Reprinted from the *Journal of Production Agriculture*
Volume 5, no. 4, October-December 1992
677 South Segoe Rd., Madison, WI 53711 USA

# Infrared Thermometry and the Crop Water Stress Index. II. Sampling Procedures and Interpretation

B. R. Gardner, D. C. Nielsen,* and C. C. Shock

**Infrared thermometry can be a valuable research and production tool for detecting and quantifying water stress in plants, as shown by a large volume of published research. Users of infrared thermometers (IRT) should be aware of the many equipment, environmental, and plant factors influencing canopy temperature measured by an IRT. The purpose of this paper is to describe factors influencing measured plant temperature, outline sampling procedures that will produce reliable Crop Water Stress Index (CWSI) values, and offer interpretations of CWSI and plant temperatures relative to crop production and other water stress parameters by reviewing previously conducted research. Factors that are considered are IRT condition, configuration, and position; psychrometer location; wind speed; solar radiation; time of day; leaf area and orientation; and appropriate non-water-stressed baseline equation. Standard sampling and CWSI calculation procedures are proposed. Use of CWSI with crops varying in type of response to water stress is described. Previously conducted research on plant temperatures or CWSI is tabulated by crop and water stress parameters measured. The paper provides valuable information to assist interested users of IRTs in making reliable water stress measurements.**

INFRARED THERMOMETRY can be used to remotely sense canopy temperature (Fuchs and Tanner, 1966). Canopy temperature can be used to calculate the CWSI which can be used to quantify water stress (Idso et al., 1981a). In a companion paper to this one (Gardner et al., 1992), we reviewed the definition of CWSI and the determination and interpretation of the non-water-stressed baseline used to compute CWSI. Use of CWSI should allow for comparison of water stress severity and effects of water stress between locations, but only if uniform sampling procedures are followed. A great deal of research has been conducted over the past two decades relating CWSI and plant temperatures to other water stress parameters and crop productivity. The purposes of this paper are to:

1. identify equipment, environmental, and plant factors that influence canopy temperature measurements made by infrared thermometry;
2. suggest sampling procedures to follow that will produce reliable CWSI values;
3. offer interpretation of CWSI and plant temperatures relative to crop production and other water stress parameters by reviewing previously conducted research.

---

B.R. Gardner, BP Research, 4440 Warrensville Center Road, Cleveland, OH 44128. D.C. Nielsen, USDA-ARS Central Great Plains Res. Stn., P.O. Box 400, Akron, CO 80720. C.C. Shock, Malheur Exp. Stn., Oregon State University, 595 Onion Ave., Ontario, OR 97914. Oregon Agric. Exp. Stn. Tech. Paper no. 9856. Received 19 Mar. 1992. *Corresponding author.

Published in J. Prod. Agric. 5:466-475 (1992).

## FACTORS AFFECTING CANOPY TEMPERATURE MEASUREMENTS

A number of factors can influence the measurement of canopy temperature with an IRT. We have chosen to discuss these under the three general categories of instrumentation, environmental, and plant factors.

### Instrumentation Factors Affecting Canopy Temperature Measurements

Most hand-held IRTs are powered by rechargeable batteries. It is essential that these batteries are regularly and fully recharged to ensure accurate readings. The IRT lens should be cleaned periodically to maintain accurate canopy temperature readings. IRTs can go out of calibration, and calibration should be checked periodically by comparing the IRT output to that of a target blackbody varying in temperature under ambient temperature conditions covering the range expected when the instrument is used in the field. The IRT calibration can also be checked in the field using a portable blackbody reference before and after measurements are taken. IRT readings may then be corrected based on any differences noted. Portable blackbodies can be purchased from IRT manufacturers or constructed following the design of Sadler and van Bavel (1982). Humidity and air temperature sensors also should be checked periodically to make sure that no changes in calibration have occurred.

Some IRTs show inaccurate readings when the temperature of the sensor is changing rapidly (e.g., moving into the field from areas not at ambient air temperature, such as an air conditioned building or the warm interior of a vehicle). This problem has been overcome by equipment manufacturers using mechanical devices called choppers or using computer algorithms to digitally compensate for equilibration errors. Equilibration errors of less than 0.2 °C (0.36 °F) are produced by these techniques (Graham et al., 1989). This same problem can affect the air temperature and humidity sensors. Unfortunately, these techniques cannot be applied to air temperature and humidity sensors. Consequently, it is essential that all sensors be at or near the ambient air conditions before readings are made to avoid inaccurate calculation of CWSI.

Location of the air temperature and vapor pressure deficit-measuring instrumentation can affect non-water-stressed baseline determinations, although the effect will be minimal for crops with non-water-stressed baseline slopes in the vicinity of $-1.9$ °C ($-3.4$ °F)/kPa (Idso et al., 1990). Site differences in air temperature are accompanied by compensatory changes in air vapor pressure deficit. As Idso et al. (1990) point out, calculating CWSI requires upper baselines (upper limit of canopy-air temperature difference) as well as non-water-stressed baselines, and different air temperature and vapor pressure deficit (VPD) measurement sites will affect the calculated CWSI values. But consistently using the same measurement site for all aspects of baseline determination and CWSI measurement will minimize the problem.

IRTs have varying fields of view that can affect the area of canopy viewed (spot size). The spot size should be calculated based on the IRT field of view, view angle, and distance from target (O'Toole and Real, 1984) so that the IRT operator is sure that the IRT is only measuring the crop canopy intended. A graphical representation (Fig. 1) and BASIC computer program listing of the field of view calculation are given in the Appendix to this paper. Another method for determining spot size is described by Jackson et al. (1980). In this method, a piece of aluminum foil is slowly moved into the IRT field of view until the sensed temperature drops considerably. A stake is placed in the ground at this point and the procedure repeated at several locations to mark off the actual area being viewed by the IRT. This is certainly a useful way for those new to IRT use to become aware of the amount of spatial averaging that the IRT is doing. Care can then be taken to point the IRT only at precise areas to be measured.

### Environmental Factors Affecting Canopy Temperature Measurements

O'Toole and Hatfield (1983) found that canopy temperature measured with an IRT declined with increasing wind speed. This occurs in response to the decline in aerodynamic resistance to sensible heat transfer that occurs with increasing wind speed. They suggested that this relationship could result in errors in CWSI determination, but their data only covered a range of about 1.0 to 6.5 mph (0.5 to 3.0 m/s). Our experience confirms that, under these low wind speeds, there is indeed an effect of wind speed on canopy temperature, but that the importance of the effect is small for wind speeds above 6 mph (2.5 m /s) since aerodynamic resistance decreases slowly with increases in wind speed above 6 mph (2.5 m/s) (Howell et al., 1986). In many locations, afternoon wind speeds are greater than 6 mph (2.5m/s). This is the time when CWSI measurements are generally taken to detect maximum water stress. In these locations, users of infrared thermometry should probably only be concerned with wind speed effects when wind speed is less than 6 mph (2.5 m/s). In locations where wind speeds during measurement times are typically less than 6 mph (2.5 m/s), and the non-water-stressed baselines were determined under low wind speeds, users should be aware of the potential for obtaining large negative CWSI values when wind speeds are high.

