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SOIL MOISTURE INFERENCES FROM THERMAL INFRARED MEASUREMENTS OF VEGETATION TEMPERATURES

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16. Abstract Thermal infrared measurements of wheat (<u>Triticum durum</u>) canopy temperatures were used in a crop water stress index to infer root zone soil moisture. Results indicated that one-time plant temperature measurement cannot produce precise estimates of root zone soil moisture due to complicating plant factors. Plant temperature measurements do yield useful qualitative information concerning soil moisture and plant condition.		
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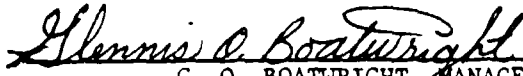
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Soil, because of its porous nature, is a ubiquitous reservoir for water. This reservoir supplies water to plants that, in turn, provide food and fiber for man. As evaporation, drainage, and uptake by plants remove water from the reservoir, that which remains becomes increasingly unavailable to plant roots. This causes the vegetation to be stressed, consequently growth is reduced. On the other hand, if the soil reservoir is full, any additional water added to the surface will run off, usually resulting in detrimental floods and erosion. Thus, soil moisture information is of considerable importance, especially to hydrology and to agriculture.

Classical methods for determining soil moisture, such as gravimetric sampling and neutron scattering techniques are essentially point measurements. They do, however, have the advantage of reaching well below the rooting depth of plants. A major disadvantage is that numerous samples are required to adequately characterize fields. Remote sensing techniques provide large area coverage, but are only sensitive to moisture in the top few cm of soil. The ability to infer soil moisture to root zone depths would greatly enhance remote sensing techniques.

Three regions of the electromagnetic spectrum, the reflected solar, the thermal infrared, and microwave have been used to obtain soil moisture information, via remote sensing. In the reflected solar region, light is reflected from the surface of the soil, and is a direct measurement of only the surface. Since the temperature of a surface heated (or cooled) from above is related to the thermal conductivity of the surface and the material below (Jaeger, 1953), thermal IR methods are sensitive to moisture below the surface. Reginato et al. (1976) demonstrated that thermal IR techniques responded to soil moisture after the surface became dry as indicated by reflected solar data. Idso et al. (1975) showed that thermal IR responded to soil moisture to depths of 4- to 5-cm. Microwave techniques can, theoretically, penetrate to about 50 cm, however, 5- to 10-cm appears to be the practical depth of sensitivity (Schmugge, 1978).

When the moisture content of the surface layers are of primary interest, several remote sensing techniques are available to provide that information. However, if the primary interest concerns plants, then the entire root zone must be considered. Because the rooting depth varies with species, age, and vigor of plants, it is difficult to characterize. For many field crops, roots penetrate to a meter or more. Extending soil moisture estimations to this

depth presents a formidable challenge. T. J. Jackson (1980) approached this problem by assuming that the soil-water potential was at equilibrium, using a remotely sensed measure of the surface soil moisture, and calculating the soil moisture with depth using an independently derived relation between soil-water potential and soil water content. The assumption of hydraulic equilibrium appears to be the weak point of the method.

Plants themselves are probably the best integrators of their aerial and soil environments. Idso and Ehler (1976) showed that the plant canopy-air temperature difference was related to the average soil moisture in the root zone. However, their results indicated that plant temperatures lost sensitivity to soil water content as the water content increased. Not all of the aerial and soil factors were considered in their analysis.

Jackson et al. (1981) used energy balance considerations to quantify how aerial and soil factors affect plant temperatures. Idso et al. (1981) employed an empirical approach to the same problem. Bot.: techniques used plant temperatures in a crop water stress index (CWSI). This report examines the feasibility of using this more quantitative approach to infer root zone soil moisture.

FACTORS AFFECTING PLANT TEMPERATURE

Aerial factors.

