized in Table 1.

1. Infrared measurement of canopy temperature and detection of plant water stress.

A. Findings

1. Leaf position, inclination and orientation within the canopy produce considerable variation of leaf temperature.
2. The rise of canopy temperature caused by a water deficit stress occurs over a small percentage of the total canopy leaf area and detection of this stress with an infrared thermometer (IRT) requires a normalizing procedure which takes into account ancillary meteorological conditions.
3. Leaf temperature distribution within a canopy is a better indicator of stress than the average value.
4. A model was developed which simulated the temperature composition of the field of view of a temperature sensor as a function of sighting angle and orientation relative to the incident solar beam.
5. Orienting the IRT towards the canopy in the same direction as the sun, and at an angle of incidence as close as possible to the solar zenith angle, improves the ability of the sensor to detect water stress.

B. Linkage

1. The water stress is defined by a decrease of the stomatal conductance. These findings rely on the quantification of the relation between stomatal conductance and soil water depletion found in report 3.
2. The significance of the logarithmic formulation of the aerodynamic boundary layer invoked here is reconsidered in report 2.
3. Report 2 confirms the predicted azimuthal variations of IRT measurements.
4. The modeling of the energy balance for classes of leaf illumination is experimentally validated in the work in report 5.
5. The leaf temperature distribution is examined experimentally in report 4.

6. Fluctuations of the crop water stress index (CWSI) predicted by the model are observed in report 6.

2. Canopy temperature-based estimates of aerodynamic resistance and latent heat flux of cotton in Texas.

C. Findings

1. Canopy temperature measured by two IRTs oriented at two azimuth angles differed by $\pm 1^{\circ}\text{C}$ throughout the day.

2. Systematic differences existed between aerodynamic and radiative canopy temperatures.

3. Aerodynamic resistance calculated from canopy temperatures were systematically less than 'standard' values calculated from meteorological measurements.

4. Evaporation calculated from canopy temperatures and measurements of available energy were in error by 20 to 30%.

D. Linkage

1. Direct use of canopy temperature measurements to estimate the latent heat flux results in errors larger than those predicted by the model described in report 5.

2. Errors in the evapotranspiration estimates can be related to the theory developed in report 1.

3. Sunlit and shaded stomatal responses of field grown cotton to radiation and soil moisture.

E. Findings

1. Average daytime shaded leaf conductance is approximately 31% and 27% of that of sunlit leaves in non-stress and severe water stress conditions, respectively.

2. Sunlit leaf conductance is primarily dependent upon photosynthetically active radiation (PAR).

3. Stomatal conductance response to PAR decreases as PAR increases, with most of the change occurring in the PAR range typically obtained in the shaded fraction of the canopy.

4. Increasing moisture stress progressively decreases the stomatal response to PAR.

5. Random variability of stomatal conductance is large.

F. Linkage

1. Provides the needed physiological input for reports 4 and 5.

4. Cotton leaf surface temperature variability.

G. Findings

1. The range of leaf temperature measurements corresponds to that predicted by the energy balance.

2. Variability attenuates the ability to detect water stress.

H. Linkage

1. Results of reports 1 and 3 were used to analyze the reported measurements.
2. Some of the random variance reported in reports 2 and 3 can explain the experimental scatter reported here.

5. Computing transpiration of sunlit and shaded cotton foliage under variable water stress.

I. Findings

1. Transpiration of the shaded portion of a cotton canopy decreases as water stress intensifies. The shaded canopy contribution increases when the advective component of the energy balance becomes larger.
2. Modeling the conductance network along the water vapor path from sunlight and shaded leaves provides an accurate estimate of transpiration.

J. Linkage

1. Uses the same physical model as report 1.
2. Provides indirect evidence that the computations of leaf temperature in report 1 are credible.

6. Evaluation of canopy temperature-based crop water stress indices for irrigation scheduling.

K. Findings

1. Important day to day fluctuations of Crop Water Stress Index (CWSI) values, determined using an empirical baseline, were observed for nonstressed crops, particularly under low vapor pressure deficit conditions.
2. The use of a theoretical CWSI, requiring measurements of net radiation, soil heat flux and wind speed and estimates of aerodynamic and canopy resistances, reduced, but did not eliminate, these fluctuations.
3. The empirical CWSI provided late indication of irrigation needs, after some water stress has developed, which may limit its application for crops sensitive to water stress.
4. The theoretical CWSI tracked the development of water stress and provided reasonable indication of irrigation needs.

L. Linkage

1. Assessment of the limitations of CWSI established in report 1.

Table 1. Supportive research findings associated with BARD project. The first two columns denote the number of and finding from a scientific report within this final report and the last two columns denote a related report and finding.

Report	Finding	Report	Finding
#1	Canopy temperature (Tc) dependent upon sensor azimuth	#2	Effect of sensor azimuth on Tc
#1	Variability of Tc vertically in canopy	#2	Aerodynamic 'surface' temperature is not equal to Tc measured with sensor
#1	Tc increased if sun and sensor azimuth angles are similar	#2	Higher Tc values if sun and sensor azimuth angles similar
#1	Vertical distribution of leaf temperature	#5	Experimental evidence of temperature distribution
#1	Variability of leaf temperatures	#6	Field measurements and simulations of variability of crop stress indices
#1	Detection of moderate stress requires a normalizing procedure which takes into account meteorological conditions	#6	Theoretical Tc-based stress index is more valid if interpreted with ancillary meteorological measurements

SCIENTIFIC REPORT #1**INFRARED MEASUREMENT OF CANOPY TEMPERATURE
AND DETECTION OF PLANT WATER STRESS¹****Marcel Fuchs****Department of Agricultural Meteorology
Agricultural Research Organization
Bet Dagan, Israel****+ 9 figures.**

¹ Contribution from the Agricultural Research Organization, The Volcani Center, Bet Dagan, Israel. No. 2638-E, 1989 series. This work was supported by grant No. US-1138-86 from the Binational Agricultural Research and Development Fund.

SUMMARY

Leaf temperature is directly determined by leaf energy and water balance. If diminished water availability decreases latent heat flux at the leaf surface, a complementary increase of sensible heat will occur and create a larger temperature difference between foliage and air. Radiation, air temperature, humidity and wind speed modify leaf temperature and may mask indications of water stress. The position, inclination and orientation of leaves within the canopy also produce considerable variation of leaf temperature. These factors were incorporated in a linear transpiration model, using physical and physiological characteristics of cotton. Water stress was simulated by imposing a limit value for stomatal conductance. The energy balance equation was solved as a function of angle between leaf and solar beam, to determine leaf temperature frequency distribution. The results show that stress induced temperature rise occurs over a small percentage of the total leaf area. Detection of moderate stress requires a normalizing procedure which takes into account meteorological conditions. The leaf temperature distribution is a better indicator of stress than the average value.

The infrared thermometer integrates thermal radiation emitted by the foliage included in its field of view. The model simulated the temperature composition of the field of view as a function of sighting angle and orientation relative to the incident solar beam. The spatial averaging of the signal in the field of view attenuated the sensitivity of the measurement to water stress. The results also indicated that pointing the infrared thermometer towards the canopy in the same direction as the sun, and at an angle of incidence as close as possible to the solar zenith angle, improved the ability to detect water stress.

INTRODUCTION

Surface temperature sets the boundary condition for the latent and sensible heat transport through vegetation, soil and atmosphere. It depends on the availability of moisture at the interface between the ground cover and the atmosphere. Accurate measurement of surface temperature by contact thermometry is considered impossible. The major theoretical contribution of the combination theory of evaporation (Penman, 1948) was to eliminate surface temperature from the energy balance equation. Penman (1956) and later Monteith (1965), extended the theory to unsaturated surfaces by introducing a surface resistance which, in the case of vegetation, bears a relation to the stomatal conductance of leaves. Tanner was among the first to recognize that the surface resistance used in the Penman-Monteith approach implied that the vegetation canopy was a single large leaf with a uniform temperature, in contradiction with the measurements of plant temperature he, and others, had made (Tanner and Fuchs, 1968). When technological progress transformed infrared thermometers into easily used field instruments, it became practical to use surface temperature to solve the energy balance equation. The resulting latent heat flux determination in conjunction with the Penman approach, established a theoretical link between surface temperature and plant water status.

The enthusiasm generated by infrared thermometers and remote sensing lead many to overlook the fact that Tanner's criticism of the way Monteith used surface resistance had a bearing also on the relation between canopy surface temperature and plant water stress. Canopy surface temperature is a statistical mean of a leaf temperature distribution. The purpose of this paper is to determine the leaf temperature distribution as a function of water stress, and to examine the consequences of the resulting variability on the radiative measurement of foliage temperature. The discussion is based on a model of radiation interception in the foliage and the consequent solution of the leaf energy balance.

MODEL

The energy balance equation was computed for a cotton canopy assuming a spherical leaf angle distribution, a frequently used approximation for real canopies (Ross, 1981). It provides an adequate representation of a fully developed cotton canopy after disappearance of the row structure.

Because solar radiation is the major input of energy, the model is driven by direct solar interception on plane leaf blade segments. The foliage

was divided into sunlit and shaded leaves. The sunlit leaf area index is (Lemeur, 1973):

$$L_* = (1 - \exp(-fL))/f \quad (1)$$

where L is the leaf area index and f is the average area of shadow cast by a unit area of foliage on a horizontal surface. For the spherical leaf angle distribution,

$$f = 0.5/\cos \theta \quad (2)$$

where θ is the zenith angle of the sun. The shaded leaf area index is then simply $(L - L_*)$.

At any given time, the range of radiative heat flux density input on shaded leaves is small. Hence the steady state temperature of shaded leaves is nearly uniform. On sunlit leaves, the heat load is proportional to the cosine of α , the angle between the normal to the blade and the incident ray. The fraction of sunlit area, $A[\alpha]$, intercepting direct radiation at angles between α_i and α_j , for a spherical leaf angle distribution is (Goudriaan, 1977):

$$A[\alpha] = (\cos \alpha_i - \cos \alpha_j) \quad (3)$$

This fraction was computed for 18 classes of angles between 0 and $\pi/2$ ($i = 0, \dots, 17; j = i + 1$).

The solar radiation flux density on each class is:

$$K[\alpha, \theta] = 1360 \times (0.78)^m \cos(\alpha_i + \alpha_j)/2 \quad (4)$$

where $m = 1/\cos \theta$ is the effective air mass on the path of a sun ray through the atmosphere for a location near sea level; 1360 W m^{-2} is the solar constant; and 0.78 is the mean scattering coefficient of a standard clear atmosphere (List, 1966).

A cotton leaves absorb 55% of the intercepted direct radiation (Moreshet, Cohen and Fuchs, 1979), but the presence of diffuse radiation and complementary scattered radiation increases the net solar radiation absorption, $K_N[\alpha, \theta]$ to:

$$K_N[\alpha, \theta] = 0.71 \times K[\alpha, \theta] \quad (5)$$

The absorption coefficient of 0.71 was calculated by assuming that multiple scattering occurred only between two layers of cotton leaves on a black background. More precise estimates of the diffuse radiation balance of leaves have been made (Goudriaan, 1977, Cohen and Fuchs, 1987). They indicate that the simple approximation used in Eq. (5) is reasonable.

The terrestrial radiation balance is approximated by the first order exchange between leaves and the proportion of clear sky, X , viewed by a sunlit leaf:

$$L_N = X(1 - e_A)\sigma T_A^4 \quad (6)$$

where T_A is the Kelvin air temperature, $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ is the Stefan-Boltzmann constant, and e_A is the emissivity of the clear sky, computed as (Brutsaert, 1982):

$$e_A = 0.767x(h e_A)^{1/7} \quad (7)$$

where h is the fractional relative humidity in the air at 2 m above the ground and e_A is the saturated water vapor pressure expressed in kPa. The isotropic view factor X is a function of the leaf area obstructing the sky. A representative average value was calculated for a horizontal leaf located below half of the leaf area. The assumption of uniform azimuthal leaf angle distribution implied in Eq. (2) simplifies the integration to:

$$X = 2 \int_0^{\pi/2} \exp(fL/2) \sin\theta \cos\theta d\theta \quad (8)$$

It is not necessary to derive a value of X for variable leaf angle, because absorption of diffuse terrestrial radiation is independent of the angle. Equation (6) assumes that leaves are at air temperature, an approximation in contradiction with the purpose of the model, but of little consequence to the leaf radiation balance. A 10°C difference would cause an error of 50 W m^{-2} , which is the inaccuracy of the incoming terrestrial radiation estimate. It also neglects the radiative thermal exchanges between leaves of different temperatures.

The radiation balance of a unit leaf area forming an angle α with the solar beam is:

$$R_N[\alpha, \theta] = K_N[\alpha, \theta] - L_N \quad (9)$$

For shaded leaves the radiation balance was assumed to be that of leaves at $\alpha = 1.48$ radian (85°). At this angle the solar radiation is 9% of maximum, a value close to the mean diffuse radiation measured on shaded cotton leaves in the field.

The photosynthetically active wave band in a clear atmosphere is a fairly constant fraction (0.49) of the direct energy flux density (Stanhill and Fuchs, 1977). Assuming that the spectral composition within the photosynthetic wave band of direct sunlight is constant, the energy flux density can be converted into a photon flux density expressed in mole $\text{m}^{-2} \text{s}^{-1}$ as:

$$\text{PhAR}[\alpha, \theta] = 0.49 \times K[\alpha, \theta] / 235000 \quad (10)$$

This conversion allows to use a relation established between cotton leaf conductance, g_L , in m s^{-1} , and $\text{PhAR}[\alpha, \theta]$ (Fuchs and Moreshet, 1985):

$$g_L = 14 \times \text{PhAR}[\alpha, \theta] \quad (11)$$

The following limit values were selected:

$$g_L = 0.030 \text{ m s}^{-1} \text{ for no stress} \quad (12a)$$

$$g_L = 0.015 \text{ m s}^{-1} \text{ for moderate stress} \quad (12b)$$

$$g_L = 0.005 \text{ m s}^{-1} \text{ for severe stress} \quad (12c)$$

Similar proportionality between light and leaf conductance in non-stressed conditions has been found for wheat (Denmead and Millar, 1976) and maize (Shawcroft, Lemon and Stewart, 1973).

The boundary layer conductance g_b of a palmately lobed cotton leaf with an average lobe width of 0.05 m is (e.g. Campbell, 1977):

$$g_b = 3.25 \times 10^{-3} (U_o / 0.05)^{0.5} \quad (13)$$

where U_o the wind speed in m s^{-1} near the top of the canopy, is assumed to remain constant with height.

The turbulent conductance, g_a , is derived from the logarithmic profile, allowing dissimilar sink or source intensities for momentum, parameterized by z_o , the roughness length, and for water vapor, parameterized by $z_e = 0.2 \times z_o$ (Garratt and Hicks, 1973):

$$g_a = k^2 U / [\ln((z-D)/z_o) \ln((z-D)/z_e)] \quad (14)$$

where U is the wind speed at height $z = 2$ m, $k = 0.41$ is the von Karman constant and D is the profile displacement height. The values for D and z_0 are taken as 70% and 13% of the average cotton canopy height (Stanhill and Fuchs, 1968). The enhancement of conductance due to buoyancy is not included in equations (13) and (14). The conductances g_A and g_B are in series and couple the surface temperature of a unit leaf area with the air temperature above the canopy:

$$1/g_U = 1/g_A + 1/g_B \quad (15)$$

As radiation balance and transport properties are applied to isothermal leaf blades, the latent heat equivalent of transpiration E (in $W\ m^{-2}$), can be obtained from the Penman-Monteith equation:

$$E = E_p / (1 + \gamma g_U / [(s + \gamma) g_L]) \quad (16)$$

$$E_p = [s R_N[\alpha, \theta] + \rho c_p g_U e_A (1-h)] / (s + \gamma) \quad (17)$$

where γ is the psychrometric constant ($\sim 0.066\ kPa\ K^{-1}$ at sea level), s is the slope of the saturated water vapor pressure temperature function ($kPa\ K^{-1}$), e_A (kPa) is the saturated water vapor pressure at air temperature T_A , h is the fractional relative humidity in the air, ρ is the air density ($\sim 1.2\ kg\ m^{-3}$), and c_p is the specific heat of air ($\sim 1000\ J\ kg^{-1}\ K^{-1}$).