An additional environmental factor to be aware of when using infrared thermometry is solar radiation level. Solar radiation influences the radiative heat load on the plant canopy. Stone et al. (1975) showed the effect of cloud passages, and the resultant decline in solar radiation, on the temperature of a grain sorghum [*Sorghum bicolor* (L.) Moench.] canopy measured with an infrared thermometer. They found that canopy temperature dropped nearly 4 °C (7.2 °F) when solar radiation dropped from 1.4 to 0.5 ly/min (975 to 350 W/sq m). Over the same radiation decline, Wiegand and Namken (1966) reported an 8 °C (14.4 °F) drop in cotton (*Gossypium hir-*

Table 1. **Previous research relating Crop Water Stress Index or plant temperatures to other water stress measurements, water use, and plant productivity. (Crop and parameter codes are defined in Table 2.)**

| Source | Crops | Parameters measured |
|---|---|---|
| Abdul-Jabbar et al., 1985 | 1 | 1, 6, 7 |
| Carter and Sheaffer, 1983 | 1 | 1, 2, 5 |
| Clawson et al., 1989 | 1 | 1, 6, 7 |
| Fuchs and Tanner, 1966 | 1, 4, 33, 37 | 1 |
| Grimes and Roberts, 1989 | 1 | 1, 2, 4, 6, 7 |
| Halim et al., 1990 | 1 | 1, 7 |
| Hatfield et al., 1983 | 1, 30, 38, 42 | 1, 6 |
| Hatfield et al., 1984a | 1, 9, 30, 31, 38 | 1, 6 |
| Hattendorf et al., 1988 | 1 | 1, 7 |
| Hattendorf et al., 1990 | 1 | 1, 5, 7 |
| Idso, 1982 | 1, 3, 4, 5, 6, 8, 9, 10 | 1 |
| Idso et al., 1981a | 1, 31, 32 | 1 |
| Idso et al., 1981c | 1 | 1, 2 |
| Jackson et al., 1983 | 1, 31, 33, 38, 42 | 1, 6 |
| Miller and Saunders, 1923 | 1, 8, 10, 27, 30, 31 | 1, 6 |
| Pinter, 1983 | 1 | 1, 7 |
| Reginato et al., 1978 | 1 | 1, 7 |
| Sharratt et al., 1983 | 1 | 1, 2, 6 |
| Tanner, 1963 | 1, 26 | 1 |
| Temple and Benoit, 1988 | 1 | 1, 2, 4, 6 |
| Oi et al., 1989 | 2 | 1, 2 |
| Hatfield et al., 1979 | 3, 42 | 1, 4, 6, 7 |
| Tubaileh et al., 1986 | 3 | 1, 2, 6 |
| Blad et al., 1978 | 4 | 1 |
| Hatfield, 1979 | 4 | 1 |
| O'Toole and Hatfield, 1983 | 4, 8, 9, 30 | 1 |
| Walker and Hatfield, 1979 | 4 | 1, 5, 7 |
| Walker and Hatfield, 1983 | 4 | 1, 7 |
| Saha et al., 1986 | 7 | 1, 4, 6 |
| Sivakumar, 1986 | 7 | 1, 6, 7 |
| Braunworth and Mack, 1989 | 8 | 1, 4, 6, 7 |
| Calle et al., 1990 | 8 | 1, 4 |
| Choudhury, 1983 | 8 | 1, 4 |
| Clawson and Blad, 1982 | 8 | 1 |
| Fiscus et al., 1991 | 8 | 1, 2, 5, 7 |
| Gardner et al., 1981b | 8 | 1, 7 |
| Gardner et al., 1981c | 8 | 1 |
| Gardner et al., 1986 | 8 | 1 |
| Geiser et al., 1982 | 8 | 1, 7 |
| Keener and Kircher, 1983 | 8 | 1, 7 |
| Kirkham et al., 1984 | 8 | 1, 7 |
| Mtui et al., 1981 | 8 | 1, 6, 7 |
| Nielsen and Gardner, 1987 | 8 | 1, 6, 7 |
| Shanahan and Nielsen, 1987 | 8 | 1, 6, 7 |
| Burke et al., 1988 | 9, 42 | 1, 7 |
| Burke et al., 1990 | 9 | 1, 7 |
| Choudhury, 1986 | 9 | 1, 3 |
| Eaton and Beldon, 1929 | 9 | 1, 6, 7 |
| Ehrler, 1973 | 9 | 1, 4, 5 |
| Garrot et al., 1987 | 9 | 1, 6, 7 |
| Hatfield et al., 1985 | 9 | 1 |
| Hatfield et al., 1987 | 9 | 1, 7 |
| Howell et al., 1984a | 9 | 1, 2, 5, 7 |
| Howell et al., 1984b | 9 | 1, 2, 7 |
| Idso and Ehrler, 1976 | 9, 30 | 1, 4 |
| Idso et al., 1982a | 9 | 1, 2, 4 |
| Idso et al., 1982b | 9 | 1, 3, 5 |
| Idso et al., 1989 | 9, 41 | 1, 3 |
| Jackson, 1991 | 9 | 1, 2 |
| Keener and Gardner, 1987 | 9, 31 | 1, 5 |
| Palmer, 1967 | 9 | 1, 4 |
| Pinter and Reginato, 1982 | 9 | 1, 2 |
| Pinter et al., 1983 | 9 | 1, 7 |
| Reginato, 1983 | 9 | 1, 2, 5, 7 |
| Reginato and Howe, 1985 | 9 | 1 |
| Reicosky et al., 1985a | 9 | 1, 4 |
| Wanjura et al., 1984 | 9 | 1, 2 |
| Wanjura et al., 1990 | 9, 30 | 1, 7 |
| Wiegand and Namken, 1966 | 9 | 1 |
| Pandey et al., 1984 | 10, 19, 24, 31 | 1, 2, 7 |
| Grimes and Williams, 1990 | 13 | 1, 2, 4, 5, 7 |
| Krauter, 1987 | 13 | 1, 5 |
| Van Zyl, 1986 | 13 | 1, 2, 4 |
| Williams and Grimes, 1986 | 13 | 1, 2, 6 |
| Peterschmitt and Perrier, 1991 | 14, 28 | 1, 6 |
| Allen et al., 1987 | 15 | 1, 2, 3, 4, 6 |
| Nakayama and Bucks, 1983 | 15 | 1, 4 |
| Nakayama and Bucks, 1984 | 15 | 1, 4, 7 |
| Chaudhuri et al., 1986 | 18, 30 | 1, 4 |
| Singh and Kanemasu, 1983 | 18 | 1, 2, 5, 6, 7 |
| Tormann, 1986 | 20 | 1, 2, 5 |
| Sandhu and Horton, 1978 | 21 | 1, 5 |
| Aston and van Bavel, 1972 | 22 | 1, 4 |
| Clark and Hiler, 1973 | 22 | 1, 2, 5 |
| Glenn et al., 1989 | 23 | 1, 6 |
| Sammis et al., 1988 | 25 | 1, 5 |
| Shock et al., 1987 | 26 | 1, 4 |
| Sithole, 1987 | 26 | 1, 7 |
| Stark and Wright, 1985 | 26 | 1, 2, 4 |
| O'Toole et al., 1984 | 28 | 1, 2, 3, 5 |
| Turner et al., 1986 | 28 | 1, 2, 4, 6, 7 |
| Ehrler and van Bavel, 1967 | 30 | 1, 4, 5, 6 |
| Faver et al., 1989 | 30 | 1, 6 |
| Gardner et al., 1981a | 30 | 1, 6, 7 |
| Hatfield et la., 1984b | 30 | 1, 4 |
| Hatfield, 1982 | 30 | 1, 2, 4, 6 |
| Hatfield, 1983 | 30 | 1, 6, 7 |
| Stone and Horton, 1974 | 30 | 1, 6 |
| Kanemasu et al., 1976 | 30, 31 | 1, 6 |
| Carlson et al., 1972 | 31 | 1, 2 |
| Cure et al., 1989 | 31 | 1, 4 |
| Dornbos et al., 1989 | 31 | 1, 7 |
| Nielsen, 1990 | 31 | 1, 2, 3, 4, 5, 6, 7 |
| Nielsen et al., 1984 | 31 | 1 |
| Reicosky et al., 1980 | 31 | 1, 6 |
| Reicosky et al., 1985b | 31 | 1, 2, 6 |
| Scherer, 1988 | 31 | 1, 4 |
| Sikkema and Decker, 1987 | 31 | 1, 7 |
| Robinson, 1984 | 34 | 1, 4 |
| Pinter et al., 1979 | 34 | 1 |
| Khera and Sandhu, 1986 | 35 | 1, 2, 4, 5 |
| Choudhury and Idso, 1984 | 36 | 1, 2, 4 |
| Nielsen and Anderson, 1989 | 36 | 1, 2, 3, 4, 5, 6 |
| Kateriji et al., 1987 | 38 | 1, 2, 5 |
| Agnew and Carrow | 39 | 1, 2, 5 |
| Slack, 1988 | 39 | 1, 5 |
| Slack et al., 1986 | 39 | 1, 6 |
| Throssell et al., 1987 | 39 | 1, 4 |
| Idso et al., 1984a | 41 | 1, 5, 6 |
| Idso et al., 1984b | 41 | 1, 3, 5, 6 |
| Berliner et al., 1984 | 42 | 1, 2, 5 |
| Blum et al., 1982 | 42 | 1, 2, 5 |
| Choudhury and Idso, 1985 | 42 | 1, 2, 5, 6 |
| Choudhury et al., 1986 | 42 | 1, 6 |
| Diaz et al., 1983 | 42 | 1, 6, 7 |
| Ehrler et al., 1978a | 42 | 1, 2, 4 |
| Ehrler et al., 1978b | 42 | 1, 2 |
| Hatfield, 1984 | 42 | 1, 2, 5 |
| Hope and Jackson, 1989 | 42 | 1, 6 |
| Howell et al., 1986 | 42 | 1, 2 |
| Idso et al., 1977a | 42 | 1, 2, 4, 7 |
| Idso et al., 1977b | 42 | 1, 7 |
| Idso et al., 1979a | 42 | 1, 7 |
| Idso et al., 1979b | 42 | 1, 7 |
| Idso et al., 1981b | 42 | 1, 2, 7 |
| Jackson, 1982 | 42 | 1, 4 |
| Jackson et al., 1977 | 42 | 1, 4, 6, 7 |
| Jackson et al., 1981 | 42 | 1, 4, 6 |
| Nielsen and Halvorson, 1991 | 42 | 1, 4, 6, 7 |
| Smith et al., 1985 | 42 | 1, 7 |
| Smith et al., 1989 | 42 | 1, 6 |
| Steiner et al., 1985 | 42 | 1, 7 |
| Tripathis et al., 1985 | 42 | 1, 2 |
| Zipoli et al., 1987 | 42 | 1, 6, 7 |