Aerial factors that affect plant canopy temperature are expressed by the energy balance equation,

$$R_n = G + H + \lambda E \quad (1)$$

where R_n is the net radiation (Wm^{-2}), G is the heat flux below the surface (Wm^{-2}), H is the sensible heat flux (Wm^{-2}) from the plant canopy to the air, λE is the latent heat flux to the air (Wm^{-2}), with λ being the heat of vaporization. In their simplest forms, H and E can be expressed as

$$H = \rho c_p (T_c - T_A)/r_a \quad (2)$$

$$\text{and} \quad \lambda E = \rho c_p (e_{sc} - e_A)/[\gamma(r_a + r_c)] \quad (3)$$

where ρ is the density of air ($kg\ m^{-3}$), c_p the heat capacity of air ($Jkg^{-1}C^{-1}$), T_c the surface temperature ($^{\circ}C$), T_A the air temperature ($^{\circ}C$), e_{sc} is the saturated vapor pressure (Pa) at T_c , e_A the vapor pressure of the air (Pa), λ the psychrometric constant (PaC^{-1}), r_a the aerodynamic resistance (sm^{-1}), and r_c the canopy resistance (sm^{-1}) to vapor transport. The term r_c is also dependent on soil and plant factors, which will be discussed further in the next section. A detailed discussion of procedures leading to equations (1), (2), and (3) is given by Monteith (1973).

Combining (1), (2), and (3), assuming that G is negligible, and

defining Δ as the slope of the saturated vapor pressure - temperature relation $(e_{sc} - e_{sA})/(T_c - T_A)$, units of PaC^{-1} , we obtain

$$T_c - T_A = \frac{r_a R_n}{\rho c_p} \cdot \frac{\gamma(1 + r_c/r_a)}{\Delta + \gamma(1 + r_c/r_a)} - \frac{e_{sA} - e_A}{\Delta + \gamma(1 + r_c/r_a)} \quad (4)$$

which relates the difference between the canopy and the air temperatures to the vapor pressure deficit of the air ($e_{sA} - e_A$), the net radiation, and the aerodynamic and crop resistances.

If the moisture content of the root zone is high and water is readily available to plants, the canopy resistance (r_c) is small. If the vegetation is damp and evaporating as a free water surface, $r_c = 0$, and the canopy-air temperature difference is almost totally dependent on the aerial environment. (An exception to this can occur when soil temperatures are low, causing water uptake by roots to be reduced.) When the soil has ample available water but the plant surfaces are dry (as for surface irrigated crops), r_c may not be zero (van Bavel and Ehler, 1968). Jackson et al. (1981) estimated that $r_c = 5 \text{ sm}^{-1}$ and $r_a = 10 \text{ sm}^{-1}$ for well watered wheat. Setting $r_c = 5$ in equation (4) results in an expression for the lower limit of $T_c - T_A$ as a function of vapor pressure deficit (for surface irrigated crops). This lower limit is shown in Fig. 1 as the line labeled 5. All lines shown in Fig. 1 were calculated for an air temperature of 30 C. Calculations for other temperatures would yield lines having slightly different slopes and intercepts, because of the temperature dependence of Δ in equation (4).

Soil and plant factors.

As soil moisture becomes limiting, water uptake by plants is reduced. In turn, plants tend to minimize water loss by closing stomates (small openings on the leaves that regulate gaseous exchange). The consequence of these and other adaptive mechanisms is that latent heat exchange is reduced, and the leaves warm. The restrictions caused by low water supply can be broadly grouped into the resistance term r_c . The effect of increasing r_c on $T_c - T_A$ is shown by lines labeled with their value of r_c at the end of the line, in Fig. 1. When transpiration ceases (usually because of senescence), $r_c \rightarrow \infty$ and equation (4) reduces to $T_c - T_A = r_a R_n / \rho c_p$, which shows that, for daylight periods ($R_n > 0$), the canopy will be warmer than air. This is the upper limit as shown by the line labeled ∞ in Fig. 1.

As can be seen in Fig. 1, there is a range of canopy minus air temperatures that might be expected for any given vapor pressure deficit. Consider points A, B, and C in Fig. 1. Point A represents the upper limit (no transpiration), point C represents the lower limit (potential transpiration) and point B represents an intermediate value. The degree of stress of plants having the canopy-air temperature difference shown at point B can be

quantified by forming the ratio of the difference of the values at B and C to the difference between A and C. This ratio is called the crop water stress index (CWSI) by Jackson et al. (1981). It is a quantitative assessment of the degree of stress to which the vegetation is subjected by both aerial and soil factors. This index can also be derived directly from energy balance considerations. (For the derivation and relevant literature, see Jackson et al., 1981).