The temperature of a leaf blade for each class of angle α is given as:

$$T_L[\alpha] = T_A + (R_N[\alpha, \theta] - E) / (\rho c_p g_U) \quad (18)$$

The relative frequency of $T_L[\alpha]$ is the fractional area of each leaf class, $A[\alpha]L_*/L$ for sunlit foliage. All shaded leaves are in a single class at temperature $T_L[s]$:

$$T_L[s] = T_L[\alpha=1.48] \quad (19)$$

with a relative frequency of $(L - L_*)/L$.

The energy exchange description in the model is considerably simplified, and therefore its predictions should be regarded as approximations. Nevertheless it has provided reliable hourly, daily, and seasonal estimates of cotton transpiration (Fuchs, Cohen, Moreshet and Cohen, 1989).

TEMPERATURE DISTRIBUTION

The temperature of the sunlit foliage was computed for the 18 classes of leaves intercepting beam solar radiation at angles between 0° and 90° in 5° increments. A set of reference meteorological parameters was selected to establish the effect of environmental conditions on a leaf. Parameters are set as follows: air temperature 30°C , relative humidity 50%, wind speed 4 m s^{-1} , solar zenith angle 15° , and clear cloudless sky. The crop is taken to be 1 m high and with a leaf area index of 4. At this stage the row structure has disappeared and vertical gap frequency on the ground is 0.14. Directly sunlit foliage area is 40% of the total. Water stress status is for the three levels of limiting leaf conductance defined in Eq. (12). The results presented in Figure 1 show, that in the absence of stress, the mean canopy temperature is 2°C lower than air temperature. However, 25% of the foliage is warmer than air, the warmest surfaces reaching 4.5°C above air temperature. The simulated temperature difference between shaded and normally sunlit leaves is of the same magnitude as that measured in cotton and other species by Ansari and Loomis (1959).

Stress elevates the temperature of the leaves receiving solar radiation flux densities above the threshold determined by Eqs. (12) and (11). Expert cotton growers consider the moderate stress defined by Eq. (12b) to indicate that irrigation is required. The corresponding temperature rise affects 23% of the foliage area, but mean canopy temperature is only 0.5°C higher than for the no-stress condition. As accuracy of infrared thermometers is approximately 0.5°C , only 20% of the foliage area shows the occurrence of water stress. Hence, determining irrigation timing depends on the ability to detect both the temperature elevation and the percentage of leaves affected.

Severe water stress increases the temperature of all sunlit foliage, the warmest leaves rising 15°C above air temperature. The average canopy temperature is elevated by more than 2°C . This water stress condition, which causes irreversible damage to the crop, is easily detected by an infrared temperature measurement.

Comparison of Figures 1 and 2 shows the effect of solar radiation on leaf temperature and its frequency distribution. The sun zenith angle in Figure 2 is 60° . This lowers the radiant flux density on a horizontal surface by approximately 50% from that in Figure 1. The temperature of the warmest leaves decreases from 45 to 41°C for severely stressed plant, and from 34.5 to 33°C for unstressed plant, and shallower ray penetration reduces the sunlit foliage area to 25%. For moderately stressed plants, less than 10% of the leaves undergo a rise in temperature. Thus, detecting the need for irrigation by a surface temperature measurement when the sun is low on the horizon may be very difficult. Furthermore, the lower radiative heat load alleviates the

water stress condition.

The effect of water vapor on surface temperature of leaves is shown in Figure 3. Increasing relative humidity from 50 to 70% elevates the temperature of the entire foliage. The temperature of leaves with high conductance increases more than that of stressed leaves with low conductance. It is obvious that the temperature of leaves with zero conductance is unaffected by relative humidity. Thus, the temperature of stressed and unstressed leaves converges at high humidity.

Wind increases the conductance of the boundary and the turbulent air layer above the canopy. It affects both sensible and latent heat transport but, because of the dryness of the leaf surface, the sensible heat flux is more sensitive to wind fluctuations. Increasing the wind speed from 4 to 6 m s^{-1} (Fig. 4) decreases the maximum temperature from 34.5 to 33°C, and from 45.5 to 43°C, respectively for unstressed and severely stressed leaves.

INFRARED TEMPERATURE SIMULATION

Infrared thermometers average the temperature of all objects included in their field of view. The mean foliage temperature they read depends on which fraction of the leaf temperature distribution they view. To avoid the confusing effect of variable sighting angle across the field of view, the forthcoming discussion is limited to instruments fitted with nearly collimated optics. Foliage area viewed by such devices and sunlit foliage area are determined by the same laws. As leaf temperature distribution depends on sun-leaf angle, the composite temperature in the field of view will be a function of the angle formed by the line of sight and the sun rays.

Higher infrared temperature readings when the instrument faces vegetation from the same direction as the sun have been reported (Fuchs, Kanemasu, Kerr and Tanner, 1967; Kimes, 1981; Nielsen, Clawson and Blad, 1984). These results are explained by a higher proportion of sunlit foliage in the field of view. Effects of sighting zenith angle on the temperature reading have been found. Kimes, Idso, Pinter, Reginato and Jackson (1980) found that infrared temperature readings of wheat were highest at nadir viewing. The measurements fitted computations of composite temperatures of bare soil and foliage included in the field of view, as derived from angular distribution of gap frequency in the canopy. A hedgerow model for partitioning sunlit and shaded foliage and soil in the field of view (Kimes and Kirchner, 1983) also indicated that nadir sighting should produce the largest temperature readings. Kimes, Smith and Link (1981) combined radiative, convective and diffusive energy transfer between canopy layers to

account for sighting angle dependence of a forest canopy infrared temperature measurements. Their model predicts a maximum temperature reading at nadir sighting. Huband and Monteith (1986) also found a zenithal and azimuthal dependence of the infrared temperature reading of winter wheat. However, their data show that the maximum temperature reading is at a sighting angle close to the sun zenith angle and not at nadir.

The composition of the field of view is a function of the angle β between the sighting line of the instrument and the solar beam. From simple solid geometry β is:

$$\cos\beta = \cos\theta \cos\delta + \sin\theta \sin\delta \cos\phi \quad (20)$$

where θ is the solar zenith angle, δ is the sighting zenith angle of the thermometer, and ϕ is the azimuth of the sighting line with respect to sun orientation ($\phi = 0$ when the sun rays and the thermometer point in the same direction).

For the spherical leaf angle distribution, the fraction of sunlit leaves with inclination α relative to the sun rays included in the field of view is:

$$C[\alpha, \beta] = 0.5 + \mu/\pi \quad (21)$$

where

$$\sin\mu = \cot\alpha \cot\beta \quad (22)$$

Equation (22) defines μ only if $|\cot\alpha \cot\beta| \leq 1$. When $\cot\alpha \cot\beta \leq -1$ then $\mu = -\pi/2$, in which case all leaves irradiated at angle α are excluded from the field of view. If $\cot\alpha \cot\beta \geq 1$ then $\mu = \pi/2$, meaning that all leaves irradiated at angle α are in the field of view. Sunlit leaves not included in the field of view are replaced by shaded leaves. Approximating σT^4 with a linear function over the temperature range of the leaves, the temperature T_{IR} , sensed by the infrared thermometer sighting the canopy at angle β with respect to the sun, is:

$$T_{IR} = \sum (C[\alpha, \beta] T_L[\alpha] + (1-C[\alpha, \beta]) T_L[s]) A[\alpha] \quad (23)$$

where the summation is performed for the 18 classes of α used in the computations. Equations (20) and (23) establish that the angular structure of temperature distribution, determined by Eq. (18), is the main cause for the zenithal and azimuthal variation of infrared thermometer readings of canopies densely covering the soil.

Figure 5 illustrates Eq.-(23) when the line of sight of the infrared thermometer is in the same vertical plane as a sun ray. The environmental and stress conditions are those defined in Figure 1. The sighting zenith angle δ is varied from -90 to 0° when the instrument pointed at the canopy is facing the sun ($\phi = \pi$), and from 0 to 90° when the line of sight and the sun rays impinge on the surface with the same orientation ($\phi = 0$). The maximum temperature reading is obtained when sighting is at the solar zenith angle as measured by Huband and Monteith (1986). In this case, all the foliar area included in the field of view is sunlit. Canopy temperature readings with the instrument pointed at the target from the same direction as sun rays, are considerably warmer than in the opposite orientation. Measurements at large zenith angle are lower and therefore less sensitive to water stress. These results are in agreement with reported measurements (Fuchs et al., 1967; Kimes et al., 1980; Kimes, 1981; Nielsen et al., 1984). Water stress increases the angular variability of the temperature measurement.

When the sun is lower on the horizon, the variation in the temperature reading caused by orientation is increased (Fig. 6). The figure shows a case for which a large zenith angle of the line of sight yields a higher reading than nadir viewing. However, this occurs only when the instrument points toward the canopy from the same side as the sun rays. This result is of interest for canopies with low leaf area index, which require a large zenith sighting angle to avoid including bare soil in the field of view.

Orienting the infrared thermometer at 90° from the sun (Fig. 7) produces a maximum temperature reading at nadir sighting angle, but this maximum is lower than the one obtained in Figure 5 for the same conditions. On the other hand, the minimum temperature at grazing incidence is raised. This orientation thus, diminishes the dependence of temperature reading on sighting zenith angle. When the sun is near the zenith, as in Figure 7, the infrared thermometer oriented at $\phi = \pi/2$ measures temperatures similar to those at $\phi = 0$. For the same orientation, but with the sun at 60° zenith angle, the greatest temperature differences between stress levels are those shown for nadir sighting in Figure 6. In this case the orientation $\phi = \pi/2$ will not detect stress-induced temperature differences.

TEMPERATURE DEFINITION OF WATER STRESS

Proper sighting can improve the performance of infrared thermometers. In order to detect plant water stress by leaf temperature measurement, it is necessary to remove the masking effect caused by changes in the aerial environment. A crop water stress index referring plant water status to the

temperature difference between the canopy and the air, as a function of the water vapor deficit in the atmospheric surface layer has been proposed (Jackson, Idso, Reginato and Pinter, 1981). The effect of radiation is minimized by taking the measurements at noon on clear days. Figure 1 shows that the definition of a mean canopy temperature for use in the crop water stress index is not a trivial problem. The concept is illustrated in Figure 8 using the computed mean temperature of the sunlit foliage, which was shown in Figure 6 to be the infrared reading most sensitive to stress.

The isopleths for the three stress values defined in Eq. (12) indicate a mere 1°C difference between adequate plant water status and an urgent need for irrigation. The lines obtained by modeling the canopy as a single large leaf, are straight (Jackson et al., 1981). The slight curvature caused by the temperature distribution within the foliage may blur moderate stress diagnosis. Severe stress, causing irremediable damage, produces a much higher canopy temperature. Its detection is therefore less sensitive to the non linearity found in Figure 8.

The crop water stress index does not normalize the effect of wind on leaf temperature. Figure 9 shows that low wind speeds increase canopy temperature, especially when humidity is high. These effects have been measured in the field (O'Toole and Hatfield, 1983).

CONCLUSIONS

The foregoing analysis confirms that the detection of water stress by a canopy temperature measurement must account for the effects of meteorological factors on the energy balance of the foliage (Jackson et al., 1981). The temperature averaging process which occurs in the field of view of infrared thermometers limits the ability of these instruments to detect the moderate stress level above which crop productivity is reduced. Sensitivity is improved when sighting is parallel to incident sun rays. Thus, for the measurements taken during noon hours when the radiative heat load is highest, near nadir sighting is recommended. However, nadir sighting in sparse vegetation and row crops introduces an error not discussed in this paper, by increasing the proportion of bare soil in the field of view (Kimes et al., 1980; Kimes and Kirchner, 1983).

Water stress raises the temperature of the foliage, but it also widens the range of temperature variation within the canopy. Measuring the surface temperature with high spatial resolution can determine temperature frequency distribution. Digital thermal images collected by infrared scanners can provide the needed data. Combining this information with data on the foliage

geometrical structure and meteorological conditions would considerably improve radiometric detection of plant water stress.

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CAPTIONS

Fig. 1 Effect of leaf conductance on the leaf temperature frequency distribution determined for a set of standard meteorological parameters.

Fig. 2 Same as Figure 1, but the solar zenith angle has been increased from 15 to 60°.

Fig. 3 Same as Figure 1, but the relative humidity has been raised from 50 to 70%.

Fig. 4 Same as Figure 1, but the wind speed has been increased from 4 to 6 m s⁻¹.

Fig. 5 Effect of sighting zenith angle on the infrared temperature reading when the line of sight is in the same vertical plane as an incident sun ray. The sun zenith angle is 15°.

Fig. 6 Same as Figure 5, but the sun zenith angle is 60°.

Fig. 7 Effect of sighting zenith angle on the infrared temperature reading when the line of sight is in a vertical plane perpendicular to the vertical plane of an incident sun ray. The sun zenith angle is 15°.

Fig. 8 Normalizing water stress evaluation by infrared canopy temperature measurements for the effect of water vapor pressure deficit in the atmosphere.

Fig. 9 Demonstrating that the normalizing procedure shown in Figure 8 is influenced by wind speed.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

SCIENTIFIC REPORT #2

CANOPY TEMPERATURE-BASED ESTIMATES OF AERODYNAMIC
RESISTANCE AND LATENT HEAT FLUX OF COTTON IN TEXASW. A. DUGAS¹

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ABSTRACT

Dugas, W.A. 1990. Canopy temperature-based estimates of aerodynamic resistance and latent heat flux of cotton in Texas. Agric. For. Meteorol., XX:0000-0000.

Hand-held infrared thermometers (IRTs) are inexpensive, simple to operate, and capable of integrating aspects of the spatially-variable field environment (e.g. soils) into one measurement of the canopy temperature (T_c). Since T_c is a boundary condition governing latent heat flux (LE) from a surface, these sensors may be appropriate for improving the efficiency of water use in row-crop agriculture. The use of IRTs for estimation of LE or stress often implicitly or explicitly involves the use of aerodynamic resistance (r_{ah}). The objective of this work was to compare temperature-derived values of r_{ah} (r_{ahT_c}) and LE (LE_{T_c}) with 'standard' values (r_{ahSt} and LE), calculated from the logarithmic wind profile and Bowen ratio/energy balance measurements, respectively. At Temple, TX, in 1988 and 1989 and at Uvalde, TX, in 1989, 30-min. measurements were made of wind and dew point and dry bulb temperature profiles, net radiation, soil heat flux, and T_c over cotton (Gossypium hirsutum L.). There were differences of $\pm 1^\circ\text{C}$ between T_c measurements from two IRTs which were oriented at different azimuth angles. Temperature differences varied depending upon the angle between the sun and sensor azimuths. The r_{ahSt} values were consistent over the three sites ($\approx 50 \text{ s m}^{-1}$), but r_{ahT_c} values were consistently lower, suggesting T_c values measured by IRTs were not an adequate representation of the 'average' canopy temperature. The standard LE values and those calculated using net radiation, soil heat flux, and T_c measurements were similar, primarily because estimated sensible heat flux at these sites was small and net radiation and soil heat fluxes were large. These results show that the use of IRTs for estimating aerodynamic resistance and latent heat flux from cotton may be suspect.

INTRODUCTION

Demands for water by the agricultural, industrial, and urban sectors nearly tripled in the United States between 1960 and 1975 and are continuing to increase (Anderson, 1983). In Texas, annual water use is about 23×10^{12} L, and over 70% of this is used by agriculture (Texas Dept. Water Resources, 1984). As the demand for water increases and the supply of water decreases, the efficiency with which water is used in irrigated row-crop agriculture is an important question.

Modern irrigation systems often provide for precise control over the timing and amount of water applied. But this accurate supply system may not be sufficient for maximizing water use efficiency without information on plant water needs. Estimates of plant water need, which is closely coupled to water use, should be field-scale, timely, easy-to-use, and accurate. Many water use and plant stress measurement techniques (e.g. micrometeorological techniques, plant water potential measurements) do not meet these conditions.