*sutum* L.) canopy temperature. Similarly, the canopy temperature of orchardgrass (*Dactylis glomerata* L.) declined 0.6 °C (1.1 °F) for each 0.14 ly/min (100 W/sq m) decrease in net radiation (C.M. Feldhake, USDA-ARS, Beckley, WV, 1990, personal communication). Pennington and Heatherly (1989) presented similar results for soybean [*Glycine max* (L.) Merr.] and cotton. They also reported that amount of change in canopy temperature for a given change in solar radiation increased with increasing water stress. Stone et al. (1975) reported that approximately 1 to 2 min were required to achieve near steady-state canopy temperature in a grain sorghum canopy on the descent portion of a radiation change, and that less time was required on the ascent portion of a radiation change. Pennington and Heatherly (1989) reported that 100 s were needed for near steady-state canopy temperatures of soybean and cotton to manifest themselves following a solar radiation change, and that the rate of change was the same for both increasing and decreasing solar radiation levels. Some crops may require longer times following a cloud passage to come back to a steady-state temperature. C.F. Krauter (California State University, Fresno, 1992, personal communication) found that for grapes (*Vitis* spp.) in California, the time to return to steady-state temperature was approximately 10 min. Consequently, it is important to not take canopy temperature measurements when solar radiation level is low or changing rapidly due to cloud passages. Equally important is to avoid making measurements when the solar radiation is low due to low solar elevation angle. Alternatively, Pennington and Heatherly (1989) present a method for correcting canopy minus air temperature values for the changing solar radiation conditions that regularly occur in humid environments with frequent, intermittent cloud cover.

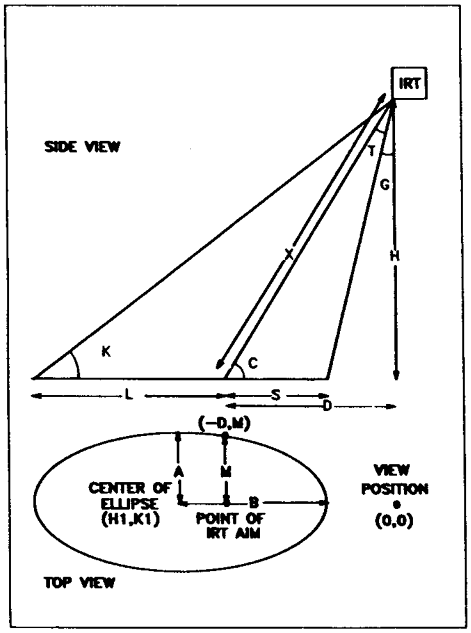

**Fig. 1. Schematic representation of spot viewed by an inclined infrared thermometer (IRT) with angles and lengths noted for use with IRT spot size calculation described in Appendix 1.**

In using infrared thermometry to detect and quantify crop water stress, we are usually most interested in detecting the maximum water stress that is occurring during the day. This most often occurs in the early afternoon when VPD is greatest. Gardner et al. (1992) discussed how non-water-stressed baselines for computing CWSI are determined, and how natural variability in measured canopy temperatures occur within a sampling period. Meaningful values of CWSI are obtained when this variability influences the CWSI calculation the least, and that occurs when VPD is large. Referring to Eq. 1, Fig. 1, and Table 1 of Gardner et al. (1992), the value of MAX-MIN under low VPD conditions is much smaller than when VPD is high. Using the Indiana baseline in Table 1 (Gardner et al., 1992) and assuming MAX = 6 °C, a change of 0.5 °C (0.9 °F) in dT at VPD = 2 kPa results in CWSI changing by 2.1 units. The same change in dT at VPD = 4 kPa results in CWSI changing by 0.7 units. Hence, the higher the VPD during measurement periods, the less likely CWSI is to be adversely affected by the natural variability of the parameters being measured.