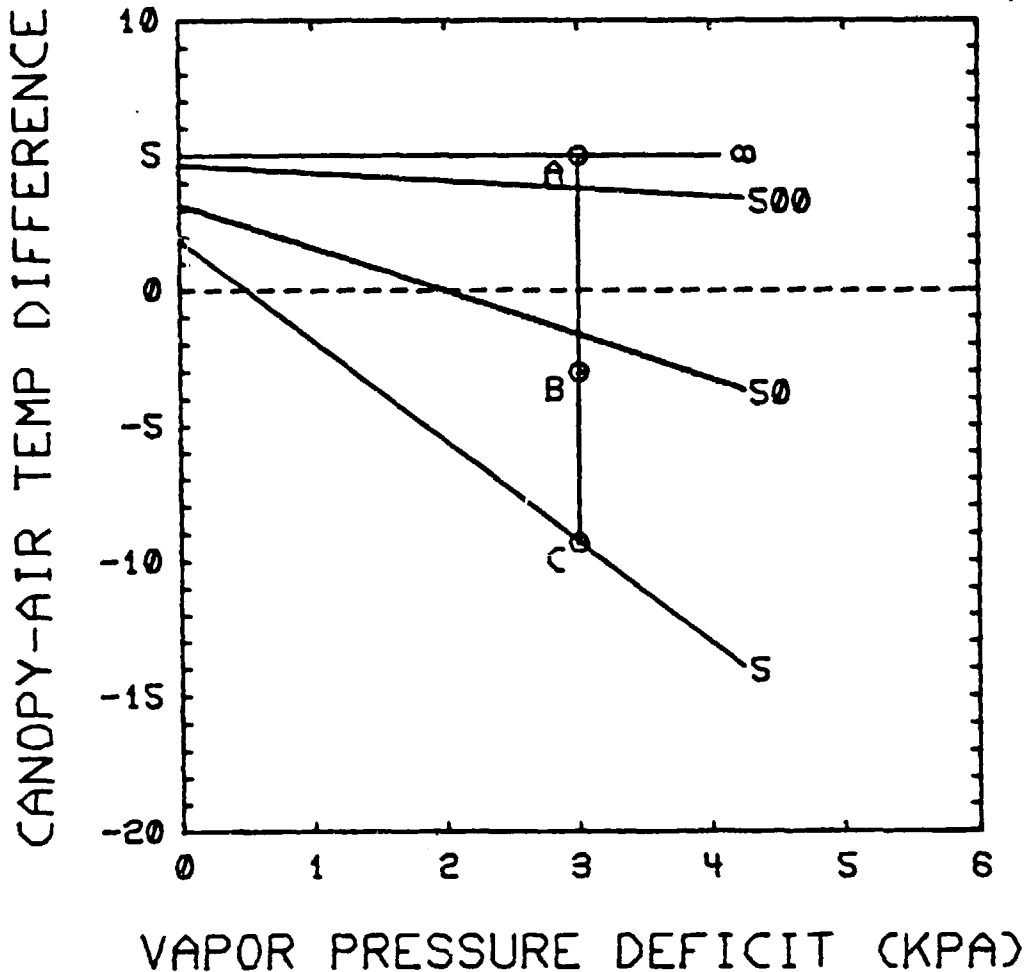


Figure 1. Theoretical relationship between the canopy-air temperature difference and the vapor pressure deficit. Numbers at the end of lines indicate the value of the canopy resistance (r_c) used for the calculations. Point B represents a data point for which a value of the crop water stress index (CWSI) can be obtained by ratioing the distance BC to AC. See text for mathematical derivation of the CWSI. All calculations were for an air temperature (T_A) of 30 C, net radiation (R_n) of 600 W m^{-2} , and an aerodynamic resistance (r_a) of 10 s m^{-1} .

EXPERIMENTAL

Wheat (*Triticum durum* Desf. var. *Produra*) was planted in 11 x 13 m plots on 6 February 1980 (Julian day 37). The three plots of interest here were first irrigated on 8 February. Plot A received a second irrigation on 9 April (day 100). Plot B was irrigated on 2 April (day 93) and 23 April (day 114). Plot C, the wettest treatment, received a second irrigation on 19 March (79), a third on 15 April (106), a fourth on 2 May (123), and a fifth on 13 May (134). All irrigations were in the range of 0.10- to 0.12-m of water applied per unit area.