Hand-held infrared thermometers (IRTs) are inexpensive, simple to operate, and capable of integrating aspects of the spatially-variable field environment (e.g. soils) into one measurement of the canopy surface temperature (T_c). These attributes make this an instrument which may be appropriate for improving the efficiency of water use in row-crop agriculture since the surface temperature is a boundary condition governing latent (LE) and sensible (H) heat flux, and, thus, also may be an indicator of plant stress.

The use of IRTs for estimation of LE (or stress) often implicitly or explicitly involves the use of aerodynamic resistance (r_{ah}). Therefore to evaluate the utility of using IRTs for estimation of stress or LE, it is appropriate to determine if resistances and LE values calculated using T_c values are accurate. The objective of this work was to compare temperature-derived values of r_{ah} (r_{ahT_c}) and LE (LE_{T_c}) for cotton (*Gossypium hirsutum* L.) with 'standard' values calculated from the logarithmic wind profile and Bowen ratio/energy balance measurements, respectively.

METHODS

Measurement sites

Measurements were made in cotton fields at the Blackland Research Center, Temple, TX, (31°06'N, 97°20'W, elevation = 219 m) in 1988 and in 1989 and near Uvalde, TX, (29°13'N, 99°45'W, elevation = 279 m) in 1989. Agronomic and measurement details of each study site varied (Table 1), but all

measurements were made when leaf area index (LAI) values were relatively high and crop height was above 0.7 m. Instrumentation was positioned in each field to ensure adequate fetch with the predominant southerly winds. At Temple in 1988, a 1.0 ha area of the field was sprinkler irrigated, with approximately 80% of this area upwind of the instrumentation. At Temple in 1989, the unirrigated field was located about 1 km west of the field used in 1988. At Uvalde, measurements were made on a commercial farm; the entire field was furrow irrigated. The soil at Temple was a Houston Black clay (fine, montmorillonitic, thermic Udic Pellustert), while the soil at Uvalde was a Uvalde silty clay loam (fine-silty, mixed, hyperthermic Aridic Caciustolls). Routine fertility and insect and weed control practices were followed at all sites.

Measurements

The following measurements were made at all sites:

1.) Wind profile. Ten-minute averages of wind speed were measured at five levels using four Model 12012 three-cup generator anemometers and, at the lowest level, one model 12012D three-cup photo chopper anemometer (R.M. Young, Traverse City, MI). Anemometers were logarithmically positioned, with the lowest level about 0.2 m above the crop height and the upper level at about 4.5 m above the soil. All anemometers were calibrated against a 'standard' anemometer (i.e. a new photo chopper) using the factory calibration.

2.) Dew point temperature profile. Dew point temperature profiles were measured at three levels using two model DEW10 cooled mirror hygrometers (General Eastern, Watertown, MA). For each mirror, air from two funnels was passed over the mirror for 1 min., switching every 1 min. Dew point measurements were for the last 30 s of each minute, sampling every 2 s. Since dew point measurements by each mirror varied ($\approx 0.5^\circ\text{C}$), one funnel from each mirror was mounted at the same height (the middle height) and the dew point profile was calculated from the two two-level gradients. Funnel heights were the same as the first, second, and fourth measurement arms (from the ground up) of air temperature profile (see below). Vapor pressure was calculated from dew point temperatures.

3.) Air temperature profile. Four levels of air temperature (T) were measured by un aspirated, unshielded, chromel/constantan fine-wire (diameter: 25 μm) thermocouples. Two values of T were measured at each height and these were averaged. Thermocouples were referenced to an aluminum block buried at 0.5 m in the soil, whose temperature was measured with a thermocouple. Temperatures were sampled every 2 s. Sensor heights were geometrically spaced with the lowest sensors about 0.2 m above crop height and the upper sensors

about 3 m above the ground.

4.) Net radiation (R_n). The R_n was measured with a model 6220 net radiometer (Science Assoc., Princeton, NJ) which was calibrated over a grass surface against a laboratory standard (same model) before each season.

5.) Soil heat flux (G). The G was measured using three model 1081 heat flux plates (Sci. Assoc.) buried at 0.1 m at positions under and between plant rows. Spatially-averaging thermocouples were buried at a depth of 0.1 m near the plates. The G was calculated from the flux at and the storage above 0.1 m. Corrections were made for differences in plate and soil conductivity and the effects of plate shape (Philip 1961).

6.) Canopy temperature. The T_c was measured with two Model 4000.2 chopper-stabilized IRTs (Everest Interscience, Fullerton, CA). Signals were sampled every 15 s. The IRTs had a 15° field of view, were mounted about 0.5 m above the canopy height, were oriented at an angle of about 30° from the horizontal, and had azimuth angles that varied at each site (Table 1). Each IRT viewed a canopy area of approximately 0.4 by 0.2 m (O'Toole and Real, 1984). IRT signals were adjusted, by adding 0.5°C , for the reflected background thermal radiation (Fuchs and Tanner, 1966). Signals were sampled every 15 s and were averaged for 30 min. periods.

7.) Wind direction. Wind direction was measured with a Model 024 wind direction sensor (Met-One).

8.) Leaf area index (LAI). The ratio of photosynthetically active radiation (PAR), measured below and above the canopy, was used with an extinction coefficient (-1.26) in Beer's Law to estimate the LAI. The extinction coefficient was calculated from simultaneous measurements of leaf area and PAR above and below the canopy at Temple in 1988. Two model LI191SB sensors (LiCor Corp. Lincoln, NE) were mounted adjacent to and parallel with each other above the canopy before and after the measurements to determine the relationship between them. Above- and below-canopy PAR measurements were made near solar noon on selected days at each site at several positions in each field. The LAI was higher at the irrigated sites (Table 1). Plant height was also measured on approximately 10 to 20 plants at all sites (Table 1).

Aerodynamic resistance

Half-hour values of the standard value of r_{ah} (r_{ahSt}) were calculated from the following (Monteith, 1973):

$$r_{ahSt} = [\ln((z-d)/z_{om}) - \Psi_h + \ln(z_{om}/z_{oh})] / (k \cdot u^*) \quad (1)$$

where z is the measurement height (1.5 m above the soil surface), d is the

roughness length (m), z_{om} and z_{oh} are the momentum and sensible heat flux zero plane displacements (m), Ψ_h is the heat stability correction, k is von Karman's constant, and u^* is the friction velocity ($m\ s^{-1}$). The d was calculated from canopy height (Stanhill, 1969) and was assumed to be equal for momentum, heat, and vapor. Errors in estimating d are not critical if $z \gg z_{om}$ (Brutsaert 1982), which it was. The Ψ_h was calculated following the method of Choudhury et al. (1986).

The z_{om} values were calculated (Thom 1975) from the intercept of the regression line of u vs. $\ln(z - d)$. The z_{oh} was calculated from the following (Rosenberg et al. 1983, p. 126)

$$z_{oh} = z_{om} / \exp(k \cdot B^{-1}) \quad (2)$$

where B^{-1} was equal to $u^* \cdot r_{ex}$, and r_{ex} , the 'excess' leaf boundary layer resistance, was equal to $4/u^*$ (Thom, 1972). The u^* was calculated (Rosenberg et al. 1983, Eq. 4.2) as an average of the values from all anemometer heights. The range of the five 30-min. u^* values was almost always $< 0.05\ m\ s^{-1}$.

The T_c -based r_{ah} (r_{ahTc}) was calculated from the following:

$$r_{ahTc} = \rho \cdot C_p \cdot (T_c - T) / H \quad (3)$$

where ρ is the air density ($kg\ m^{-3}$), C_p is the specific heat of dry air ($J\ kg^{-1}\ C^{-1}$), and H ($W\ m^{-2}$) was calculated from the R_n , G , and Bowen ratio (β) measurements (see below). The two T_c values were averaged. The T values from the profile height nearest 1.5 m were used to calculate $T_c - T$. The 30-min. resistance values were averaged for daylight periods (see below).

Latent heat flux

The energy balance of a two-dimensional surface can be described by the following:

$$R_n = LE + H + G \quad (4)$$

The sign convention used herein was that R_n toward the surface and LE , H , and G away from the surface were positive.

The Bowen ratio/energy balance is a micrometeorological method for LE measurements that has been used often with good results (Tanner, 1960; Fritschen, 1965; Blad and Rosenberg, 1974), with a typical accuracy of about 10% (Sinclair et al., 1975). The LE is calculated from the following:

$$LE = (R_n - G)/(1 + \beta) \quad (5)$$

where β was calculated from the following:

$$\beta = [(P \cdot C_p)/(L \cdot e)] \cdot [(d\theta/dz)/(de/dz)] \quad (6)$$

where P is atmospheric pressure (kPa), L is latent heat of vaporization (MJ kg^{-1}), e is ratio of the mole weights of water to air, and $d\theta/dz$ and de/dz are above-canopy potential temperature ($^{\circ}\text{C m}^{-1}$) and vapor pressure (kPa m^{-1}) gradients. In Eq. (8), it was assumed the eddy diffusivities for heat and water vapor were equal. Values of $d\theta/dz$ and de/dz were calculated as finite differences using the extreme upper and lower air temperature and dew point measurements, respectively.

Daylight LE totals were summed from the 30-min. fluxes calculated from Eq. (7). The daylight period was typically from 0700 through 1800 h Local Standard Time (LST), although equipment malfunction and precipitation resulted in some partial days.

The T_c -based LE estimates were calculated from the following:

$$LE_{T_c} = R_n - G - H_{T_c} \quad (7)$$

where H_{T_c} was calculated from the following:

$$H_{T_c} = \rho \cdot C_p \cdot (T_c - T)/r_{ahu} \quad (8)$$

where r_{ahu} was calculated from wind speed (Thom and Oliver, 1977).

RESULTS

Meteorological conditions

Values of net radiation, maximum temperature, and wind speed and direction were similar at the three study sites (Table 2). Soil heat flux values were greater at Temple in 1989 because of the lower LAI. Precipitation totals varied.

Canopy temperatures

Differences ($\pm 1^{\circ}\text{C}$) between T_c measurements from the two IRTs (Fig. 1) depended upon sensor (Table 1) and solar azimuth angles. At Temple in 1988, the IRT with an azimuth of 280° (i.e. essentially pointed to the west) had a greater temperature in the morning than the IRT at an azimuth of 180° because

its azimuth angle was similar to that of the sun (Fuchs, 1991). In the afternoon, temperatures from this sensor were less than the other sensor. At Temple in 1989, T_c differences were smaller, likely because both sensors had azimuth angles toward the north and not directly east or west. Differences still reflected the same trend, however. Before noon, temperature differences were negative, i.e. measurements from the IRT with an azimuth of 340° were greater; they were less than the other sensor just after noon. At Uvalde, the IRT at an azimuth of 100° was 'seeing' the back of sunlit leaves before noon more than the other sensor and thus temperature differences were positive. All of these data are supportive of the measurements and modelling results, respectively, of Huband and Monteith (1986) and Fuchs (1991). Considering the effects a 1°C difference in T_c could have on empirical or theoretical stress indices (Stockle and Dugas, 1991), these T_c differences have implications for using IRTs for estimating water use or determining crop stress levels. The T_c differences between the two IRTs were $< |0.3^\circ\text{C}|$ at night at all sites (results not shown).

Aerodynamic resistance

Averages of r_{ahst} values were consistent over the three sites (Table 3), due primarily to similarities in wind speed (Table 2). However, daily r_{ahTc} values were generally less than r_{ahst} values (Fig. 2 and Table 3). The extreme positive and negative r_{ahTc} values were caused by measured H values near 0 [Eq. (3)]. Thus, there was more scatter at the irrigated sites of Temple in 1988 and Uvalde in 1989 because H was closer to 0. This consistent underestimate of resistance suggest T_c measurements, primarily of the cool, upper portion of the canopy, were lower than the 'average' canopy temperature which was the driving gradient for sensible heat flux [Eq. (3)]. These data are supported by the modelling work of Fuchs (1991). The smaller root mean square error at Temple in 1989 (Table 3) also suggests the difference between 'radiative' and 'aerodynamic' temperatures (Huband and Monteith, 1986) is decreased as LE decreases and H increases. The irrational negative r_{ahTc} values (Fig. 2) are associated with times when the sign of $T_c - T$ did not match the sign of the measured H [Eq. (3)].

At Temple in 1989 (where differences between the two resistances were least, Table 3), r_{ahst} and r_{ahTc} differences were consistent throughout the day on 22 July 1989 (Fig. 3). The instability of r_{ahTc} values early in the morning and late in the day was associated with $H \approx 0$ [Eq. (3)], while the large r_{ahst} values in the morning were due to low wind speeds. There was little difference in resistances calculated using daylight averages of the variables

[Eqs. (1 and 3)] as opposed to averaging the 30-min. resistance values for the daylight period (results not shown).

Latent heat flux

Means of LE calculated from Bowen ratio/energy balance measurements [Eq. (5)] and from measurements of net radiation, soil heat flux, and T_c [Eq. (7)] differed by <20% (Fig. 4 and Table 3). Differences in LE between sites were due to differences in soil water and LAI (Table 1). Even though mean LE values were reasonably close, the root mean square errors between the LE values were large (Table 3), varying from 37 to 89 W m^{-2} (~ 0.5 to 1.3 mm d^{-1}). These errors are even more significant considering that H values at these sites were relatively small (mean β varying from 0.05 to 0.6). Thus, errors in H_{rc} [Eq. (8)] did not translate into large LE errors. Had β values been larger, LE errors would have been larger.

At Temple on 2 July 1988, LE values calculated from β measurements were consistently lower (Fig. 5). The underestimate of the 'true' T_c by the IRT decreased H_{rc} , which increased LE_{rc} [Eqs. (7 and 8)]. Differences of LE varied from 20 to 80 W m^{-2} and were greatest around noon. On this day sensible heat flux values were generally < 100 W m^{-2} .

CONCLUSIONS

These results show that the potential use of infrared thermometer (IRT) measurements of canopy temperature (T_c) for estimating aerodynamic resistance (r_{ah}) and latent heat flux (LE) from cotton may be limited because, among other reasons, of the following:

- 1.) Canopy temperatures (T_c) measured by two infrared thermometers (IRTs) differed by $\pm 1^\circ\text{C}$ throughout the day, depending upon solar and sensor azimuth angles.
- 2.) Values of r_{ah} and calculated from T_c measurements were consistently less than those calculated using standard methods.
- 3.) Latent heat flux estimated from measurements of available energy and T_c were reasonably close to measured values, but the scatter was large, even though under these conditions calculated LE values were relatively insensitive to errors in T_c measurements.

However, for a specific crop, soil, and sites, IRTs may, with local calibration, provide a relative measure of stress or LE.

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Table 1. Agronomic and measurement details at study sites.

Item	Temple 1988	Temple 1989	Uvalde 1989
Variety	GP3774	GP3774	Delta-Pine 20
Pl. date	5.4.88	12.4.89	11.4.89
Pl. Den. (m ⁻²)	15	15	10
Row Spac. (m)	0.67	0.76	1.0
Row direction	NE-SW	E-W	N-S
Irrigation	Yes	No	Yes
Period of measurements	160-207 (I) 235-250 (II)	210-215	220-229
IRT azimuth (Deg.)	180 and 280	40 and 340	60 and 100
Crop Ht. (m)	0.8 (I) 1.0 (II)	0.7	0.95
LAI	2-3	0.8	2.2
Field size/dimension	5 ha	96 m E-W by 303 m N-S	192 m E-W by 720 m N-S
Equip. position	Fetch: ca. 150 m with S winds	230 m N and 40 m E of SW corner	112 m S and 64 m E of NW corner

Table 2. Typical values of climatic elements during period of measurements (see Table 1) at three study sites. Midday values for clear days are shown for net radiation and soil heat flux, and daylight averages of wind speed and direction are shown. I and II correspond to two measurements periods at Temple in 1988 (Table 1).