## Plant Factors Affecting Canopy Temperature Measurements

As noted earlier, solar radiation, by its influence on the radiative heat load of the plant, is an important factor affecting measured canopy temperature. But even when incoming solar radiation levels are high and nearly constant, there is still variability in the measured canopy temperature due to the differing radiative heat load between sunlit and shaded leaves. Fuchs et al. (1967) and Nielsen et al. (1984) showed how the measured canopy temperatures of various crop canopies were strongly influenced by whether primarily sunlit or shaded leaves were being measured. Gardner and Shock (1989) found stressed and nonstressed leaves had virtually the same temperature in the shade. If our objective is to measure the maximum water stress on the plant, then measurements of mostly sunlit leaves are preferable since these leaves are more likely to experience water stress sooner and to a greater degree than shaded leaves. Shaded leaves can be much cooler than sunlit leaves, resulting in values of dT much lower than predicted by the non-water-stressed baseline equation. Care also should be exercised to avoid shading of individual leaves by the IRT when measurements are made very close to the canopy (Nielsen and Anderson, 1989).

Early in the growing season when plants are small, or under conditions of low plant populations, a significant amount of soil surface may be viewed with the plant surface when making IRT measurements. This can greatly increase the measured canopy temperature (Hatfield, 1979; Heilman et al., 1981; Matthias et al., 1987). To minimize viewing of soil surface by the IRT, measurements can be made at right angles to the row direction and at a shallow angle of incidence (e.g., the IRT pointed down at a small angle from horizontal). Nielsen and Anderson (1989) also suggested using an IRT with a narrow field of view to get temperatures of individual, sunlit leaves of broadleaf plants that are small or widely spaced.

## SAMPLING PROCEDURES

The CWSI normalizes the canopy-air temperature difference for differences in vapor pressure deficit. This should allow measurements made in different locations to be compared. But, as noted above, there are a number of other equipment, environmental, and plant factors affecting canopy temperature measurements made with an IRT that can greatly influence the calculated CWSI and destroy comparability between measurements made by researchers at different locations. We suggest the following standard sampling and calculation procedures for determing CWSI to enhance the opportunity for comparing measurements between locations.

1. Make sure the IRT batteries are fully charged.
2. Make sure the IRT lens is clean.
3. Calibrate the IRT annually and check the calibration daily with a portable blackbody source.
4. Periodically check the calibration of the air temperature and humidity sensors.
5. If humidity measurements are made with a psychrometer, be sure the wet bulb wick is clean and free of contaminants such as dirt, salt, or oils.
6. Allow the IRT and air temperature and humidity sensors sufficient time in a shaded environment to equilibrate to ambient conditions (30–60 min is usually sufficient).
7. Determine spot size of the IRT for the given instrument field of view, distance from target, and height above target to be sure that only the desired canopy surfaces are measured.
8. Begin readings no earlier than 30 min before solar noon and finish readings no later than 3 hr after solar noon to ensure that measurements are made during the time when daily maximum water stress is likely to occur, and when solar radiation and vapor pressure deficit are high.
9. Take readings only when solar radiation levels are high, normally under a clear sky. Measurements can generally be taken even with a thin layer of cirrus clouds in front of the sun if solar radiation levels are still high enough for objects to cast distinct shadows. In areas where convective cumulus clouds typically develop in early and mid-afternoon, measurements can continue following brief passages of clouds if sufficient time (about 60–100 s) is allowed between the end of the cloud passage and the resumption of measurements for canopy temperatures to return to pre-cloud-passage levels. (Alternatively, correct canopy minus air temperature measurements for changing solar radiation levels following the method of Pennington and Heatherly [1989]).
10. Be sure that plant foliage is dry.
11. Air temperature and humidity measurements should be made close to where the canopy temperature measurements are made, but avoiding abnormal areas, such as over roads. We suggest air temperature and humidity measurements be made as close to the standard observation height (5 ft [1.5 m]) as possible.
12. Keep the sun approximately at your back, aiming the IRT generally away from the direction of the sun to maximize the percentage of sunlit leaves in the IRT field of view.
13. Avoid including shadows, wood, soil, sky, dead leaves, and anything else that is not green, sunlit vegetation in the IRT view. Avoid viewing soil by using low viewing angles and aiming the IRT at approximately right angles to the row direction. Avoid vegetation on the borders of fields and plots.
14. Make measurements when wind speed is greater than 6 mph (2.5 m/s) and VPD is greater than 2 kPa.
15. If instantaneous measurements of canopy temperature are being made, we suggest taking at least 12 measurements per area viewed to average out fluctuations due to wind speed and spatial variability.
16. Calculate CWSI using a non-water-stressed baseline that has been generated with data covering a VPD range of 1 to 6 kPa, if possible. If this is not available, be sure that the applicable VPD range for the baseline is reported, and that you are not using the baseline outside of the range of data used to generate it.
17. We suggest that the upper limit of the canopy-air temperature difference (MAX as defined by Gardner et al., 1992) be a constant as determined from observations of severely water-stressed canopies.
18. Be consistent. Use the same premeasurement and sampling protocol each time measurements are made. When reporting experimental results, fully describe measurement and calculation procedures.

## CWSI AND PLANT FUNCTION AND PRODUCTIVITY

Each crop has a unique productivity response to water stress. Consequently, the relationship of CWSI values to crop productivity also varies from crop to crop. We have identified four general categories of yield/quality vs CWSI relationships.

*Crops extremely sensitive to water stress.* Crops in this category cannot be scheduled for irrigation based on changes in CWSI readings, since any water stress that can be detected by a change in CWSI can reduce economic yield (Stark and Wright, 1985). Potatoes (*Solanum tuberosum* L.) are an example of this category of crop. Water stress during tuber growth rapidly leads to a loss in tuber grade and internal tuber quality. Even though CWSI cannot be used to schedule irrigations for crops in this very sensitive category, CWSI can be used to monitor fields for uniformity of irrigation application or to detect disease problems by looking for hot spots.

*Crops that tolerate mild water stress.* Crops in this category can very effectively have irrigations scheduled by CWSI because no significant economic loss is incurred by allowing the plant to experience a mild water stress during the time between stress detection with the IRT and application of irrigation. Crops in this category include

Table 2. Crop and parameter codes used in Table 1.

| Code | Crop | Code | Crop | Code | Crop |
|---|---|---|---|---|---|
| 1 | Alfalfa | 15 | Guayule | 29 | Rutabaga |
| 2 | Almond | 16 | Kohlrabi | 30 | Sorghum |
| 3 | Barley | 17 | Lettuce | 31 | Soybean |
| 4 | Beans | 18 | Millet | 32 | Squash |
| 5 | Beet | 19 | Mungbean | 33 | Sudangrass |
| 6 | Chard | 20 | Nectarines | 34 | Sugarbeet |
| 7 | Chickpea | 21 | Oats | 35 | Sugarcane |
| 8 | Corn | 22 | Pea | 36 | Sunflower |
| 9 | Cotton | 23 | Peach | 37 | Tobacco |
| 10 | Cowpeas | 24 | Peanut | 38 | Tomato |
| 11 | Cucumber | 25 | Pecans | 39 | Turf |
| 12 | Fig tree | 26 | Potato | 40 | Turnip |
| 13 | Grapes | 27 | Pumpkin | 41 | Water hyacinth |
| 14 | Groundnut | 28 | Rice | 42 | Wheat |

| Code | Parameter measured |
|---|---|
| 1 | CWSI/plant temperature |
| 2 | Plant/leaf water potential |
| 3 | Leaf photosynthesis |
| 4 | Soil water content |
| 5 | Stomatal resistance/conductance |
| 6 | Evapotranspiration/leaf transpiration |
| 7 | Yield |

wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), and cotton. CWSI is allowed to rise 2 to 3 index units (on a scale of 0 = no stress, 10 = maximum stress) between irrigations. Wine and raisin grapes can tolerate mild water stress, and may experience improvements in quality at mild CWSI levels (C.F. Krauter, California State University, Fresno, 1992, personal communication).