Canopy temperatures were measured with a portable infrared thermometer held at an angle of about 30° from horizontal. By the time the plants were about 0.2 m tall (day 70), the instrument viewed predominately plants (when held at 30°). Plot canopy temperatures were taken as the average of eight measurements, four facing east and four facing west (to minimize sun angle effects). Wet and dry bulb temperatures were measured with a psychrometer held at a height of 1.5 m. Incoming solar radiation was recorded, from which net radiation was estimated.

Soil water contents were measured with a neutron soil moisture meter in each plot at 0.2 m intervals to a depth of 1.6 m, two to three times per week. Water contents for each depth were smoothed using a sliding cubic technique briefly described by Jackson et al. (1977). The smoothing procedure allowed the interpolation of water contents for each day.

Not all water held in the soil reservoir can be taken up by plants. The traditional way to determine the amount of "available" water is to calculate the amount held at "field capacity" and subtract the amount held at the "wilting point" (as estimated by a laboratory measurement that determines the water remaining in the sample after being subjected to 1.5 MPa of air pressure). Ritchie (1980) proposed that "extractable" water is a more precise measure of water availability to plants because the measurements are made in situ. This can be done by measuring the water content of a full soil profile (with an actively growing, fully developed crop) shortly after irrigation (taking drainage into account). This is called the drained upper limit (\approx field capacity). The lower limit is determined by withholding water from the crop, and, when the plants die, measure the profile water content. The extractable water is the difference between the two profile measurements. Ritchie (1980) suggested that it be measured for each soil and each crop.

The drained upper limit and the lower limit for the wheat plots were measured. The total extractable water to 1.1 m was obtained (0.175 m), and the fraction of extractable water used to that depth was calculated from the smoothed water content data.

RESULTS AND DISCUSSION

Measured data for the CWSI are shown in Fig. 2. Lines were drawn through the points by eye. The data show the day to day change in CWSI in addition to the scatter that might be expected due to errors in measurements of canopy temperatures and wet and dry bulb air temperatures. The plus (+) symbols represent the fraction of extractable water used. As stated earlier, the measured water contents were smoothed and interpolated to yield daily values.

The fraction of extractable water used increased with time, dropping to a minimum following irrigation (zero would indicate a full profile). The CWSI also increased with time, being relatively parallel with the extractable water used. At first glance, it appears that a reasonably good relation exists between the two factors. However, it can be seen that the CWSI does not drop to its lowest value immediately after irrigation. Instead, the CWSI required 5- to 6-days to reach a minimum, implying that stressed wheat requires some time to recover. Some reasons for this are that leaves need to rehydrate and roots that were previously in dry soil need to develop new root hairs. The length of the recovery period depends largely upon the degree of stress the plants were subjected to, but it may also vary with plant species and age. A similar recovery period has been documented for cotton by Ehrler (1973), and for sorghum by Idso and Ehrler (1976).

The existence of a recovery period for the temperature based index is evidence that a unique relationship does not exist between plant temperatures and soil moisture. This is further demonstrated by plots of the CWSI versus extractable water used, as shown in Figs. 3 and 4. For plots A and B, the circles represent data after the first irrigation (at planting). These data are rather similar for both plots, the CWSI increases in a linear manner with increasing amounts of extractable water used. The second irrigation was given plot B seven days prior to the one given to plot A, thus plot A was the most stressed of the three plots. This point is also evident in the greater recovery time required for plot A as seen in Figs. 2, 3, and 4. The wettest plot (Fig. 4) required nearly the same recovery time for irrigations 3 (cross symbols) and 4 (triangles) as did plots A and B (Fig. 2). However, the second irrigation (circles) recovered in 1 to 2 days. This irrigation was given early in the season while the plants were actively growing and were not stressed. The fifth irrigation, given late in the season when much of the vegetation was senesced, showed no recovery period but also no decrease in the CWSI after irrigation.