Element	Temple 1988	Temple 1989	Uvalde 1989
Net radiation (W m^{-2})	500-600 (I) 500 (II)	500	500-600
Soil heat flux (W m^{-2})	100(I) 50 (II)	150	100
Max. Temp. ($^{\circ}\text{C}$)	34 (I and II)	34	32
Total Precip. (mm)	184 (I) 0 (II)	70	17
Wind speed (m/s)	2-3 (I and II)	3	3
Wind direction	SSE (I) SE (II)	S	ESE

Table 3. Average daylight values of 'standards' of aerodynamic (r_{ah}) resistance and latent heat flux (LE) at three sites. Bias and RMSE represent the average difference and the root mean square error between standard value and canopy temperature-based value.

Value	Site	Average	Bias	RMSE
r_{ah}	Temple 1988	46 s/m	17 s/m	54 s/m
	Temple 1989	53	17	22
	Uvalde 1989	53	17	53
LE	Temple 1988	328 W m ⁻²	-47 W m ⁻²	65 W m ⁻²
	Temple 1989	161	29	37
	Uvalde 1989	289	13	89

FIGURE CAPTIONS

Fig. 1. Difference (#1 - #2) in canopy temperature measured by two infrared thermometers at Temple in 1988 (22 July) and in 1989 (30 July) and at Uvalde in 1989 (16 August). The two thermometers were oriented at azimuths of 280° (#1) and 180° (#2) at Temple in 1988, of 40° and 340° at Temple in 1989, and of 60° and 100° at Uvalde in 1989.

Fig. 2. Daylight averages of aerodynamic resistance calculated using the standard equation (r_{ahST}) and calculated from canopy temperature measurements (r_{ahTc}) at Temple in 1988 and 1989 and Uvalde in 1989. The 1:1 line is shown. (One value at Temple in 1988 with $r_{ahTc} = 20 \text{ s m}^{-1}$ and $r_{ahST} = -95 \text{ s m}^{-1}$ is not shown for clarity).

Fig. 3. Half-hour values of aerodynamic resistance (r_{ah}) on 22 July 1989 at Temple calculated from canopy temperatures and using the standard equation.

Fig. 4. Daylight averages of latent heat flux calculated from Bowen ratio/energy balance measurement (LE_{BR}) and as a residual in the energy balance equation where sensible heat flux was calculated from canopy temperatures (LE_{RESID}) at Temple in 1988 and 1989 and Uvalde in 1989. The 1:1 line is shown.

Fig. 5. Half-hour values of latent heat flux (LE) on 2 July 1988 at Temple calculated from Bowen ratio/energy balance measurement (BR) and as a residual in the energy balance equation where sensible heat flux was calculated from canopy temperatures (RESID).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

SCIENTIFIC REPORT #3

SUNLIT AND SHADED STOMATAL RESPONSES OF FIELD GROWN COTTON
TO RADIATION AND SOIL MOISTURE¹K.L. Petersen, S. Moreshet and M. Fuchs²

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ABSTRACT

Field research conducted on stomatal responses to water stress have generally focused on sunlit leaves and ignored the role of shaded leaf conductance. This study was carried out on a cotton crop (Gossypium hirsutum, cv. Acala SJ2) to quantify and compare sunlit and shaded stomatal conductance under variable water stress conditions, and to identify the primary environmental parameters regulating the stomatal conductance of sunlit and shaded leaves. Photosynthetically active radiation (PAR), leaf temperature, humidity, and stomatal conductances for both abaxial and adaxial leaf surfaces were measured on cloudless days during two field seasons in 1988 and 1989. Average daytime shaded leaf conductance was approximately 31% and 27% that of sunlit leaves in non-stress and severe water stress conditions, respectively. The primary environmental parameter affecting sunlit leaf conductance was PAR. Shaded leaf conductance was weakly correlated to PAR and leaf temperature, respectively, under non-stress conditions. Under water stress, shaded and sunlit leaf conductances were not correlated to leaf temperature. Leaf conductance was not observed to be correlated to humidity under all conditions. Stomatal conductance response to PAR decreased as PAR increased, with most of the change occurring in the PAR range typically obtained in the shaded fraction of the canopy. Increasing moisture stress progressively decreased the stomatal response to PAR. When sunlit and shaded leaves were pooled together, a curvilinear regression improved the correlation with PAR. Abaxial conductance comprised a greater percentage of leaf conductance for shaded than for sunlit leaves.

Additional Index Words: Gossypium hirsutum, cv. Acala SJ2, stomatal conductance, photosynthetically active radiation, water stress.

Sunlit leaves are the sites where most of the solar radiation impinging on a crop is absorbed and converted into sensible, latent and chemical energy. Studies investigating the stomatal conductance of a crop have likewise focused on the sunlit leaves, while relatively little attention has been given to shaded leaf stomatal conductance (Bielorai et al., 1983). However, with most crops, including cotton, the sunlit leaves often represent only a minor fraction of the total leaf area. Modeling the stomatal conductance of both sunlit and shaded leaves under varying soil moisture regimes is useful in understanding the influence of stress on crop growth and development (Ephrath, 1987), and in providing a more accurate parameterization of the stomatal input for certain meteorologically based transpiration estimates (Fuchs et al., 1987; Allen et al., 1989). From the standpoint of computing crop transpiration, neglecting the shaded leaf resistance can lead to erroneous estimates. Although the water loss per unit leaf area of a shaded leaf may be several times smaller than that of a sunlit leaf, the contribution of shaded leaves to overall canopy transpiration may be significant by virtue of the large, shaded leaf area in the later stages of the growing season.

For sunlit cotton leaves, researchers have related stomatal resistance to soil water potential (Bielorai and Hopmans, 1975), leaf water potential (Ackerson et al., 1977; Cutler and Rains, 1977; Davies, 1977; Ackerson, 1980; Radin et al., 1985), ABA accumulated in the leaf (Ackerson, 1980), intercellular CO_2 (Radin and Ackerson, 1981), and light incident to the leaf surface (Ackerson et al., 1977; Davies, 1977; Moreshet and Falkenflug, 1978). Under well watered soil conditions, Moreshet and Falkenflug (1978) found that cotton sunlit leaf stomatal conductance was linearly related to incoming solar flux density with a high degree of certainty ($R^2 = 0.97$). Ackerson et al. (1977) reported that stomatal conductance responded primarily to radiation intensity incident at the leaf surface, with vegetative and reproductive leaves responding similarly. Ackerson et al. (1977), and Moreshet and Falkenflug (1978) indirectly, also found that the influence of diurnal leaf water potential changes on the relationship of stomatal conductance to incident radiation was small. However, the development of soil moisture stress over a period of several days shifted the stomatal response to light. Fuchs and Moreshet (1985) proposed a two-step linear function to describe the stomatal response to light under water stress conditions, but their data set was too small to account for the random variability of stomatal conductance in the field. In non-stress conditions, the stomatal response function of Moreshet and Falkenflug (1978) was applied to model transpiration (Fuchs et al., 1987).

Shading effects on cotton stomatal conductance have been investigated in

greenhouse and growth chamber work (Pasternak and Wilson, 1973; Nagarajah, 1975). Field studies in relation to cotton shaded leaf stomatal conductance and environmental parameters are lacking, whether with or without soil moisture stress. Cotton stomata of field grown plants are less sensitive to decreases in leaf water potential than stomata of greenhouse or growth chamber plants, and under growth chamber conditions plants exhibit higher photosynthetic rates (Davies, 1977). For these reasons, stomatal studies conducted in the greenhouse or growth chamber cannot be reliably applied to field conditions.

This study was conducted to quantify and compare the sunlit and shaded leaf stomatal conductance responses of field grown cotton to environmental factors, influenced by varying soil moisture regimes. Light, humidity and leaf temperature were measured simultaneously to stomatal conductance in the field to examine their separate or combined influence on stomatal opening. Possible explanations for differing stomatal conductance response to radiation in the sun and shade are discussed. Abaxial and adaxial conductances were examined as well as total stomatal conductance.

MATERIALS AND METHODS

Field description

The study was conducted during the summers of 1988 and 1989 in a large commercial cotton (*Gossypium hirsutum*, cv. Acala SJ2) field operated by Kibbutz Na'an in central Israel: latitude, 32° 20'N; longitude, 34° 45'E; altitude, 100 m. Seed was sown in rows 0.96 m apart in early April in a Typic Chromoxerert soil. Volumetric soil water content was measured at 0.289 and 0.494 m³ water per m³ soil at soil water potentials of -1.5 and -0.03 MPa, respectively. Fertilizer and pest control were carried out according to standard commercial practices. Plant population density about 80,000 plants ha⁻¹ in both years. Cotton yield was similar to that of the commercial fields surrounding the experimental area.

Irrigation

Watering was done with a drip irrigation system employing one lateral per row. Drip emitters were spaced 1 m apart and delivered 1 liter h⁻¹. Soil moisture stress was allowed to develop over two consecutive periods after early July in 1988, and over three consecutive periods in after late June in 1989, with soil moisture being restored to field capacity at the end of each period. No rain fell during either summer.

Porometry and leaf water potential

A model LI 1600 Steady State Porometer (LI-COR, Lincoln, NE, USA) was used to measure stomatal conductance. Before each set of measurements within

a day, the cuvette was acclimated to ambient conditions. Porometry data were gathered on 8 separate days between June 30 and August 7 in 1988; and on 8 days between June 27 and August 15 in 1989. Measurements were taken at half-hourly or hourly intervals throughout the day, beginning no earlier than 9.00 a.m. Israel standard time, to avoid any influence of dew on the shaded leaves. Only measurements from cloudless days are reported. Measurements were made first on the abaxial (lower) and then on the adaxial side of each sunlit and shaded leaf measured. The sensor head of the porometer was held at the natural position and angle of the leaf during measurement of the abaxial stomatal conductance. For the adaxial stomatal conductance, the same leaf was inverted and the measurement was taken on the same lobe of the leaf, in the same position opposite the abaxial measurement. Measurements were taken to determine whether touching the adaxial surface prior to the adaxial reading (touching occurring from the clamp pad when reading the abaxial side), influenced the adaxial reading. No effect was observed.

Individual leaf conductance measurements were analyzed against contemporary environmental parameters. Leaves were measured on plants chosen at random in the field. A "sunlit leaf" was classified after the following criteria: a fully expanded leaf which must be completely sunlit. A "shaded leaf" was classified as a fully expanded leaf (main stem or subtending leaf) located at a height approximately one-half that of average canopy height, which is fully shaded from direct solar radiation. Leaves which showed any signs of insect damage or senescence were avoided. Shaded leaves were measured on the side of the row opposite the side of impinging solar radiation, except at solar noon. At solar noon, shaded leaves were selected from the side of the row that had been in the shade before solar noon. The range of photon flux density on sunlit leaves was achieved by selecting leaves of many different orientations and angles to the sun, and by using neutral filters covering 3 m x 3 m sections in the field at random. When the neutral filters were used, they were set up in the evening of the day just prior to the measurements in an untouched area of the field.

Indices of water stress

Indices of water stress were identified by measuring percent soil moisture availability, and the midday leaf water potential. Volumetric soil moisture content was monitored with a neutron scattering device (Ronli Electronics, Rishon LeZion, Israel) in the upper 1.20 m of soil throughout the growing season, to assess the percent soil moisture availability on the basis of the volume of water held between -1.5 and -0.03 MPa soil water potential. Leaf water potential (Arimad 2, ARI, Kfar Charuv, Israel) was measured both seasons in the experimental plot at approximately 1200 hours Israel standard

time on sunlit and shaded leaves meeting the same criteria as for the porometry measurements. Leaf water potential data presented in Table 1 were measured on the same day as porometry measurements, but not necessarily on the identical leaves sampled by the porometer. To avoid sources of error in leaf water potential measurements, leaves were wrapped in a plastic bag at the time of excision, and measured less than 30 seconds after excision (Meron, Grimes, Phene, and Davis, 1987).

Light, humidity and leaf temperature

Photosynthetically active radiation (PAR, 400-700 nm waveband) was measured by a quantum sensor (LI-190S-1, Licor, Lincoln, NE, USA) mounted on the porometer's sensor head parallel to the plane of the leaf area sampled. As the sensor head was held at the angle and approximate position of the leaf being sampled, a corresponding measure of PAR impinging on the leaf could thus be estimated. The PAR for the abaxial and the adaxial readings was recorded as the PAR when abaxial stomatal conductance was measured; that is, the PAR striking the adaxial leaf surface. This was the case because the leaf was not moved from its natural position and angle for the abaxial stomatal conductance measurement, whereas it had to be inverted for the adaxial measurement. Thus, PAR and abaxial porometry measurements were simultaneous. Humidity (in 1988 - Model 201, Campbell Scientific, Logan, UT, USA; in 1989 - SKH 1012, Skye Instruments, Llandrindod Wells, UK) was measured 2 meters above the canopy surface at an automated meteorological station in the field. Data were averaged for 30 minute periods and recorded with a CR-21 datalogger (Campbell Scientific). Leaf temperature was measured with an IR thermometer (Telatemp 43S, Fullerton, CA, USA) fitted with a parallax corrected scope to sight precisely the adaxial surface of an individual leaf. Sunlit and shaded leaves were measured with the IR thermometer in this manner immediately before each porometer reading.

RESULTS

Indices for levels of stress corresponding to the leaf conductance data are presented in Table 1. Midday sunlit leaf water potential became more negative with the progressive depletion of available soil moisture. The mild water stress index was set at -1.8 MPa sunlit leaf water potential at midday, until which condition the influence of decreasing leaf water potential on stomatal conductance was found to be minor (Yogev, 1986). Continued soil water depletion eventually caused wilting of some of the very young leaves at the top of the canopy. This condition was defined as severe stress, and occurred when the available soil moisture dropped to 30% and the sunlit leaf water potential at noon decreased to -2.35 MPa.

The effects of moisture stress on the relationship between stomatal conductance and PAR incident on a leaf is shown in Fig. 1. Separate linear regressions were performed to underscore differences in magnitude and variability of leaf conductance for sunlit and shaded environments. The justification for separate analyses of sunlit and shaded leaf conductance is that almost no overlap occurs in the PAR level for the two light environments.

The magnitude of sunlit leaf conductance in non-stress and mild stress conditions (Fig. 1A, B) is similar to that reported by Fuchs and Moreshet (1985). Non-stress sunlit leaf conductance was lower than that reported by Radin et al. (1989) at similar hours. With the progression of soil moisture stress, the response of leaf conductance as a function of PAR decreased steadily for sunlit leaves after the mild stress level was reached. In severe stress (Fig. 1C), sunlit leaf conductance reached levels only one third to one half of those in similar light conditions in the well-watered and mild stress treatments. In each soil moisture condition, leaf conductance apparently did not reach full saturation at the highest PAR levels measured in the field.

Analysis of covariance for multiple regression fits was conducted to test for homogeneity among slopes and intercepts, and for pairwise comparisons between sunlit and shaded leaf conductance at each level of moisture stress. The slope of shaded leaf conductance was significantly steeper than that of the sunlit leaves ($p < 0.05$) at each level of moisture stress. The intercept of sunlit leaf conductance was significantly higher ($p < 0.05$) than that of shaded leaves at each respective level of moisture stress. Comparison among sunlit leaf conductance slopes showed that mild stress was slightly but significantly higher than that of non-stress, while both were steeper than that of the severe stress condition (Table 2). Shaded slopes decreased significantly at each level of decreasing soil moisture content (Table 2). Testing for equality among intercepts showed that the intercept of both the sunlit and shaded leaf conductance decreased significantly at each level of decreasing soil moisture content (Table 2). The root mean squared error of shaded and sunlit leaf conductance decreased with decreasing soil moisture content. The R^2 value for sunlit leaves was higher than that of shaded leaves for each soil moisture condition. Light accounted for a significant amount of variation ($p < 0.05$) in leaf conductance for each regression data set in Table 2.