*Crops that tolerate moderate water stress.* CWSI can be allowed to rise to moderate levels (5 index units) before irrigations are applied. Sugarbeets (*Beta vulgaris* L. subsp. *vulgaris*) are an example of this category of crop. Experiments have shown that significant water can be saved with only a slight reduction in yield of recoverable sugar when irrigations are scheduled based on a moderate level of allowable water stress (Shock et al., 1989).

*Crops that benefit from severe water stress.* Crops in this category actually have improved yield under severe water stress, and CWSI can be used effectively to monitor and control the severity and timing of water stress. Seed alfalfa (*Medicago sativa* L.) is an example of this type of crop. Under high levels of CWSI, it appears that insect pollinator activity is increased, vegetative growth is restricted producing a more open canopy, and flower production is enhanced. In situations such as alfalfa seed production, it is critical that once extreme stress levels have been reached, that stress be removed with an irrigation. CWSI provides an effective means of cycling water stress between high and low levels to promote seed production.

Successful use of CWSI in monitoring water stress and scheduling irrigations requires identification of the category of productivity response to water stress that exists for a particular crop, and learning through experience what target levels of CWSI are appropriate. As an aid to those readers wishing to pursue the use of CWSI and infrared thermometry for water stress detection and quantification, we present in Table 1 a compilation of previous work conducted on a variety of crop and plant species relating plant temperature or CWSI to other water stress measurements, soil water content, evapotranspiration, and yield. The crop and parameters-measured codes used in Table 1 are defined in Table 2. The table is not all-inclusive of research conducted in this area, but does provide sufficient data to assist and support the practical use of CWSI and infrared thermometry to quantify water stress in a wide variety of plant species. In general, increasing CWSI or plant temperature is shown to be well correlated with decreasing leaf water potential, stomatal conductance, photosynthesis rate, soil water content, evapotranspiration, and yield. Several references are listed in which only plant temperature or CWSI is reported. These are included because of the information reported regarding irrigation scheduling, non-water-stressed baselines, or measurement technique.

## INTERPRETIVE SUMMARY

Infrared thermometry has been used as a research tool to measure plant temperatures and quantify water stress for over two decades. The CWSI normalizes plant minus air temperature measurements made with an IRT to vapor pressure deficit, reducing variability in water stress measurements due to environmental variability. To reduce measurement variability and increase the usefulness of CWSI further, users should understand the effects on canopy temperature of: IRT condition, field of view, distance from target, and azimuthal position relative to sun; location of air temperature and humidity measurements; variable wind speed and solar radiation; time of day; leaf area and orientation; and non-water-stressed baseline definition. Standard sampling procedures should be defined, documented, and consistently followed.

Interpreting the meaning of CWSI measurements relative to the water status of a particular plant species requires knowledge of a plant's productivity response to water stress. Crops that are extremely sensitive to water stress may not have irrigations adequately scheduled by CWSI, while crops that tolerate mild to moderate water stress, or that benefit from water stress imposed at specific growth stages, can have irrigations very effectively scheduled by CWSI.

A large body of literature exists describing research on using infrared thermometry to measure water stress on a wide range of agronomic and horticultural crops. Interested users should refer to this literature when developing plans for water stress measurements or irrigation scheduling with an IRT.

## APPENDIX. CALCULATION OF IRT SPOT SIZE.

Given:

$H$ = IRT height above viewed surface
$D$ = horizontal distance from IRT to target
$T$ = one-half of IRT field of view (in degrees)

then:

$$X = \sqrt{D^2 + H^2} \qquad [1]$$

$$C = \tan^{-1}\left(\frac{H}{D}\right) \qquad [2]$$

$$G = 90 - T - C \qquad [3]$$

$$K = C - T \qquad [4]$$

By the Law of Sines:

$$S = \frac{\sin(T) \times X}{\sin(G + 90)} \qquad [5]$$

$$L = \frac{\sin(T) \times X}{\sin(K)} \qquad [6]$$

then:

$$B = \frac{S + L}{2} \qquad [7]$$

Next, solve for $A$ using the equation for an ellipse with center at point ($H1$, $K1$):

$$\frac{(X1 - H1)^2}{B^2} + \frac{(Y - K1)^2}{A^2} = 1 \qquad [8]$$

With the view position at location $(0,0)$, then the known point on the ellipse has coordinates $(-D, M)$ where

$$M = \tan(T) \times X \qquad [9]$$

and the center of the ellipse ($H1$, $K1$) has coordinates $(-(D + L - B), 0)$.

Substituting for $X1$, $H1$, $Y$, and $K1$ into Eq. 8 gives:

$$\frac{(L - B)^2}{B^2} + \frac{M^2}{A^2} = 1 \qquad [10]$$

Rearranging Eq. 10 yields:

$$A = \frac{M}{\sqrt{1 - \left(\frac{L - B}{B}\right)^2}} \qquad [11]$$

so that:

width of ellipse is $2A$
length of ellipse is $2B$
declination angle of IRT is $C$
length of short axis of field of view is $S$
length of long axis of field of view is $L$
area of ellipse of $\pi \times A \times B$

```
10  REM ****************************************************************
15  REM ** THIS PROGRAM CALCULATES THE AREA OF THE VIEWED SPOT SEEN BY      **
20  REM ** AN IRT. THE INPUTS FOR THE PROGRAM ARE THE HEIGHT OF THE         **
25  REM ** INSTRUMENT ABOVE THE VIEWED SURFACE, HORIZONTAL DISTANCE         **
30  REM ** FROM THE INSTRUMENT LOCATION TO THE VIEWED SURFACE, AND THE      **
35  REM ** FIELD OF VIEW OF THE INSTRUMENT (IN DEGREES). HEIGHT AND         **
40  REM ** DISTANCE MUST BE IN THE SAME UNITS OF MEASURE.                   **
45  REM **                                                                  **
50  REM ** A IS 1/2 OF THE MINOR AXIS OF THE VIEWED ELLIPSE                 **
55  REM ** B IS 1/2 OF THE MAJOR AXIS OF THE VIEWED ELLIPSE                 **
60  REM ****************************************************************
70  CLS
80  INPUT "ENTER IRT HEIGHT ABOVE THE VIEWED SURFACE (ANY UNITS)";H
90  PRINT "ENTER HORIZONTAL DISTANCE FROM IRT LOCATION TO VIEWED SURFACE"
100 PRINT "(use same units as for IRT height)"
110 INPUT D
120 INPUT "ENTER IRT FIELD OF VIEW (DEGREES)";T
130 RAD=.017453293#
140 T=T/2
150 C=(ATN(H/D))*360/(2*3.14159)
160 X=SQR(D^2+H^2)
170 G=90-T-C
180 K=C-T
190 S=SIN(T*RAD)*X/SIN((G+90)*RAD)
195 SK=SIN(K*RAD):IF SK<.02 THEN SK=.02
200 L=SIN(T*RAD)*X/SK
210 B=.5*(S+L)
220 M=X*TAN(T*RAD)
230 A=M/SQR(1-((L-B)/B)^2)
240 PRINT
250 PRINT "ELLIPSE WIDTH IS";2*A
260 PRINT "ELLIPSE LENGTH IS";2*B
270 PRINT "IRT DECLINATION ANGLE IS";C
280 PRINT "LENGTH OF SHORT AXIS IS";S
290 PRINT "LENGTH OF LONG AXIS IS";L
300 PRINT " AREA OF ELLIPSE IS";3.14159*A*B
310 PRINT
320 IF K<1 THEN PRINT "CAUTION - SOME SKY MAY BE SEEN"
330 IF K<-1 THEN PRINT "DO NOT USE AT THIS ANGLE"
340 END
```