The CWSI lines for each irrigation do not overlay the values for a prior irrigation, even after the plants have recovered. This is further evidence that the relation between CWSI and soil moisture is not unique. This results, in part, from changes in rooting volume with time due to plant growth and the location of available water. The complexity of the situation becomes evident when one

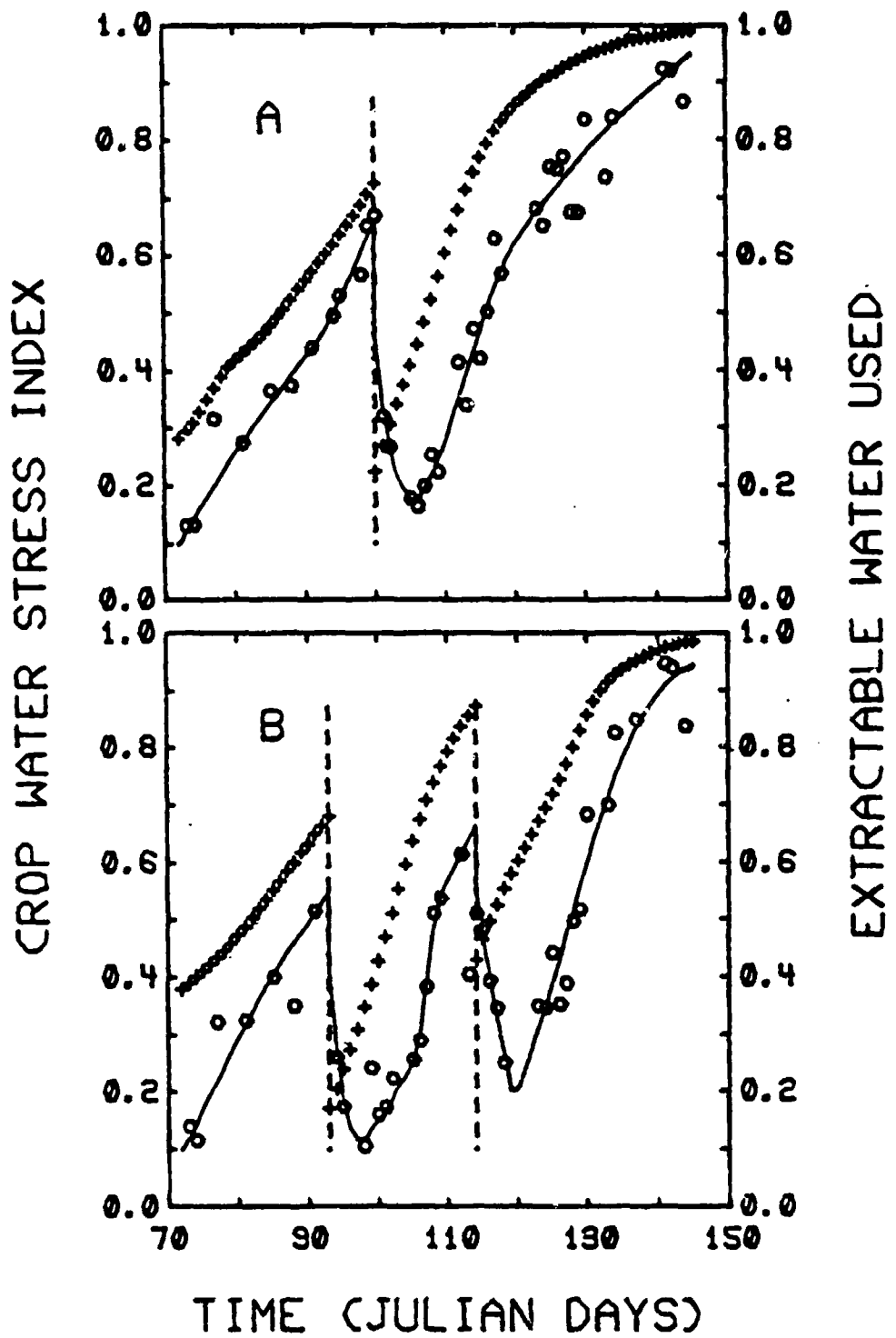


Figure 2. The crop water stress index (circles represent data points) and the relative amount of extractable water used (plus symbols) as a function of Julian day for two wheat plots. Dashed vertical lines indicate irrigations.