Leaf conductance was calculated with the linear regressions at average sunlit and shaded light levels (1200 and 150 micromoles $m^{-2} s^{-1}$, respectively). Reducing the percent available soil moisture from 80 to 30 decreased the calculated sunlit leaf conductance from 24.7 to 7.7 $mm s^{-1}$, and the shaded

from 10.2 to 2.8. The resulting fraction of shaded to sunlit leaf conductance decreased from 31% to 27%.

In view of the non-linear fit when sunlit and shaded leaf conductances are lumped into a single data set and regressed for PAR, curvilinear regressions were computed to unify the mathematical description of the relation (Table 3). The correlation coefficients indicate that the curvilinear fits for each soil moisture condition accounted for 56% or more of the variation in leaf conductance (Table 3). By contrast, the segmented linear fits to shaded and sunlit leaves yield a weaker correlation with the data, except in the case of sunlit leaf conductance for PAR under mild stress (Table 2). The resulting curvilinear functions may be applied when modeling transpiration of the whole canopy under variable water stress (Fig. 2). The leaf conductance response at -2.05 MPa (Fig. 2) demonstrates a gradual rather than abrupt change in the coefficients for the function relating stomatal conductance to PAR between moderate and severe stress. Such a response would justify using a family of curves to quantify leaf conductance between moderate and severe stress conditions.

Regression analyses were performed on shaded and sunlit leaf conductance for leaf temperature for the same days. Data for leaf conductance and leaf temperature are presented in Figs. 3A and 3B for non-stress and severe stress conditions, respectively. The non-stress correlation coefficient for leaf temperature (Table 2) showed a weaker correlation than that for PAR for sunlit leaves, and a better correlation than that for PAR for shaded leaves. In severe stress, no correlation between leaf temperature and leaf conductance was observed. Leaf temperature of shaded leaves showed a shift of 2.5 °C higher in stress than in non-stress conditions. The average shift in the sunlit leaf data was 1.5 °C higher for stress conditions. No correlation between humidity variation and stomatal conductance was found at any stage of the measurements. The addition of leaf temperature or humidity to light (PAR) as independent variables in a multiple regression analysis did not significantly enhance the prediction of the pooled sunlit and shaded leaf conductance. These results would agree indirectly with the greenhouse work of Sharkey and Raschke (1981), who found that nearly 90% of the total response of cotton stomata exposed to high and low irradiance levels was a direct response to light incident to the leaf, although they varied only the CO₂ levels while maintaining constant temperature and humidity conditions. Hofstra and Hesketh (1969) were unable to find a consistent relationship between cotton stomatal opening in a range of temperatures covering those found in these field conditions.

The average abaxial and adaxial stomatal conductance of sunlit and

shaded leaves for all soil moisture conditions is displayed in Fig. 4. With the progressive levels of stress, the roles of the sunlit abaxial and adaxial stomatal conductances are relatively unchanged through the course of each day. The abaxial stomatal conductance of sunlit and shaded leaves was always greater than the adaxial stomatal conductance, whatever the state of the soil moisture. Sunlit abaxial stomatal conductance comprised an average of 59%, 56% and 62% of the sunlit leaf conductance for the non-stress, moderate stress, and severe stress periods, respectively. The corresponding figures for shaded abaxial conductance were 74%, 70% and 65%.

DISCUSSION

In all soil moisture conditions, shaded leaf conductance increased more per unit PAR than did sunlit leaf conductance, but correlation coefficients show that the regression fits for sunlit leaves accounted for more variability than those of the shaded leaves (Table 2). The smaller correlation coefficients in the shaded leaf conductance-PAR relationship may arise from inaccurate positioning of the PAR sensors with respect to the identical position of the leaf. The long time response of stomatal conductance to a step change in PAR (Fig. 5) indicates that fluctuating sunflecks due to wind movement have a minor effect on the variability of stomatal conductance of shaded leaves. General sources of variation when using a random sampling approach for both sunlit and shaded leaf conductance would include dissimilar soil moisture and nitrogen content from one plant to another, variations in leaf water potential, and leaf aging (Constable and Rawson, 1980). Despite these sources of variation associated with a field study, the curvilinear model was able to predict leaf conductance from PAR over the full range of sunlit and shaded light environments with a good level of correlation ($R^2 > 0.56$ for all soil moisture conditions).

What can be learned about the relative magnitude of sunlit and shaded leaf conductance per unit PAR? The data from Fig. 1 which show shaded stomatal conductance responding with a steeper slope to PAR than sunlit leaf conductance, point to the existence of a trigger mechanism suited to open stomata at low levels of light. This mechanism brings about a relatively high degree of stomatal opening per unit PAR. The slope of the stomatal conductance-PAR relationship in the direct light shows a more gradual stomatal opening per additional unit of PAR. These results may possibly be explained by the work of Zeiger and Field (1982), who identified two photosystems which drive stomatal opening. One photosystem operates on the guard cells at very low levels of blue light alone, serving as a sharp stomatal opening signal. The other photosystem is linked to photosynthesis, with a CO_2 -regulated energy

source being transported from the photosynthesizing mesophyll to the guard cells, and is regulated by photon flux density in the entire PAR spectral waveband.

Shading a sunlit leaf causes stomatal conductance to fall within a few minutes to levels normally found in the shade. Reopening stomata to fully sunlit levels requires more than 30 minutes when shading is removed (Fig. 5). Under intermittent shading, this asymmetry reduces photosynthesis more than if leaf conductance were responding in direct proportion to the photon flux density. Zeiger et al. (1985) also suggest that the blue light photosystem opening stomata at low quantum flux levels may assist in exploiting sunfleck energy within the shaded fraction of the canopy.

Our measurements showed that shaded leaf water potential was always 0.30 to 0.35 MPa higher than that of sunlit leaves (Table 1). This difference was maintained both diurnally and over the course of the season in 1989. It is possible that the higher leaf water potential of shaded leaves enhanced the photosynthetic activity of the shaded leaves (Ackerson et al., 1977), and thereby increased their stomatal response to PAR.

The larger abaxial contribution to leaf conductance found for shaded leaves agrees with the earlier findings of Davies (1977) and of Sharkey and Raschke (1981), who showed that abaxial stomatal opening is more sensitive than adaxial stomatal opening at low light levels. The results for the sunlit abaxial/adaxial relationship were in general agreement with those of Sharpe (1973) except under severe stress conditions, when we did not observe parity in afternoon conductances between the two surfaces.

In summary, this study investigated the response of field grown cotton sunlit and shaded stomatal conductance to radiation, leaf temperature, humidity and soil moisture factors. Results showed that average shaded leaf conductance of a cotton crop is approximately 31% and 27% that of sunlit leaves in non-stress and severe stress conditions, respectively. Sunlit and shaded leaf conductance is driven primarily by the photosynthetically active radiation incident on the leaf, and can be predicted as a function of PAR in both non-stress and stress conditions. These data for field grown cotton stomatal conductance allow expansion of current models which predict crop transpiration, to include the shaded leaves, and to extend the prediction to periods of stress.

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FIGURE LEGENDS

Fig. 1. Linear regressions of leaf conductance for PAR of sunlit and shaded leaves in non-stress (A), moderate stress (B), and severe stress (C) conditions.

Fig. 2. Curvilinear functions of leaf conductance for PAR in 4 conditions of water stress (as identified by midday sunlit leaf water potential)..

Figure 3. Linear regressions of sunlit and shaded leaf conductance for leaf temperature in non-stress conditions (A), and sunlit and shaded leaf conductance for leaf temperature in severe stress conditions (B).

Fig. 4. Abaxial and adaxial stomatal conductance compared between the mid-morning and mid-afternoon hours (Israel Standard Time) for sunlit and shaded leaves during non-stress, moderate stress, and severe stress conditions.

Fig. 5. Abaxial stomatal conductance of uppermost fully expanded leaf before shading, during shading, and after shading is removed. PAR (micromoles $\text{m}^{-2} \text{s}^{-1}$) before and after shading = 1950; during shading = 120. Percent available soil moisture = 45%.

Table 1. Percent available soil moisture and leaf water potential corresponding to non-stress, mild stress, moderate stress, and severe stress conditions.

Level of Stress	Noon Sunlit	
	Percent Available Soil Moisture	Leaf Water Potential (MPa)
non-stress	80 %	- 1.09 (± 0.06)
mild stress	45 %	- 1.85 (± 0.05)
moderate stress	-----	- 2.05 (± 0.05)
severe stress	30 %	- 2.35 (± 0.04)

Table 2. Linear regression analyses of leaf conductance for PAR and leaf temperature at various levels of water stress. PAR units are in micromoles $m^{-2} s^{-1}$

Figure, and leaf illumination	Intercept ($mm s^{-1}$)	Slope ($mm s^{-1}$ per unit PAR)	Root mean squared error ($mm s^{-1}$)	R^2
1A, sunlit	11.83 a*	0.01078 a	5.4	0.37
1B, sunlit	8.56 b	0.01271 b	5.2	0.58
1C, sunlit	3.12 c	0.00378 c	2.6	0.33
1A, shaded	5.96 d	0.02838 d	4.5	0.12
1B, shaded	4.21 e	0.02053 e	2.8	0.29
1C, shaded	1.76 f	0.00685 f	1.8	0.17
		($mm s^{-1}$ per $^{\circ}C$)		
3A, sunlit	-59.1	2.75	5.4	0.22
3A, shaded	-59.6	2.36	4.2	0.21

* Numbers within a column not sharing a common letter differ at the 0.05 probability level using the LSD multiple range test.

Table 3. Curvilinear regression analyses of pooled sunlit and shaded leaf conductance for PAR at 3 levels of water stress. PAR units are in micromoles $m^{-2} s^{-1}$

Water stress level	Regression Equation	Root mean squared error ($mm s^{-1}$)	R^2
non-stress	$3.9 + 0.4644*PAR^{0.5} + 0.00412*PAR$	5.0	0.81
mild stress	$0.5600*PAR^{0.5} + 0.00405*PAR$	4.9	0.72
severe stress	$0.2196*PAR^{0.5} + 0.00021*PAR$	2.2	0.57

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

SCIENTIFIC REPORT #4

COTTON LEAF SURFACE TEMPERATURE VARIABILITY

M.Fuchs and S. Moreshet

ABSTRACT

Infrared measurements of foliage temperature is becoming a popular method for detecting plant water stress. Spatial variability of leaf temperature confuses the interpretation of readings. Temperature, inclination angle and orientation of cotton leaves were measured in cotton (*Gossypium hirsutum*, L. cv. Acala SJ-2) field plots with severe, moderate and no water stress. The range of leaf to air temperature difference data corresponded to those computed from the leaf energy balance. However, the dependence on solar energy incidence was much weaker than that predicted by the theory. The large scatter of data suggests that experimental errors were large. Statistics for stress detection were weak.

INTRODUCTION

The surface temperature of a transpiring vegetation canopy depends on the external heat load and the water transport capability of the plant hydraulic system. Diminished water availability shifts the energy dissipation mechanism towards generation of a larger sensible heat flux density, which increases the difference between canopy and air temperature. This straightforward physical logic has raised the hope that simple infrared thermometry of vegetation could easily detect water stress in plants and serve as an irrigation scheduling tool (Tanner, 1963; Jackson, Reginato and Idso, 1977). Leaf temperature, however, expresses an equilibrium state of the leaf energy balance. As the energy input of each single plane leaf surface within the canopy depends on its exposure to solar radiation, the angular and position distribution of leaf area produces a geometrical variability of leaf temperature. The theoretical implications of this variability is to lower the sensitivity of infrared canopy temperature measurements to water stress (Fuchs, 1990).

Temperature isotherm maps of single leaves have been published in the past. They were intended for showing the variability of convective and stomatal conductance across the surface of a leaf. However systematic attempts to determine the causes of temperature variability within the entire foliage have not been made. In this report, measurements of individual cotton leaf temperature are analyzed to determine the possible contribution of stomatal

conductance and sun leaf angle to the observed variability.

METHODS

Leaf temperature of cotton (*Gossypium hirsutum*, L. cv. Acala SJ-2) were measured on 9 July 1989, in two adjacent plots. One plot was drip irrigated every second day. The second plot had been irrigated 13 days earlier with 68 mm of water which restored moisture content of the 1 m soil profile to field capacity, corresponding to a total of 205 mm of available water. Soil water depletion as computed from a transpiration model (Petersen et al., 1991b), at the time of the measurements, was 94 mm. The plant water stress as defined by Petersen et al., 1991a, was moderate. A second set of measurements was made on 18 Aug. 1989. Irrigation in the previously well watered plot had been interrupted for 5 days, to depress excessive vegetative growth. The degree of the water stress of the plot was not defined. The dry plot had been irrigated 17 days earlier during which period it had lost 119 mm of water. It was under severe water stress.

The surface temperature of sunlit leaves was measured with an infrared thermometer having a 3° field of view, and fitted with a parallax corrected optical sighting device (Telatemp model 43, Fullerton, CA). The instrument was held a distance between 0.30 to 0.45 m from the target leaf. It was aimed at an angle as close as possible to leaf normal without casting its own shadow on the target. Leaf inclination was determined with a self leveling, pivoting protractor to which a compass was attached for obtaining the azimuth.

Measurements were carried out during the hour surrounding solar noon. Weather data for the 2 days are summarized in Table I.

Table I. Weather conditions at the time of the leaf temperature measurements.

	UNITS	A	B
DOY		190	230
SOLAR RADIATION	$W\ m^{-2}$	986	865
T air	°C	30.1	30.6
HUMIDITY	%	67	62
WIND SPEED	$m\ s^{-1}$	2.73	2.44

RESULTS

Fully sunlit leaves were found only in the upper level of the canopy.

Tracking of the leaf target was extremely difficult because of wind induced leaf flutter. Leaf motion also disturbed considerably the angle determinations. Errors directly caused by the measurements are certainly responsible for the large scatter displayed in Figure 1. The linear regression against the cosine of sun ray incidence angle α , summarized in Table II, reveals nevertheless that the mean leaf to air temperature rises from -0.3 to 0.6 , and finally to 0.8°C when plant stress water changes from none to moderate, and severe. However the large standard errors weaken the statistical significance of these results. The corresponding computed values for leaf stomatal conductance are 30 , 24 and 12 mm s^{-1} .

Table II. Water stress and sun angle effect on leaf temperature.

DOY	n ¹	Stress	T leaf-T air		T leaf - T air versus $\cos \alpha$	
			Mean $^{\circ}\text{C}$	Error ² $^{\circ}\text{C}$	slope	R ²
190	21	none	-0.31	0.79	0.52	0.020
190	20	moderate	0.58	0.88	0.96	0.055
230	26	moderate ?	0.68	0.88	1.83	0.392
230	10	severe	0.83	1.21	1.45	0.083

¹Sample size

²Standard error of estimate.

They should have produced larger temperature differences (Fig. 2). The analysis also shows that leaf heating increases as sun rays impinges at an angle closer to normal. The slope of the relation increases with stress indicating that the range of temperature in stressed should be wider than for unstressed leaves, as predicted theoretically (Fuchs, 1990). The large standard errors and the poor correlations deprive these results of any quantitative physical meaning.

DISCUSSION

The theoretical shape of the relation between leaf-air temperature difference and the solar angle of incidence was computed by solving the energy balance of single leaves (Fuchs, 1990), using the stomatal conductance functions derived by Petersen et al. (1991a). The results (Fig. 2) indicate that the linear analysis applied to the experimental results is justified.

The slopes of the theoretical lines are 2 to 3 times steeper than those fitted to the scattered experimental data. However the theoretical predictions are within the range of the measured values, indicating that the physical model used to solve the energy balance is reasonable.

The wide scatter of the experimental data is largely the result of uncontrollable measurement errors. Considerable variability was also found during the investigation of the stomatal conductance (Petersen et al., 1991a). Thermal imagery, by increasing the number of surfaces included in the sample is likely to improve the procedures for infrared measurements of vegetation temperature. It will also refine the interpretation of results to diagnose plant water stress.

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LIST OF FIGURES

Figure 1. Measured leaf to air temperature difference in relation to the cosine of sun ray angle of incidence α .

Figure 2. Computed leaf to air temperature difference in relation to the cosine of sun ray angle of incidence α .