## REFERENCES

Abdul-Jabbar, A.S., D.G. Lugg, T.W. Sammis, and L.W. Gay. 1985. Relationships between crop water stress index and alfalfa yield and evapotranspiration. Trans. ASAE 28:454-461.

Agnew, M.L., and R.N. Carrow. 1985. Soil compaction and moisture stress preconditioning in Kentucky Bluegrass. II. Stomatal resistance, leaf water potential, and canopy temperature. Agron. J. 77:878-884.

Allen, S.G., F.S. Nakayama, D.A. Dierig, and B.A. Rasnick. 1987. Plant water relations, photosynthesis, and rubber content of young guayule plants during water stress. Agron. J. 79:1030-1035.

Aston, A.R., and C.H.M. van Bavel. 1972. Soil surface water depletion and leaf temperature. Agron. J. 64:368-373.

Berliner, P., D.M. Oosterhuis, and G.C. Green. 1984. Evaluation of the infrared thermometer as a crop stress detector. Agric. For. Meteorol. 31:219-230.

Blad, B.L., J.R. Steadman, and A. Weiss. 1978. Canopy structure and irrigation influence white mold disease and microclimate of dry edible beans. Phytopathology 68:1431-1437.

Blum, A., J. Major, and G. Gozlan. 1982. Infrared thermal sensing of plant canopies as a screening technique for dehydration avoidance in wheat. Field Crops Res. 5:137-146.

Braunworth, W.S., Jr., and H.J. Mack. 1989. The possible use of the crop water stress index as an indicator of evapotranspiration deficits and yield reductions in sweet corn. J. Am. Soc. Hortic. Sci. 114:542-546.

Burke, J.J., J.L. Hatfield, and D.F. Wanjura. 1990. A thermal stress index for cotton. Agron. J. 82:526-530.

Burke, J.J., J.R. Mahan, and J.L. Hatfield. 1988. Crop-specific thermal kinetic windows in relation to wheat and cotton biomass production. Agron. J. 80:553-556.

Calle, J.L., H.L. Manges, and P. Barnes. 1990. Scheduling irrigation of corn with infrared thermometry. Paper no. 90-2004, ASAE, St. Joseph, MI.

Carlson, R.E., D.N. Yarger, and R.H. Shaw. 1972. Environmental influences on the leaf temperatures of two soybean varieties grown under controlled irrigation. Agron. J. 64:224-229.

Carter, P.R., and C.C. Sheaffer. 1983. Alfalfa response to soil water deficits. II. Plant water potential, leaf conductance, and canopy temperature relationships. Crop Sci. 23:676-680.

Chaudhuri, U.N., M.L. Deaton, E.T. Kanemasu, G.W. Wall, V. Marcarian, and A.K. Dobrenz. 1986. A procedure to select drought-tolerant sorghum and millet genotypes using canopy temperature and vapor pressure deficit. Agron. J. 78:490-494.

Choudhury, B.J. 1983. Simulating the effects of weather variables and soil water potential on a corn canopy temperature. Agric. Meteorol. 29:169-182.

Choudhury, B.J. 1986. An analysis of observed linear correlations between net photosynthesis and a canopy-temperature-based plant water stress index. Agric. For. Meteorol. 36:323-333.

Choudhury, B.J., and S.B. Idso. 1984. Simulating sunflower canopy temperatures to infer root-zone soil water potential. Agric. For. Meteorol. 31:69-78.

Choudhury, B.J., and S.B. Idso. 1985. Evaluating plant and canopy resistances of field-grown wheat from concurrent diurnal observations of leaf water potential, stomatal resistance, canopy temperature, and evapotranspiration flux. Agric. For. Meteorol. 34:67-76.

Choudhury, B.J., R.J. Reginato, and S.B. Idho. 1986. An analysis of infrared temperature observations over wheat and calculation of latent heat flux. Agric. For. Meteorol. 37:75-88.

Clark, R.N., and E.A. Hiler. 1973. Plant measurements as indicators of crop water deficit. Crop Sci. 13:466-469.

Clawson, K.L., and B.L. Blad. 1982. Infrared thermometry for scheduling irrigation of corn. Agron. J. 74:311-316.

Clawson, K.L., R.D. Jackson, and P.J. Pinter, Jr. 1989. Evaluating plant water stress with canopy temperature differences. Agron. J. 81:858-863.

Cure, W.W., R.B. Flagler, and A.S. Heagle. 1989. Correlations between canopy reflectance and leaf temperature in irrigated and droughted soybeans. Remote Sens. Environ. 29:273-280.

Diaz, R.A., A.D. Matthias, and R.J. Hanks. 1983. Evapotranspiration and yield estimation of spring wheat from canopy temperature. Agron. J. 75:805-810.

Dornbos, D.L., Jr., R.E. Mullen, and R.M. Shibles. 1989. Drought stress effects during seed fill on soybean seed germination and vigor. Crop Sci. 29:476-480.

Eaton, F.M., and G.O. Belden. 1929. Leaf temperatures of cotton and their relation to transpiration, varietal differences and yields. USDA Tech. Bull. 91.

Ehrler, W. 1973. Cotton leaf temperatures as related to soil water depletion and meteorological factors. Agron. J. 65:404-409.

Ehrler, W.L., S.B. Idso, R.D. Jackson, and R.J. Reginato. 1978a. Diurnal changes in plant water potential and canopy temperature of wheat as affected by drought. Agron. J. 70:999-1004.

Ehrler, W.L., S.B. Idso, R.D. Jackson, and R.J. Reginato. 1978b. Wheat canopy temperature: Relation to plant water potential. Agron. J. 70:251-256.

Ehrler, W.L., and C.H.M. van Bavel. 1967. Sorghum foliar responses to changes in soil water content. Agron. J. 59:243-246.

Faver, K.L., J.C. O'Toole, and D.R. Krieg. 1989. Short-term estimation of sorghum evapotranspiration from canopy temperature. Agric. For. Meteorol. 48:175-183.

Fiscus, E.L., A.N.M. Mahbub-ul Alam, and T. Hirasawa. 1991. Fractional integrated stomatal opening to control water stress in the field. Crop Sci. 31:1001-1008.

Fuchs, M., E.T. Kanemasu, J.P. Kerr, and C.B. Tanner. 1967. Effect of viewing angle on canopy temperature measurements with infrared thermometers. Agron. J. 59:494-496.