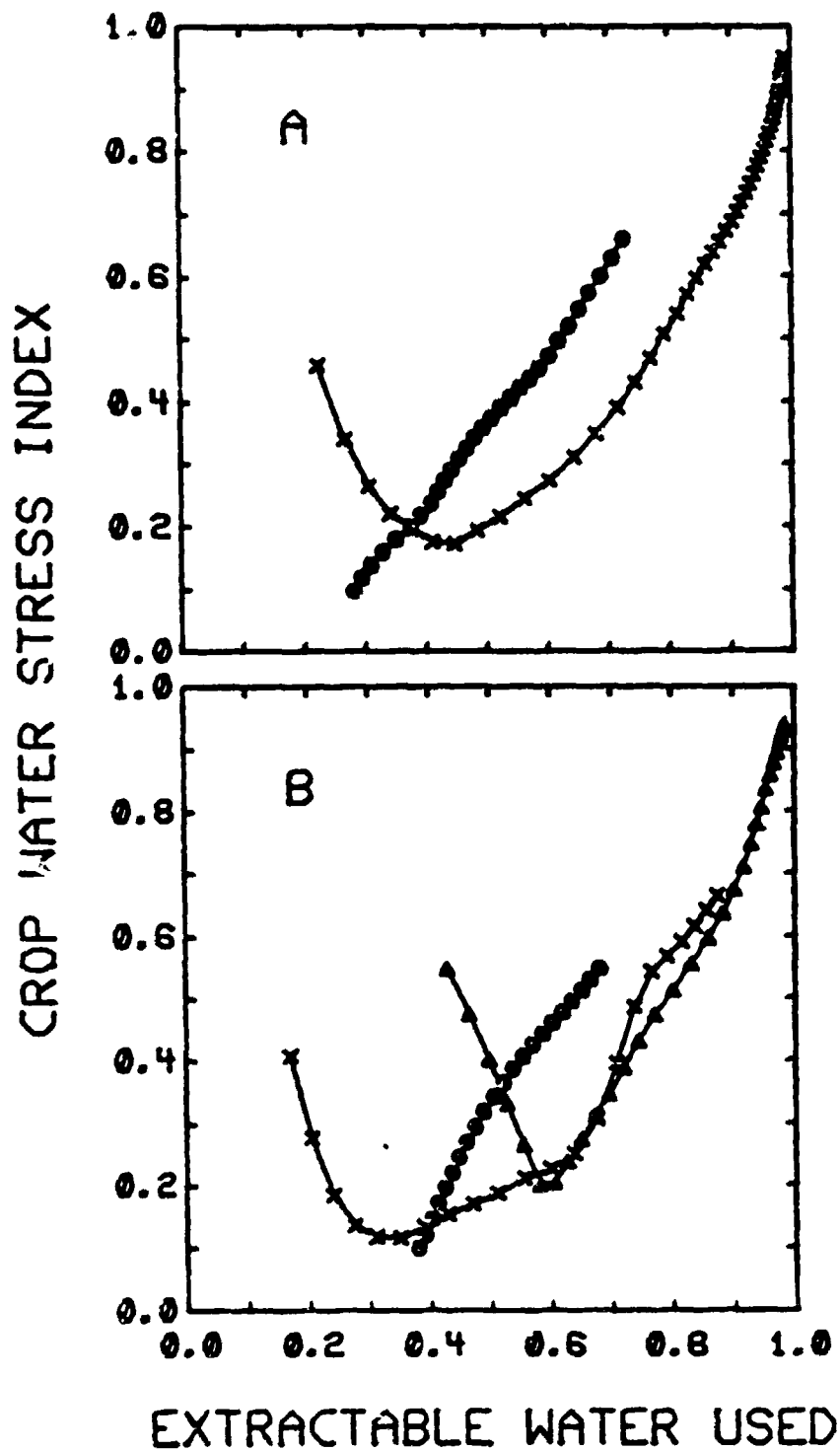


Figure 3. Crop water stress index versus relative amount of extractable water used for two wheat plots. Circles indicate data after the first irrigation, crosses the second, and triangles the third (plot B only).

considers that soil-water availability is dependent on root distribution, which, in turn, is determined predominately by irrigation history (Chaudhary and Bhatnagar, 1980), and also by soil and aerial factors such as nutrient availability and evaporative demand. Since the precise rooting volume cannot be determined, exact correspondence of CWSI and extractable water cannot be expected.