Fig. 1

Fig. 2

SCIENTIFIC REPORT #5

COMPUTING TRANSPIRATION OF SUNLIT AND SHADED COTTON FOLIAGE

UNDER VARIABLE WATER STRESS¹

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ABSTRACT

Transpiration was computed from the sunlit and shaded fractions of a cotton (Gossypium hirsutum, cv. Acala SJ2) canopy using the Penman-Monteith energy balance equation, during two field seasons in 1988 and 1989. Adjusting the relationship between absorbed radiation and leaf conductance for decreasing leaf water potential sensitized the computation to variable water stress conditions. A heat pulse system measuring stem sap flow and the crop surface energy balance by the Bowen ratio were used as independent validation procedures in the field. Leaf area index during the measurement period was between 3.0 to 4.2. Results showed that the computed transpiration of the shaded canopy comprised 0.21, 0.28, and 0.33 of the total during severe water stress in normal atmospheric demand, non-stress in normal atmospheric demand, and non-stress in very high atmospheric demand, respectively. The average daily computed transpiration over the two seasons was within 5% of that measured by the heat pulse and the Bowen ratio. The hourly computation responded well to fluctuations in atmospheric demand and to the change of available soil moisture. The linear regression of computed transpiration for measured water uptake by the heat pulse yielding an R^2 value of 0.96. Quadratic regression analyses during non-stress and stress for computed hourly transpiration versus evapotranspiration yielded R^2 values of 0.97 and 0.92, respectively. They show that midday evapotranspiration is systematically higher than computed transpiration, presumably due to evaporation from the soil. Computed hourly and daily transpiration of a canopy under a neutral filter which transmitted 0.2 of the incident flux, exhibited good agreement with contemporary water uptake measurement in two plants, showing experimentally that the model responds correctly to alterations of the radiative input.

Additional Index Words: Gossypium hirsutum, cv. Acala SJ2, transpiration, water stress, stomatal conductance, heat pulse, Bowen ratio.

Automated trickle irrigation systems allow precise control over the timing and amount of soil water recharge. Needed in tandem with such technology is the field-level, real time determination of crop water use. With this information, water use efficiency may be maximized by regulating plant water stress precisely and minimizing deep percolation. The approach for estimating crop water use should be convenient for the grower's use in the field, while remaining accurate over a broad range of atmospheric and soil moisture conditions. Micrometeorological devices used to measure evapotranspiration, and heat tracer methods for measuring stem sap flux, while precise, are generally restricted to research applications due to the high level of technical expertise and attention required for sustained operation. Most of the systems which estimate the soil water balance are very time consuming because of the amount of sampling needed to overcome spacial variability (Grantz et al., 1990).

Fuchs et al. (1987) published a model aimed at providing a real time estimate of cotton transpiration from routine meteorological data. They used the Penman-Monteith formula (Monteith, 1965) to compute water vapor loss directly from the sunlit leaf surface by applying a function which estimates sunlit leaf conductance for incoming photosynthetically active radiation (PAR) (Fuchs and Moreshet, 1985). Similar relationships of sunlit leaf conductance for absorbed radiation have been reported for wheat and pearl millet (Denmead and Millar, 1976; Squire, 1979). By integrating single leaf conductance into a canopy conductance for Monteith's formula, Fuchs et al. (1987) eliminate the need for relating a reference evaporation to the crop in question with empirical crop coefficients (Doorenbos and Pruitt, 1977). Required field data are obtained with a simple micrometeorological station and weekly plant canopy sampling.

The Fuchs et al. model is, however, constrained in that crop water use is computed only from sunlit leaves transpiring without water stress. Under field conditions it may be desirable to broaden the model to include periods of water stress, and to account for the contribution of water loss from shaded leaves. Because shaded leaves comprise a large fraction of the leaf area in the latter stages of the growing season, their overall water loss may be significant despite a much lower gas exchange per unit leaf area. A model by Cohen et al. (1987), and experimental evidence from Moreshet et al. (1990), demonstrate conclusively that although the fraction of deeply shaded leaves in a citrus orchard canopy may contribute little to photosynthesis, the transpiration from these leaves comprises a significant portion of the crop water balance. A recent study which parameterized sunlit and shaded cotton leaf conductance for PAR under variable soil moisture conditions showed that

significant gas exchange occurs in the shaded fraction of the canopy throughout the season (K.L. Petersen, S. Moreshet, and M. Fuchs, submitted to Agronomy J.). Fuchs et al. (1989) suggest that their model's systematic underestimation of transpiration may arise from neglecting the vapor loss through the shaded leaves.

Jagtap and Jones (1989) propose a model which computes the transpiration of a soybean crop from the sunlit and shaded leaves. The measure meteorological data above the crop at a reference height, and apply a curvilinear relationship for the leaf conductance predicted by photosynthetically active radiation. But experimental field validation has not been published. In addition, the Jagtap and Jones model (1989) is limited to well-watered conditions.

This study was aimed at providing a simple computation of transpiration from the sunlit and shaded fractions of a cotton canopy using the Penman-Monteith energy balance equation. Adjusting the relationship between absorbed radiation and leaf conductance for decreasing leaf water potential sensitizes the computation to variable water stress conditions. A heat pulse system measuring stem sap flow and the crop surface energy balance by the Bowen ratio are used as independent validation procedures in the field. Sunlit and shaded fractions of computed canopy transpiration are compared under variable soil moisture and atmospheric demand.

MATERIALS AND METHODS

Production of plant material

The study was conducted during the summers of 1988 and 1989 in a 1.8 ha experimental plot located within a large commercial cotton (Gossypium hirsutum, cv. Acala SJ2) field operated by Kibbutz Na'an in central Israel: latitude, 32° 20'N; longitude, 34° 45'E; altitude, 100 m. Seed was sown in rows 0.96 m apart in early April in a Typic Chromoxerert soil. Fertilizer applications and pest control were carried out according to standard commercial practices. Plant population density was close to 80,000 plants ha⁻¹ in both years. Bulk cotton yield (lint and seed) was measured in the experimental plot in 1989 at 5.45 t ha⁻¹, compared with 5.6 t ha⁻¹ harvested in commercial fields surrounding the experimental area.

Leaf area index (LAI) was monitored weekly by randomly cutting seven one-meter long sections in different rows and measuring the area of all the collected leaves in the laboratory with an optical area meter (Delta T Devices, Burwell, Cambridge, England). Average crop height was also

quantified weekly by measuring plant height at 20 locations throughout the field.

Irrigation

Watering was accomplished by a drip irrigation system with one lateral per row. Drip emitters were spaced 1 m apart and delivered 1 liter h⁻¹. Irrigations were carried out during the early season growth periods to maintain ample soil moisture availability until late June. Moisture stress was then permitted to develop over two consecutive periods in 1988 and three consecutive periods in 1989, with soil moisture being restored to field capacity at the end of each drought period. No rain fell during either summer. Water stress levels based on midday sunlit leaf water potential and corresponding available soil moisture (Table 1) were arbitrarily defined to correspond with irrigation scheduling recommendations (Petersen et al., submitted to Agron. J.).

Environmental measurements

Global radiation (Kipp and Zonen, Delft, Netherlands), air temperature and humidity (in 1988 - Model 201, Campbell Scientific, Logan, UT, USA; in 1989 - Skye Instruments 1012, Llandrindod Wells, UK), wind speed (Model 014A Met One, Sunnyvale, CA, USA), photosynthetically active radiation (LI 190S, LI-COR, Lincoln, NE, USA) were measured 3 m above the soil surface at an automated meteorological station in the field. Data were averaged for 30 minute intervals and recorded with a CR-21 datalogger (Campbell Scientific).

Model

Transpiration was calculated separately for the sunlit and shaded canopies after the Penman-Monteith combination equation (Monteith, 1965):

$$T = \{ [s/(s+\gamma)]R_n + [\rho c_p e_a g_w / (s+\gamma)](1-h) \} / \lambda \{ 1 + \gamma g_w / [(s+\gamma)g_c] \} \quad (1)$$

where s is the slope of the saturation vapor curve, γ is the psychrometric constant, R_n is the radiation absorbed by transpiring sunlit or shaded leaves, λ is the latent heat of vaporization, ρ is the density of air, c_p is the specific heat of air, e_a is the saturation water vapor pressure at air temperature, g_w is the aerodynamic conductance of the sunlit or shaded canopy, h is the relative humidity, and g_c is the integrated stomatal conductance of

either the sunlit or shaded foliage.

The aerodynamic conductance, g_u , of the sunlit and shaded canopies was computed separately after Thom (1975):

$$1/g_u = 1/g_a + 1/(g_b/L_x) \quad (2)$$

where g_a is the turbulent transfer coefficient, g_b is the boundary layer transport coefficient of a leaf, and L_x ($x = 1$ or 2) is either the sunlit (1) or the shaded (2) LAI.

The turbulent transport coefficient, g_a , for the crop is computed after Fuchs et al. (1987):

$$g_a = k^2 U / [\ln((z-D)/z_0) \ln((z-D)/z_e)] \quad (3)$$

with $k = 0.41$ as the von Karman constant, U is the wind speed measured at height z , D is a displacement height taken as 70% of the average height of the cotton canopy (H) (Stanhill and Fuchs, 1968), z_0 is the roughness length - 13% of H , and z_e is 20% of z_0 (Garratt and Hicks, 1973).

The maximum increase of the turbulent transport coefficient caused by buoyancy is less than 10% for both the sunlit and shaded fractions of the canopy. As g_a is the largest coefficient in the water vapor pathway, the effect of buoyancy on the computation of transpiration is small.

The boundary layer conductance of a leaf is (e.g. Campbell 1977):

$$g_b = (U_x)^{0.5} / 50 \quad (4)$$

assuming the average lobe of a cotton leaf is 0.03 m in width (Fuchs et al., 1987) and U_x is the wind speed in $m s^{-1}$ computed at the top of either the sunlit ($x = 1$) or the shaded ($x = 2$) canopy. The top of the sunlit canopy is simply the top of the canopy and U_1 is obtained by interpolating the logarithmic wind profile to $z = H$. U_2 is computed by applying a general relationship from Thom (1975) for computing the wind speed profile within plant canopies:

$$U_2 = U_1 * e^{-n\zeta} \quad (5)$$

where n is an attenuation coefficient ranging from 2 to 4 depending on vegetation type (here $n = 3$), and ζ is a dimensionless term representing

the "fractional LAI depth". Thom (1975) defines ζ as:

$$\zeta = (H-z)/H \quad (6)$$

If we may assume that L_2/LAI directly corresponds to the fraction of shaded canopy height, then:

$$\zeta = 1 - L_2/LAI \quad (7)$$

Integrated stomatal conductance of the foliage, g_c , was determined as:

$$g_c = g_x L_x \quad (8)$$

where g_x is the stomatal conductance of either a sunlit or shaded leaf. Sunlit leaf area was estimated from directly measured total leaf area index, assuming a spherical leaf angle distribution (Fuchs et al., 1987). Shaded leaf area was calculated as the difference between total and sunlit leaf area.

Leaf conductance under conditions of variable soil moisture was obtained from Petersen et al. (submitted to Agron. J.), as a function of photosynthetically active radiation (PAR, micromoles $m^{-2} s^{-1}$) (Table 1):

$$g_x = 3.3 + 0.548*PAR^{0.5} + 0.00159*PAR \text{ (non-stress)} \quad (9)$$

$$g_x = 0.2 + 0.558*PAR^{0.5} + 0.00389*PAR \text{ (mild stress)} \quad (10)$$

$$g_x = 0.2 + 0.249*PAR^{0.5} + 0.00669*PAR \text{ (moderate stress)} \quad (11)$$

$$g_x = 0.2 + 0.159*PAR^{0.5} + 0.00222*PAR \text{ (severe stress)} \quad (12)$$

The gradual change in the coefficients of the function relating leaf conductance to PAR between mild and severe water stress justified interpolating for the days between these stress conditions (i.e., between sunlit leaf water potentials of -1.85 to -2.35 MPa - see Petersen et al., submitted to Agron. J.). Computations of PAR intercepted by the sunlit foliage followed the procedure described by Fuchs et al. (1987).

Absorbed radiation in the shaded canopy was computed after a light model adapted from Sinoquet (1990), which simulates the radiative balance from the following inputs: LAI, direct and diffuse radiation at the top of canopy, sun height, and the leaf and soil reflection coefficients. A spherical leaf angle distribution was assumed. Intercepted fluxes were calculated for ten

sublayers per unit LAI using Beer's classical radiation extinction law for direct, diffuse and scattered components. Scattering was characterized by exchange coefficients between each pair of vegetation sublayers, similar to view factors. The radiative balance of the canopy was then solved using the radiosity method (Ozsisik, 1981) which directly includes multiple scattering. The total radiation intercepted by each sublayer consists of the incident radiation intercepted in the sublayer and part of the radiation scattered by each sublayer and the soil. This is the total radiation intercepted by the scattering item, weighed by the scattering coefficients and the view factors. Such a formalism allows one to establish the radiative balance as a system of linear equations in which fluxes intercepted in each sublayer are the unknowns.

Diffuse and direct components of the global radiation at the top of the canopy were computed after Bugler (1977), using a cloudiness factor estimated as the ratio of measured global radiation over computed solar radiation for a standard clear sky (Fuchs et al., 1984). For the whole solar spectrum, a mean leaf reflection coefficient of 0.225 was used (Stanhill, 1976) and the reflectance/transmittance ratio was approximated at 1.0 (Gausman, 1985). Although the absorbed radiation could be computed separately for the PAR and near infra-red fractions with their respective reflection and transmission coefficients, employing the mean reflection coefficient provides a sufficiently accurate estimate and greatly simplifies the computation. The mean soil reflection coefficient was taken as 0.1 from previous measurements on a similar soil (Cohen and Fuchs, 1987).

Model validation

Water uptake was measured on ten cotton plants using a calibrated heat pulse technique (Cohen et al., 1988). These measurements spanned two irrigation cycles in 1988, and three in 1989. Selected plants represented the full range of stem diameters found in the field (Cohen and Fuchs, 1989). Measurements were made simultaneously on the ten plants every half hour. A CR7X battery-operated datalogger (Campbell Scientific) was used to monitor the probes and control the relays operating the heaters.

Evapotranspiration above the canopy was measured in 1989 by the energy balance Bowen ratio method. Pieri and Fuchs (1990) discuss the theory of the Bowen ratio measurement and its validity as a reference evapotranspiration estimate in depth. The siting of the instrument was 110 m from the leading downwind border of the field; and the shortest fetch was 70 m to the southeast, from which direction daytime wind rarely blows. A detailed

description of the Bowen ratio apparatus and its operation is found in Fuchs et al. (1987). Net radiation was measured with a Funk type pyrriadiometer (Swissteco, Melbourne, Australia), and soil heat flux with four heat flux plates installed at 0.05 m below the soil surface. All measurements required for the Bowen ratio method were controlled and recorded with a CR7 battery-operated datalogger (Campbell Scientific). The power supply used for the Bowen ratio and heat pulse systems was two 12 V lead acid rechargeable batteries, charged by a solar voltaic panel.

RESULTS

Diurnal courses of computed transpiration, water uptake, and evapotranspiration are shown in Figures 1 and 2, and of computed transpiration and water uptake in Fig. 3. These data represent typical days of non-stress at normal atmospheric demand, severe stress at normal atmospheric demand, and non-stress at extremely high atmospheric demand, respectively. By comparing the daily total transpiration from Figures 1 and 2, one observes that while leaf conductance decreased by a factor of almost three, transpiration was reduced by only 29%: from 7.3 to 5.2 mm day⁻¹. This indicates the low efficacy of water balance control exerted by the stomata. Potential canopy evaporation, computed as though stomatal conductance was infinite, was virtually identical for these two days (9.3 mm day⁻¹). The highest daily potential evaporation over both seasons was 12.7 mm, occurring on 11 July 1988 (Fig. 3). This day was characterized by very low humidity and high wind speeds from the east, increasing the advection of sensible heat into the canopy. Under these conditions of extremely high atmospheric demand, the computed transpiration of 9.8 mm corresponded well with the 9.6 mm of measured water uptake.