Fuchs, M., and C.B. Tanner. 1966. Infrared thermometry of vegetation. Agron. J. 58:597-601.

Gardner, B.R., B.L. Blad, D.P. Garrity, and D.G. Watts. 1981a. Relationships between crop temperature, grain yield, evapotranspiration and phenological development in two hybrids of moisture stressed sorghum. Irrig. Sci. 2:213-224.

Gardner, B.R., B.L. Blad, R.E. Maurer, and D.G. Watts. 1981b. Relationship between crop temperature and the physiological and phenological development of differentially irrigated corn. Agron. J. 73:743-747.

Gardner, B.R., B.L. Blad, and D.G. Watts. 1981c. Plant and air temperatures in differentially irrigated corn. Agric. Meteorol. 25:207-217.

Gardner, B.R., B.L. Blad, and G.D. Wilson. 1986. Characterizing corn hybrid moisture stress sensitivity using cnaopy temperature measurements. Remote Sens. Environ. 19:207-211.

Gardner, B.R., D.C. Nielsen, and C.C. Shock. 1992. Infrared thermometry and the Crop Water Stress Index. I. History, theory, and baselines. J. Prod. Agric. 5:462-466.

Gardner, B.R., and C.C. Shock. 1989. Interpreting the Crop Water Stress Index. Paper no. 89-2642, ASAE, St. Joseph, MI.

Garrot, D., Jr., D.D. Fangmeier, and S.H. Husman. 1987. Scheduling irrigations on cotton based on the crop water stress index. Univ. of Arizona Agric. Exp. Stn.—USDA Cotton Report Series P-69.

Geiser, K.M., D.C. Slack, E.R. Allred, and K.W. Stange. 1982. Irrigation scheduling using crop canopy-air temperature difference. Trans. ASAE 25:689-694.

Glenn, D.M., J.W. Worthington, W.V. Welker, and M.J. McFarland. 1989. Estimation of peach tree water use using infrared thermometry. J. Am. Soc. Hortic. Sci. 114:737-741.

Graham, M.W.D., G.W. Thurtell, and G.E. Kidd. 1989. Calibration of a small infrared sensor for measuring leaf temperature in the field: Non-steady state conditions. Agric. For. Meteorol. 44:295-305.

Grimes, D.W., and B. Roberts. 1989. Irrigation management for optimum alfalfa seed. Proc. California Alfalfa Seed Prod. Symp., Fresno, CA. 7 March. Alfalfa Seed Producers Research Board, Dinuba, CA.

Grimes, D.W., and L.E. Williams. 1990. Irrigation effects on plant water relations and productivity of Thompson Seedless grapevines. Crop Sci. 30:255-260.

Halim, R.A., D.R. Buxton, M.J. Hattendorf, and R.E. Carlson. 1990. Crop water stress index and forage quality relationships in alfalfa. Agron. J. 82:906-909.

Hatfield, J.L. 1979. Canopy temperature: The usefulness and reliability of remote measurements. Agron. J. 71:889-892.

Hatfield, J.L. 1982. The utilization of thermal infrared radiation measurements from grain sorghum crops as a method of assessing their irrigation requirements. Irrig. Sci. 3:259-268.

Hatfield, J.L. 1983. Evapotranspiration obtained from remote sensing methods. Adv. Irrig. 2:395-416.

Hatfield, J.L. 1984. Effects of panicles on infrared thermometer measurements of canopy temperature in wheat. Agric. For. Meteorol. 32:97-105.

Hatfield, J.L., A. Perrier, and R.D. Jackson. 1983. Estimation of evapotranspiration at one time-of-day using remotely sensed surface temperatures. Agric. Water Manage. 7:341-350.

Hatfield, J.L., J.E. Quisenberry, and R.E. Dilbeck. 1987. Use of canopy temperatures to identify water conservation in cotton germplasm. Crop Sci. 27:269-273.

Hatfield, J.L., R.J. Reginato, and S.B. Idso. 1984a. Evaluation of canopy temperature-evapotranspiration models over various surfaces. Agric. Meteorol. 32:41-53.

Hatfield, J.L., R.J. Reginato, R.D. Jackson, S.B. Idso, and P.J. Pinter, Jr. 1979. Remote sensing of surface temperature for soil moisture, evapotranspiration and yield estimation. p. 460-466. *In* Proc. 5th Canadian Symp. Remote Sens., Victoria, British Columbia. August 1978.

Hatfield, J.L., M. Vauclin, S.R. Vieira, and R. Bernard. 1984b. Surface temperature variability patterns within irrigated fields. Agric. Water Manage. 8:429-437.

Hatfield, J.L., D.F. Wanjura, and G.L. Barker. 1985. Canopy temperature response to water stress under partial canopy. Trans. ASAE 28:1607-1611.

Hattendorf, M.J., R.E. Carlson, R.A. Halim, and D.R. Buxton. 1988. Crop water stress index and yield of water-deficit-stressed alfalfa. Agron. J. 80:871-875.

Hattendorf, M.J., D.W. Evans, and R.N. Peaden. 1990. Canopy temperature and stomatal conductance of water-stressed dormant and nondormant alfalfa types. Agron. J. 82:873-877.

Heilman, J.L., W.E. Heilman, and D.G. Moore. 1981. Remote sensing of canopy temperature at incomplete cover. Agron. J. 73:403-406.

Hope, A.S., and R.D. Jackson. 1989. Early morning canopy temperatures for evaluating water stress in a wheat crop. Water Res. Bull. 25:1009-1014.

Howell, T.A., J.L. Hatfield, J.D. Rhoades, and M. Meron. 1984a. Response of cotton water stress indicators to soil salinity. Irrig. Sci. 5:25-36.

Howell, T.A., J.L. Hatfield, H. Yamada, and K.R. Davis. 1984b. Evaluation of cotton canopy temperature to detect crop water stress. Trans. ASAE 27:84–88.

Howell, T.A., J.T. Musick, and J.A. Tolk, 1986. Canopy temperature of irrigated winter wheat. Trans. ASAE 29:1692–1698, 1706.

Idso, S.B. 1982. Non-water stressed baselines: A key to measuring and interpreting plant water stress. Agric. Meteorol. 27:59–70.

Idso, S.B., S.G. Allen, B.A. Kimball, and B.J. Choudhury. 1989. Problems with porometry: Measuring net photosynthesis by leaf chamber techniques. Agron. J. 81:475–479.

Idso, S.B., and W.L. Ehrler. 1976. Estimating soil moisture in the root zone of crops: A technique adaptable to remote sensing. Geophys. Res. Lett. 3:23–25.

Idso, S.B., J.L. Hatfield, R.D. Jackson, and R.J. Reginato. 1979a. Grain yield prediction: Extending the stress degree day approach to accommodate climatic variability. Remote Sens. Environ. 8:267–272.

Idso, S.B., R.D. Jackson, P.J. Pinter, Jr., R.J. Reginato, and J.L. Hatfield. 1981a. Normalizing the stress-degree-day parameter for environmental variability. Agric. Meteorol. 24:45–55.

Idso, S.B., R.D. Jackson, and R.J. Reginato. 1977a. Remote sensing for agricultural water management and crop yield prediction. Agric. Water Manage. 1:299–310.

Idso, S.B., R.D. Jackson, and R.J. Reginato. 1977b. Remote sensing of crop yields. Science (Washington, DC) 196:19–25.