Another factor of importance that is evident in Fig. 4 (data for the fifth irrigation, square symbols) is effect of plant senescence on the CWSI-extractable water relation. As the wheat matured, green leaves began to die, causing transpiration (with

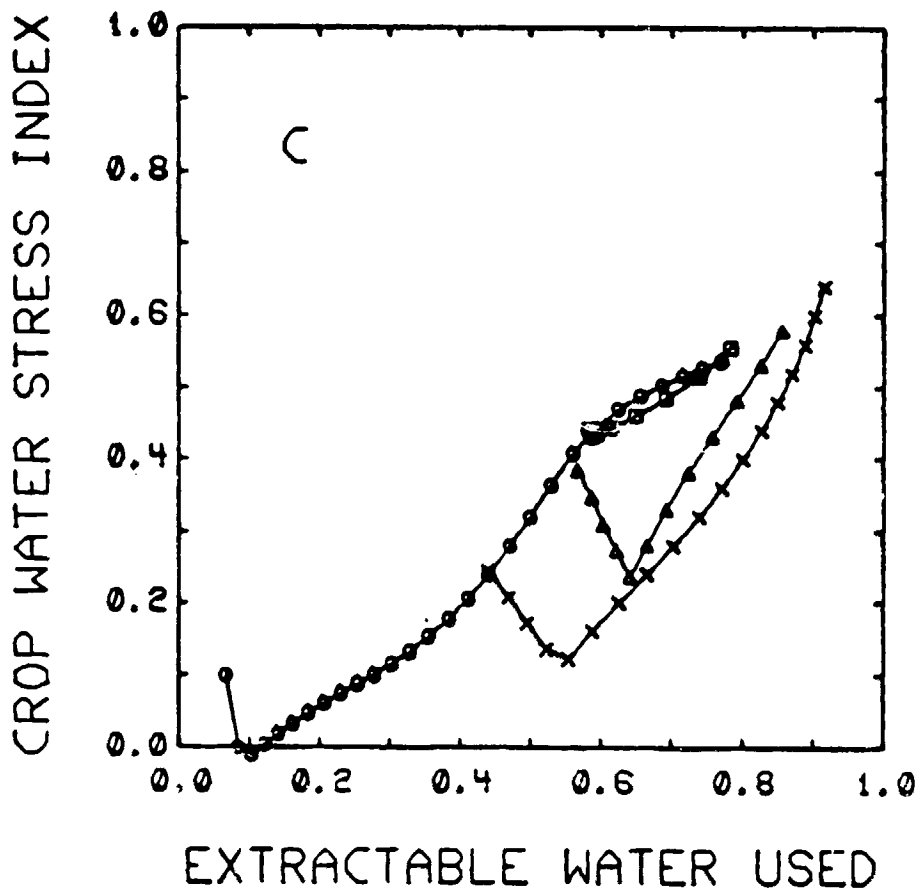


Figure 4. Crop water stress index versus relative amount of extractable water used for a wheat plot that received total of 5 irrigations. Circles indicate data after the second irrigation, crosses the third, triangles the fourth, and squares the fifth.

its consequent evaporative cooling) to decrease. Thus, after an irrigation, plant temperatures remained high (causing a high GWSI) even though the fraction of extractable water used was low.

CONCLUDING REMARKS

From the preceding discussion it is evident that precise estimates of root zone soil moisture cannot be obtained from plant temperatures alone, mainly because of the recovery period required after an irrigation, changing root volume, and plant senescence. Other factors of importance not explicitly shown by the data include changes in biomass, and changes in canopy architecture, such as the development of heads and awns.

At this point it does not appear feasible to estimate soil moisture from a one-time plant temperature measurement because of the complicating plant factors. However, a multi-spectral approach might resolve this problem. Multi-temporal measurements in the reflected solar region could monitor the increase and decrease of green biomass as the growing season progresses. Temporal measurements in the thermal IR would allow the detection of the onset and the degree of stress. Inferences could then be made concerning the amount of extractable water left in the root zone.

Although exact relationships with soil moisture cannot be expected, plant temperatures contain useful qualitative information concerning soil moisture, and perhaps most importantly, they are responsive indicators of plant condition. As such, plant temperatures are useful in determining when to irrigate, and as inputs in yield models.

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