The computation's sensitivity to fluctuations in atmospheric demand and soil moisture content is depicted in Fig 4, where the linear regression of hourly computed transpiration versus hourly water uptake is given for 23 days. The R^2 value of computed transpiration for water uptake is 0.96 and the standard error of the prediction is 0.06 mm h⁻¹. The regression line has a slight positive offset, with a slope approximately 6% less than unity. Examining the hourly results reveals that the offset and slope are explained by the heat pulse data, which were slightly below those of computed transpiration in the early morning and late afternoon (see also, Fuchs and Cohen, 1989). The lower value in early morning water uptake is probably caused by either water storage in the plant tissues during the night, or the evaporation of dew (Pieri and Fuchs, 1990). The late afternoon difference (generally

occurring after 1600 hours) protruded more during non-stress and moderate stress days, and could be due to an overestimation of stomatal conductance during these hours (Ackerson et al., 1977). Forcing the linear regression through zero produced a slope of 1.01 and a R^2 of 0.95, showing that the systematic discrepancy between water uptake and computed transpiration is small.

The scatter diagram of computed hourly transpiration versus evapotranspiration over 13 days of non-stress and mild stress, and 5 days of severe stress, indicates that midday data from the computation are systematically lower than those from the Bowen ratio (Fig. 5). Leaf area index during the measurement period was between 3.0 to 4.2. Latent heat flux density from the Bowen ratio incorporates both transpiration and evaporation from the soil surface. The higher amount of midday evapotranspiration in Fig. 5 is presumably caused by an elevated contribution of evaporation from the soil when the sun is high in the sky and irradiates a larger fraction of the soil surface (Stanhill, 1973). Separate quadratic functions were fitted to non-stress and severe stress data. The offsets for both curves in Fig. 5 are positive but not significantly different from zero. Non-stress and stress analyses carried R^2 values of 0.97 and 0.92, with standard errors of the prediction being 0.03 and 0.07 mm h⁻¹, respectively. By comparison the linear regressions for non-stress data yielded a lower R^2 value of 0.95. The linear R^2 for severe stress data was identical to that obtained for the quadratic fit, indicating that the midday evapotranspiration excess is less when the soil is dry.

The average daily computed transpiration was within 5% of that from corresponding days measured by the heat pulse and the Bowen ratio. Water uptake and computed transpiration from 23 days measured in 1988 and 1989 was 6.65 and 6.95 mm day⁻¹, respectively. Evapotranspiration and computed transpiration from 18 days was 6.50 and 6.85 mm day⁻¹, respectively. Both differences are within the absolute accuracy of the instrumentation used for the validation.

Table 2 shows that the modeled contribution of the shaded canopy to overall transpiration represents at least 21% of crop water loss in all environmental and soil moisture conditions. In addition, fluctuations in atmospheric demand and soil moisture content influence the partitioning of transpiration between the sunlit and shaded fractions of the canopy. The average fraction of shaded/total canopy transpiration decreased with decreasing available soil moisture from 0.28 to 0.21 over a typical non-stress to severe stress period. For a day of high atmospheric demand and non-stress soil moisture (Fig. 3), the fraction of shaded/total canopy transpiration

increased to 0.33.

Computed hourly and daily transpiration of a canopy under several layers of a polyethylene neutral filter, transmitting 0.2 of the incident flux, exhibited excellent agreement to the contemporary water uptake measurement of two plants. Fig. 6 illustrates the diurnal course of the data from one of 4 days measured. This shows experimentally that the model responds correctly to alterations of the radiative input.

DISCUSSION

Expanding the Fuchs et al. (1987) model to include the shaded leaves increases the accuracy of simulated transpiration, as demonstrated by comparing the linear regression analysis for contemporary water uptake in Fig. 4 with that of the previous model (Fuchs et al., 1989). Furthermore, adding the computation of shaded canopy transpiration to the model does not seriously complicate its practical use, as sunlit and shaded leaf conductances are contained in the same mathematical expressions and the same meteorological data were utilized. The results also demonstrate that altering the coefficients of the function relating leaf conductance to PAR according to midday sunlit leaf water potential sensitizes the model to decreasing soil moisture.

At high atmospheric demand, computed transpiration and water uptake (Fig. 3) corresponded well to Naot and Mahrer's (1989) report of 9.5 mm for like climatic conditions. Moving from normal (Fig. 1) to high atmospheric demand in well-watered soil, the model increases daily shaded transpiration by 58%: from 2.1 to 3.3 mm. Daily sunlit transpiration increased only 25%: from 5.3 to 6.6 mm. The result arises from the greater impact of water vapor deficit on foliage with low incident radiation in Eq. (1). The decrease in the average fraction of shaded/total canopy transpiration with intensifying water stress (Table 2) may be traced to a significant decrease in the fraction of shaded/sunlit leaf conductance with the development of water stress (Petersen et al., submitted to Agron. J.).

Under similar atmospheric demand, modeled and measured cotton transpiration at a leaf water potential of -2.35 MPa (severe stress) is 70% that of non-stressed (Figures 1 and 2), whereas leaf conductance dropped by a factor of almost 3. By contrast, Kowalik and Turner (1983) reported that a similar percentage drop in soybean transpiration resulted from decreasing soybean leaf conductance by a factor of approximately 1.5. To explain the discrepancy between cotton and soybean, the partial derivative of computed transpiration with respect to leaf conductance is shown in Fig. 7 for constant

environmental conditions. The sensitivity of transpiration to changes in conductance is low for high leaf conductance. Below 8 mm s^{-1} , however, the derivative becomes large and increases rapidly for any further drop in conductance. Midday sunlit leaf conductance for most crops, including soybean (Bennett et al., 1987), crosses the 3 mm s^{-1} level when conductance diminishes with increasing water stress while that of cotton remains above this "threshold" until at least -2.4 MPa leaf water potential (Petersen et al., submitted to Agron. J.). Therefore, water stress weakly influences cotton transpiration as its very high leaf conductance retains dT/dg_c at a low level. Leaf water potentials approaching -2.4 MPa for most field crops result in either drastic stomatal closure during much of the day (Bennett et al., 1987; Turner et al., 1978), or lethal desiccation (Bonanno, 1983). By contrast, cotton maintains high stomatal conductance at lower leaf water potentials than other plants (Ackerson et al., 1977; Turner, 1974). This may be due to a greater decrease in cotton guard cell osmotic potential with abating epidermal turgor (Brown et al., 1976). The greater sensitivity of transpiration to alterations of low leaf conductance also corresponds with the earlier observation that water stress decreases a greater percentage of shaded than sunlit transpiration (Table 2).

In summary, this study shows that cotton transpiration from the shaded canopy comprises 21 to 33% of the total transpiration, and should therefore be included when modeling crop water loss. Water stress reduces transpiration less in cotton than in many other field crops, due to its high leaf conductance. The computed daily transpiration was within 5% of the value measured by the heat pulse and Bowen ratio methods. Agreement between computations and measurements on an hourly time basis was very good and remained valid for a very wide range of soil moisture content. This accuracy exceeds the design requirements of most systems delivering high frequency irrigation.

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FIGURE LEGENDS

Fig. 1. Hourly and daily computed transpiration, measured water uptake, and measured evapotranspiration during non-stress conditions with normal atmospheric demand.

Fig. 2. Hourly and daily computed transpiration, measured water uptake, and measured evapotranspiration during severe stress conditions with normal atmospheric demand.

Fig. 3. Hourly and daily computed transpiration and measured water uptake during non-stress conditions with extremely high atmospheric demand.

Fig. 4. Linear regression of hourly computed transpiration versus hourly measured water uptake by the heat pulse method for 23 days spanning non-stress to severe stress conditions.

Fig. 5. Quadratic regressions of hourly computed transpiration versus hourly measured evapotranspiration by the Bowen ratio for 13 days of non-stress and moderate stress, and 5 days of severe stress, respectively.

Fig. 6. Hourly and daily computed transpiration and measured water uptake by the heat pulse method of a canopy under a neutral filter of several layers of polyethylene, transmitting 0.2 of the incident radiant flux.

Fig. 7. The partial derivative of hourly computed transpiration with respect to leaf conductance for constant environmental conditions.

Table 1. Percent available soil moisture and leaf water potential corresponding to non-stress, mild stress, moderate stress, and severe stress conditions.

Level of Stress	Percent Available Soil Moisture	Noon Sunlit	
		Leaf Water	Potential (MPa)
non-stress	80 %	- 1.09	(± 0.06)
mild stress	45 %	- 1.85	(± 0.05)
moderate stress	-----	- 2.05	(± 0.05)
severe stress	30 %	- 2.35	(± 0.04)

Table 2. Computed sunlit and shaded transpiration for 3 water stress and evaporative demand conditions.

Water Stress	Daily Potential Transpiration	Computed		<u>Shaded Total</u>
		Sunlit	Shaded	
non-stress	9.3 (mm)	5.27 (mm)	2.06 (mm)	0.28
severe stress	9.3	3.91	1.08	0.21
non-stress	12.7	6.60	3.27	0.33

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

SCIENTIFIC REPORT #6

EVALUATION OF CANOPY TEMPERATURE-BASED CROP WATER

STRESS INDICES FOR IRRIGATION SCHEDULING

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ABSTRACT

Since the development of commercial versions of infrared sensors, they have been increasingly used to determine canopy temperature and schedule irrigations. However, some shortcomings of the technique have been identified, among them the sensitivity of canopy temperature measurements to weather fluctuations. Based on field and computer simulated data, an analysis of the suitability of crop water stress indices (CWSI's) developed from canopy temperature under variable weather conditions was done. Important day to day fluctuations of CWSI values determined using an empirical baseline (empirical CWSI) were observed for nonstressed crops, particularly under low vapor pressure deficit conditions. These fluctuations generate uncertainty in the use of the empirical index to determine needs for irrigation. The use of an improved index (theoretical CWSI) requiring measurements of net radiation, soil heat flux and wind speed, and estimates of aerodynamic and canopy resistances reduced but did not eliminate these fluctuations. Results using a simulation model showed that the empirical CWSI provided late indication of irrigation needs, after some water stress has developed, which may limit its application for crops sensitive to water stress. These simulations also indicated that the theoretical CWSI was able to track the development of water stress and provide reasonable indication of irrigation needs, but this result may not be fully realized in field applications due to various sources of variability affecting the determination of CWSI values which are not accounted for by the model.

INTRODUCTION

When a crop becomes water stressed, stomatal conductance and latent heat exchange are reduced, the cooling effect of evaporation is reduced, and leaves become warmer relative to a nonstressed crop. This concept constitutes the basis for the use of canopy temperature measurements for assessing crop water status.

The use of canopy temperature measurements for irrigation scheduling became practical with the development of inexpensive infrared thermometers (IRTs) able to measure emitted thermal radiation. Tanner (1963) and Monteith and Szeicz (1962) reported the use of IRTs for measuring canopy temperature (T_c) a few decades ago, but the commercial use of these sensors is a relatively recent development (Gardner and Shock, 1989).

Some shortcomings of the application of the technique for irrigation scheduling include the difficulty in measuring T_c of row crops in early stages of development (Jackson et al., 1981; Howell et al., 1984; and Field, 1989), and the fact that T_c -based irrigation scheduling allows determination of irrigation timing but not amounts. In addition, canopy temperature measurements are highly sensitive to the view angle of the sensor and its relation to the solar zenith angle (Huband and Monteith, 1986; and Fuchs, 1990). Therefore, standardization of and consistency in the procedures are important.

The interpretation of T_c values to quantify water stress and determine irrigation timing is not a simple procedure. Differences between T_c and air temperature (T_a), originally proposed as a simple stress index (Idso et al., 1977; and Jackson et al., 1977), are a poor measure of plant stress. Effects of other energy balance factors determining T_c must be accounted for (Jackson et al., 1981; Jackson, 1982; Campbell and Norman, 1990).

Jackson et al. (1981, 1988) derived the following expression to estimate the difference between canopy and air temperature for a given set of conditions:

$$T_c - T_a = \frac{r_a(Rn - G)}{\rho C_p} + \frac{\gamma(1 + r_d/r_a)}{\Delta + \gamma(1 + r_d/r_a)} - \frac{e^* - e}{\Delta + \gamma(1 + r_d/r_a)} \quad (1)$$

where

- $T_c - T_a$ = Canopy minus air temperature (C)
- Rn = Net radiation (W/m^2)
- G = Soil heat flux (W/m^2)
- r_a = Aerodynamic resistance (s/m)

r_c	=	Canopy resistance (s/m)
e^*	=	Saturated air vapor pressure (kPa)
e	=	Actual air vapor pressure (kPa)
Δ	=	Slope of the saturated vapor pressure function (kPa/C)
γ	=	Psychrometric constant (kPa/C)
ρ	=	Density of the air (kg/m ³)
C_p	=	Heat capacity of the air (J/kg/C)

The upper and lower limits of $T_c - T_a$ for a given set of conditions may be obtained from equation 1. The upper limit of $T_c - T_a$, $(T_c - T_a)_{ul}$, represents a completely stressed, nontranspiring canopy, and may be estimated by assuming r_c approaches infinity. This reduces equation 1 to (Jackson et al., 1988):

$$(T_c - T_a)_{ul} = \frac{r_a(Rn - G)}{\rho C_p} \quad (2)$$

The lower limit, $(T_c - T_a)_{ll}$, represents a nonstressed canopy transpiring at potential rate, and may be estimated by replacing r_c in equation 1 with r_{cp} , the r_c at potential transpiration. To calculate $(T_c - T_a)_{ll}$, r_{cp} and r_a must be estimated. The former can be approximated by dividing the minimum stomatal resistance for a single leaf by the canopy leaf area index (LAI) effective in evaporation (Allen et al., 1989). The r_a can be computed as proposed by Campbell (1977).

Using the upper and lower limit estimates, a crop water stress index (CWSI) can be defined as (Jackson et al., 1988):

$$CWSI = \frac{(T_c - T_a) - (T_c - T_a)_{ll}}{(T_c - T_a)_{ul} - (T_c - T_a)_{ll}} \quad (3)$$

For this paper, this approach will be referred to as the theoretical approach, and the index will be noted as CWSI(T).

An empirical approximation to determine $(T_c - T_a)_{ul}$ and $(T_c - T_a)_{ll}$ was introduced by Idso et al. (1981), which has become widely used for irrigation scheduling. In this approach, $(T_c - T_a)_{ll}$ is assumed to be a linear function of vapor pressure deficit (VPD) and is obtained from measurements in a well-watered crop transpiring at potential rate. This regression line is usually referred as the "baseline". Idso et al. (1981) suggested that $(T_c - T_a)_{ul}$ could be estimated by extrapolation of the baseline to a value of

$T_c - T_a$ at which the vapor pressure gradient between the canopy and the air, and therefore transpiration, is zero. The stress index (Eq. 3) determined using this empirical approach will be noted as CWSI(E).

The use of CWSI(E) has been criticized because of its inability to account for changes in temperature due to radiation and windspeed (Jackson et al., 1988). The sensitivity of empirical baselines to changes of various weather elements can be large (Hipps et al., 1985; Campbell and Norman, 1990). O'Toole and Hatfield (1983) compared the empirically-estimated upper limit with measured values on severely water stressed crops and found that the poor agreement between measurements and estimates was mostly explained by fluctuations in windspeed. Therefore, the suitability of CWSI(E) for irrigation scheduling under variable weather conditions is open to question.

The objective of this work was to analyze the suitability of theoretical and empirical values of CWSI to determine irrigation timing under variable weather conditions. A combination of measurements and computer simulation was used, the latter in an attempt to eliminate the variability in the measurements as a factor and as a means of creating alternative scenarios for the analysis.

MATERIAL AND METHODS

Canopy temperatures of cotton (*Gossypium hirsutum* L. 'GP3774') growing in a 3-m² weighing lysimeter at Temple, TX (Dugas et al., 1985) were measured during the 1988 growing season. Results for a period of 13 days (days 203 through 215), during which the soil water content was adequate and the crop did not experience water stress are reported here. Cotton was sown in the lysimeter and a surrounding 5 ha field at 15 plants m⁻² in 0.67-m wide rows on day 95, 1988. The T_c was measured using an Everest model 4000.2 chopper-stabilized IRT (Everest Interscience, Fullerton, CA). Signals from the IRT were measured by a 7X data logger (Campbell Scientific, Inc., Logan, UT), sampling every 15 s. The IRT had a 15-degree field of view, was mounted 0.25 m from the northeast corner of the lysimeter and facing west, and was viewing an area in the center of the lysimeter with dimensions of approximately 0.4 by 0.2 m (O'Toole and Real, 1984). Other measurements were T_a and relative humidity (RH) with a Model 207 probe (Campbell Scientific, Inc.), wind speed (u), with a Model 014A anemometer (Met-One, Grant Pass, OR), global radiation (R_g) with a Model LI200S pyranometer (LiCor Corp., Lincoln, NE), and G with three Model 1081 heat flux plates (Science Assoc.) buried at 0.1 m under and between plant rows in the lysimeter. The G was calculated from the flux at and the storage above 0.1 m. Differences in plate and soil conductivity and the effects of plate shape were considered (Philip, 1961).

All measurements were averaged for one hour.

The ratio of light below and above the canopy (F) was determined near solar noon on six days during the growing season using two Model LI191SB sensors (LiCor Corp.) and LAI was estimated from this measurement by inversion of the expression $F = [1 - \exp(-K \text{ LAI})]$, where the extinction coefficient K was determined in a field adjacent to the lysimeter. The r_s of fully expanded sunlit leaves in the upper canopy of well-watered plants was determined near solar noon on three days during the growing season using a Model LI1600 diffusion porometer (LiCor Corp.). From these measurements, r_{cp} was estimated to be 15 s/m for the 13-day period.

A linear regression of $T_c - T_a$ as a function of VPD, using average data for the period between 1200 and 1300 Local Standard Time (LST) on days 203 through 215, was used as the baseline to estimate $(T_c - T_a)_{ll}$. From this baseline, $(T_c - T_a)_{ul}$ was derived (Idso et al., 1981). Using these empirical limits and equation 3, an average CWSI(E) value for the hour from 1200 to 1300 LST was calculated on each day of the 13-day period. Values of CWSI(T) for the same days and time were also determined.

Baselines reported in the literature for cotton and other crops and the corresponding data points were used to investigate the variability of CWSI(E) for other conditions. Boundaries of CWSI(E) variability were calculated by determining $(T_c - T_a)_{ll}$ from the respective baseline equations and using as $(T_c - T_a)$ in equation 3 the outer values of a band including most of the scatter of the $(T_c - T_a)$ data points above and below the baselines.

To further examine the use of CWSI for irrigation scheduling, T_c , soil water depletion, and photosynthesis of cotton during the 13-day period of this study were simulated for different scenarios of water availability and values of CWSI(E) and CWSI(T) were determined. Simulations were performed using AQUA (Stockle 1989), a process-oriented model that simulates water and energy transport in the soil-plant-atmosphere continuum.

AQUA computes radiation interception by the crop canopy using Norman's (1979) radiation model combined with the canopy architecture model developed by Campbell (1986). Water vapor and energy fluxes from leaves grouped in angle classes and canopy layers are exchanged with a single node within the canopy, which exchanges with nodes at the soil surface and at a reference height above the crop canopy (Goudriaan et al., 1984; Shuttleworth and Wallace, 1985; and Jagtap and Jones, 1986). Canopy transpiration and soil evaporation are calculated independently and simultaneously with hourly time steps. Water uptake fluxes are driven by the gradient of water potential between the root/soil system and the canopy foliage through a series of resistances (soil, soil/root, and plant resistances). To match canopy

transpiration and water uptake, iterations are needed, with r_i for each leaf class and canopy layer being modified in each iteration as a function of the class water potential (Campbell, 1985; Stockle and Campbell, 1985). Inputs to the model are hourly weather parameters including R_g , T_a , RH, and u . In addition, the canopy LAI and the distribution of root length density by soil layer (Bland and Dugas, 1989) are required for each day.

RESULTS AND DISCUSSION

Weather elements (R_g , T_a , u , and VPD), measured between 1200 and 1300 LST, varied during the 13-day period of this study (Fig. 1). Values of VPD and u were the most variable. The R_g was stable during the first half of the period, but became variable thereafter. The T_a and VPD values decreased markedly after day 208.

As discussed by Hipps et al. (1985), weather variability affects the scatter of the regression between $T_c - T_a$ and VPD for a well-watered crop (lower limit or baseline). The scatter of the baseline determined in this study (Fig. 2) was large ($r^2 = 0.67$), and the intercept and slope were lower than those of other baselines reported for cotton (Idso et al., 1982; Reginato, 1983; Howell et al., 1984; and Assadian-Mahmoodjigh, 1986). Temperatures recorded by another sensor viewing the same spot from a different corner were similar.

Because the upper limit to compute CWSI is given as a constant value when using the empirical approach, and the lower limit is determined by the baseline regression equation, the scatter around the baseline translates into fluctuating values of CWSI. These fluctuations, which occur independently of the water status of the crop, may generate uncertainty when applying the index for irrigation scheduling, particularly under low VPD conditions. The lower the VPD, the smaller the difference between the upper and lower limits, and therefore, the greater the effect of scatter on the calculation of CWSI.

In this study, CWSI(E) values fluctuated from extremes of -0.5 to +0.5 (Fig. 3), and typically from -0.2 to +0.2, a large variation for an index defined as 0 for nonstress and 1 for maximum stress. Negative values also resulted from the scatter around the baseline. Furthermore, the boundaries of variability of CWSI(E) for nonstressed crops, determined from the scatter of the data points around baselines reported in the literature for cotton and other crops, also indicated potential for significant fluctuation of this empirical index. This potential increased rapidly as VPD decreased (Fig. 4). This variability of CWSI(E) for nonstressed crops suggests that the interpretation of the index for irrigation scheduling may not be simple, particularly if weather elements fluctuate frequently and/or low VPD

conditions are dominant.

Because R_n , G and u are included in the calculation of $CWSI(T)$, this index should be less sensitive to weather fluctuations. In this study, the variability of $CWSI(T)$, with extremes of -0.13 and $+0.15$ and typical values within ± 0.1 , was lower than that of $CWSI(E)$ (Fig. 3). This lower variability of $CWSI(T)$ was an improvement, although its magnitude may still be large for reliable irrigation scheduling of water stress sensitive crops.

With respect to the computer simulation analysis, the T_c values used corresponded to the average of all predicted temperatures of nine classes of sunlit leaves and a class of shaded leaves for the upper first unit of canopy LAI. Because this average probably represents a different condition to the portion of the canopy "viewed" by the IRT in the field at its particular angle of installation, comparison of measured and simulated T_c values was not attempted. Instead, comparisons of model-estimated ET with lysimetric measurements were used as indication of model performance (Fig. 5).

Based on a simulation run assuming a fully wet profile throughout the 13-day period, a baseline was developed using simulated $T_c - T_a$ values and average VPD data from 1200 through 1300 LST (Fig. 6). The scatter of the simulated baseline ($r^2 = 0.67$) was the same than that of the measured baseline, and the regression equation from simulated data ($T_c - T_a = 2.19 - 1.98$ VPD) was similar to others reported for cotton: $T_c - T_a = 2.0 - 2.4$ VPD (Idso et al., 1982), $T_c - T_a = 2.0 - 2.24$ VPD (Reginato, 1983), $T_c - T_a = 2.08 - 1.8$ VPD (Howell et al., 1984), and $T_c - T_a = 2.13 - 2.06$ VPD (Assadian-Mahmoodjigh, 1986).

Simulated $CWSI$ values for a well-watered crop (Fig. 7) indicated that $CWSI(T)$ was stable through the 13-day period (extremes of 0.02 and 0.08), while $CWSI(E)$ was variable (extremes of -0.24 and 0.21). Both indices were more stable than those obtained from measurements. The larger variability of values from measured data was possibly due to factors like instrumental errors (IRT and other sensors), continuous movement of the canopy due to wind and soil temperature background, which were not a factor in the simulations.

Suitability of the $CWSI$ to determine irrigation time was analyzed using a set of 13-day simulation runs. These simulations assumed different initial water contents and no irrigation, but same meteorological conditions, causing the onset of water stress to occur at different times during the period. Because the simulated pattern of $CWSI$ values behavior was similar, regardless of the day of stress onset, only one case (initial plant available water of 0.39 m/m) is presented to illustrate the point (Fig. 8). The relative value of photosynthesis corresponds to the ratio of simulated daily photosynthesis for the given condition over the value simulated for a nonstressed crop. This ratio was 1 (no stress) until day 208, when it started to decrease (onset of

water stress), first slowly and then more rapidly, to reach a minimum value of about 0.75. CWSI(E) fluctuated greatly below and above a zero value until day 211, increasing rapidly afterwards. Although the index responded to water stress, it did not give a reliable indication of stress until day 212, when relative photosynthesis had decreased to 0.96. This may be a late indication of irrigation needs from an operational standpoint, particularly for crops sensitive to water stress. CWSI(T) was stable until day 208 (onset of water stress), increasing slowly first and rapidly after day 211, conforming well to the development of water stress. This illustrates the advantage of using a more theoretically sound index, although this advantage is unlikely to be fully realized under actual field conditions (Fig. 3), where other sources of variability will affect the calculation of the index (rapid changes of aerodynamic resistance with wind speed fluctuations, effect of thermally induced turbulence, instrumentation and measurement errors, etc.).

CONCLUSIONS

Variability of CWSI(E), and to a lesser degree, of CWSI(T) in the absence of water stress was found important. This variability would be likely augmented in on-farm applications (variable time of the measurement and view angle, changing portions of the canopy being measured each day, instrumental errors, etc.), so that reliable identification of the point when irrigations are required may not be possible until water stress of some magnitude has developed. This appears to restrict the utility of the technique for irrigation scheduling under variable weather, particularly under low VPD conditions.

As shown by Jackson (1982) and Campbell and Norman (1990), variability of T_c measurements increases with increased r_c . Therefore, the limitations discussed for cotton, a crop with a low resistance, could be more severe for crops with larger r_c values. Field (1989), using CWSI(T) to schedule irrigations for alfalfa in Prosser, WA, concluded that the method was unreliable due to daily changes of the index from 0.0 to 0.5 or higher even though soil water content varied little.

Reliable identification of irrigation needs using CWSI(E) under variable weather may only be possible when stress has developed and CWSI has started to increase rapidly. This may generate problems with crops susceptible to water stress and with low water holding capacity soils. Consistency in the procedures to determine T_c , e.g. proper inclination of the sensor, measurements near solar noon and with sensor pointed at the upper part of the canopy, measurements with the sun at the back of the observer, adequate number of replications, and others (Gardner and Shock, 1989) may help to reduce

variability and facilitate the identification of irrigation needs.

The use of the theoretical approach for determining CWSI may improve the reliability of the technique. However, the additional weather information required (i.e., net radiation and wind speed), and the uncertainty in the estimation of r_a and r_c limit its practical application, as recognized by Jackson et al. (1988).

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FIGURE CAPTIONS

Fig. 1. Average for the hourly period from 1200 to 1300 LST of: a) global radiation, b) temperature, c) wind speed and d) vapor pressure deficit (VPD) from day 203 through 216, 1988 at Temple, TX.

Fig. 2. Canopy - air temperature differential ($T_c - T_a$) vs. air vapor pressure deficit (VPD) for well-watered cotton grown at Temple, TX. Measurements were between 1200 and 1300 LST on days 203 through 215, 1988. Equation of the line is $T_c - T_a = -2.07 - 0.92 \text{ VPD}$ ($r^2 = 0.67$).

Fig. 3. Crop water stress index (CWSI) determined empirically (Idso et al., 1981) and theoretically (Jackson, 1988) for cotton grown in a lysimeter at Temple, TX, 1988.

Fig. 4. Boundaries of variability of CWSI(E) values determined from baselines reported in the literature and their corresponding data points for a) cotton and b) soybeans, alfalfa and wheat.

Fig. 5. Predicted and measured evapotranspiration (ET) of cotton grown in a lysimeter on days a) 203 and b) 204, 1988 at Temple, TX. Predictions were made using a simulation model.

Fig. 6. Simulated canopy - air temperature differential ($T_c - T_a$) vs. air vapor pressure deficit (VPD) for well-watered cotton at Temple, TX, 1988. Equation of the line is $T_c - T_a = 2.19 - 1.98 \text{ VPD}$ ($r^2 = 0.67$).

Fig. 7. Crop water stress index (CWSI) determined empirically (Idso et al., 1981) and theoretically (Jackson, 1988) using simulated canopy temperatures for cotton at Temple, TX, 1988.

Fig. 8. Simulated relative photosynthesis, relative soil plant available water (PAW), and crop water stress index (CWSI) determined empirically (Idso et al., 1981) and theoretically (Jackson, 1988) for cotton at Temple, TX in a 13-day period of 1988.

Figure 1a

Figure 1b

Figure 1c

Figure 1d

figure 2

Figure 3

Figure 4a

Figure 4b

Figure 5a

Figure 5b

figure 6

Figure 7

Figure 8

Description of cooperation

Cooperation in this project included activities in the three following areas:

1. Supportive findings of the research. Because of the coordinated planning at the beginning of this research regarding objectives and methods, many of the research findings determined independently in the U.S. and in Israel were supportive (Table 1).

2. Joint experiment. The measurement of transpiration is cardinal in the experimental validation of the theories developed during the project. Heat tracing methods were used in the US and in Israel but the techniques differed. Dr W.A. Dugas visited Israel in October 1989 to conduct a collaborative experiment. The objective of this experiment was to evaluate the performance, accuracy, and attributes of the heat pulse method developed in Bet Dagan and the constant-power, steady-state heat balance method used in Texas. The scope of this experiment grew beyond the framework of the project. This collaboration between the two laboratories will be documented.

Preliminary results showed the following:

- a. At high heat velocities, the thermal diffusivity used in the calculation of heat velocity with the heat pulse gauges (Cohen et al., 1989) may be dependent upon plant water status and may vary with plant age. As this coefficient can be determined by following the diurnal cycle of sap flow, this variation can easily be corrected.
- b. The empirical factor (0.71, see Cohen et al., 1989) to convert heat to sap velocity is species dependent and may also vary with age induced anatomical changes of the stem.
- c. Constant-balance heat balance gauges (Baker and van Bavel, 1987) with 'narrow' heaters (Ham and Heilman, 1990) are inaccurate at high flow rates (e.g. $> 150 \text{ g hr}^{-1}$).
- d. The heat balance gauges have a short time constant (ca. 1-5 min.) at high flow rates.

3. Final report preparation.. In October 1990, Dr. M. Fuchs traveled to Temple for completion of the final report.

Benefits to agriculture

The benefits to agriculture from this research relate to the potential use of infrared thermometer (IRT) measurements of canopy temperature (T_c) for irrigation scheduling, especially via estimates of cotton water use or stress

level. Specifically, these research results highlight the following:

- 1.) There is a large distribution of leaf temperatures within a canopy.
- 2.) The interpretation of T_c in relation to water stress is ambiguous because, among other reasons, transpiration from the shaded portion of the canopy, which the IRT does not accurately measure, may be an important component of total transpiration.
- 3.) Problems in using IRTs for detection of stress or estimation of transpiration are accentuated under conditions with low vapor pressure deficits, prevalent in the coastal plain of Israel and central Texas.

Thus, the use of IRTs for irrigation scheduling should be approached with caution. For a specific crop, soil, and location, IRTs may provide a relative measure of stress, with local calibration, and the IRT measurements could be used to detect stress level and, thus, schedule irrigation.

List of publications

Journal Articles:

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Petersen, K.L., Fuchs, M. Moreshet, S., and Sinoquet, H. 1991. Computing transpiration of sunlit and shaded cotton foliage under variable water stress. Agron. J. (Submitted).

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