Idso, S.B., B.A. Kimball, and K.L. Clawson. 1984a. Quantifying effects of atmospheric $CO_2$ enrichment on stomatal conductance and evapotranspiration of water hyacinth via infrared thermometry. Agric. For. Meteorol. 33:15–22.

Idso, S.B., P.J. Pinter, Jr., J.L. Hatfield, R.D. Jackson, and R.J. Reginato. 1979b. A remote sensing model for the prediction of wheat yields prior to harvest. J. Theor. Biol. 77:217–228.

Idso, S.B., P.J. Pinter, and R.J. Reginato. 1990. Non-water-stressed baselines: The importance of site selection for air temperature and vapour pressure deficit measurements. Agric. For. Meteorol. 53:73–90.

Idso, S.B., P.J. Pinter, Jr., R.J. Reginato, and K.L. Clawson. 1984b. Stomatal conductance and photosynthesis in water hyacinth: Effects of removing water from roots as quantified by a foliage temperature-based plant water stress index. Agric. For. Meteorol. 32:249–256.

Idso, S.B., R.J. Reginato, and S.M. Farah. 1982a. Soil- and atmosphere-induced plant water stress in cotton as inferred from foliage temperatures. Water Resour. Res. 18:1143–1148.

Idso, S.B., R.J. Reginato, R.D. Jackson, and P.J. Pinter, Jr. 1981b. Measuring yield-reducing plant water potential depressions in wheat by infrared thermometry. Irrig. Sci. 2:205–212.

Idso, S.B., R.J. Reginato, and J.W. Radin. 1982b. Leaf diffusion resistance and photosynthesis in cotton as related to a foliage temperature based plant water stress index. Agric. Meteorol. 27:27–34.

Idso, S.B., R.J. Reginato, D.C. Reicosky, and J.L. Hatfield. 1981c. Determining soil-induced plant water potential depressions in alfalfa by means of infrared thermometry. Agron. J. 73:826–830.

Jackson, R.D. 1982. Canopy temperature and crop water stress. p. 43–85. *In* D. Hillel (ed.) Advances in irrigation. Vol. 1. Academic Press, New York.

Jackson, R.D., J.L. Hatfield, R.J. Reginato, S.B. Idso, and P.J. Pinter, Jr. 1983. Estimation of daily evapotranspiration from one time-of-day measurements. Agric. Water Manage. 7:351–362.

Jackson, R.D., S.B. Idso, R.J. Reginato, and P.J. Pinter, Jr. 1981. Canopy temperatures as a crop water stress indicator. Water Resour. Res. 17:1133–1138.

Jackson, R.D., P.J. Pinter, Jr., R.J. Reginato, and S.B. Idso. 1980. Hand-held radiometry. USDA-SEA Western Region, ARM-W-19.

Jackson, R.D., R.J. Reginato, and S.B. Idso. 1977. Wheat canopy temperature: A practical tool for evaluating water requirements. Water Resour. Res. 13:651–656.

Jackson, S.H. 1991. Relationship between normalized leaf water potential and crop water stress index values for acala cotton. Agric. Water Manage. 20:109–118.

Kanemasu, E.T., L.R. Stone, and W.L. Powers. 1976. Evapotranspiration model tested for soybean and sorghum. Agron. J. 68:569–572.

Katerji, N., B. Itier, I. Ferreira, and L.S. Pereira. 1987. Water stress indicators for tomato crop. p. 155–161. *In* R.J. Hanks and R.W. Brown (ed.) Proceedings of International Conference on Measurement of Soil and Plant Water Status, Logan, UT. 6–10 July. Utah State University, Logan.

Keener, M.E., and B. Gardner. 1987. CWSI and stomatal resistance of cotton and soybeans. p. 560–567. *In* Proc. Irrigation & Drainage Div., Portland, OR. 28–30 July. ASCE, New York, NY.

Keener, M.E., and P.L. Kircher. 1983. The use of canopy temperature as an indicator of drought stress in humid regions. Agric. Meteorol. 28:339–349.

Khera, K.L., and B.S. Sandhu. 1986. Canopy temperature of sugarcane as influenced by irrigation regime. Agric. For. Meteorol. 37:245–258.

Kirkham, M.B., K.I. Suksayretrup, C.E. Wassom, and E.T. Kanemasu. 1984. Canopy temperature of drought-resistant and drought-sensitive genotypes of maize. Maydica 29:287–303.

Krauter, C.F. 1987. Vineyard water management by the direct measurement of plant-water stress. California State Univ., Fresno, Publ. no. 871002.

Matthias, A.D., S.R. Yates, R. Zhang, and A.W. Warrick. 1987. Radiant temperature of sparse plant canopies and soil using IR thermometers. IEEE Trans. Geosci. Remote Sens. GE25:516–520.

Miller, E.C., and A.R. Saunders. 1923. Some observations on the temperature of the leaves of crop plants. J. Agric. Res. 26:15–42.

Mtui, T.A., E.T. Kanemasu, and C. Wassom. 1981. Canopy temperatures, water use and water use efficiency of corn genotypes. Agron. J. 73:639–643.

Nakayama, F.S., and D.A. Bucks. 1983. Application of a foliage temperature based crop water stress index to guayule. J. Arid Environ. 6:269–276.

Nakayama, F.S., and D.A. Bucks. 1984. Crop water stress index, soil water and rubber yield relations for the guayule plant. Agron. J. 76:791–794.

Nielsen, D.C. 1990. Scheduling irrigations for soybeans with the Crop Water Stress Index. Field Crops Res. 23:103–116.

Nielsen, D.C., and R.L. Anderson. 1989. Infrared thermometry to measure single leaf temperatures for quantification of water stress in sunflower. Agron. J. 81:840–842.

Nielsen, D.C., K.L. Clawson, and B.L. Blad. 1984. Effect of solar azimuth and infrared thermometer view direction on measured soybean canopy temperature. Agron. J. 76:607–610.

Nielsen, D.C., and B.R. Gardner. 1987. Scheduling irrigations for corn with the crop water stress index (CWSI). Appl. Agric. Res. 5:295–300.

Nielsen, D.C., and A.D. Halvorson. 1991. Influence of nitrogen fertility on water stress and yield of winter wheat. Agron. J. 83:1065–1071.

O'Toole, J.C., and J.L. Hatfield. 1983. Effect of wind on the crop water stress index derived by infrared thermometry. Agron. J. 75:811–817.

O'Toole, J.C., and J. Real. 1984. Canopy target dimensions for infrared thermometry. Agron. J. 76:863–865.

O'Toole, J.C., N.C. Turner, O.P. Namuco, M. Dingkuhn, and K.A. Gomez. 1984. Comparison of some crop water stress measurement methods. Crop Sci. 24:1121–1128.

Oi, D.H., J.P. Sanderson, R.R. Youngman, and M.M. Barnes. 1989. Developmental times of the Pacific spider mite (Acari: Tetranychidae) on water-stressed almond trees. Environ. Entomol. 18:208–212.

Palmer, J.H. 1967. Diurnal variation in leaf and boll temperatures of irrigated cotton grown under two soil moisture regimes in a semi-arid climate. Agric. Meteorol. 4:39–54.

Pandey, R.K., W.A.T. Herrera, and J.W. Pendleton. 1984. Drought response of grain legumes under irrigation gradient: II. Plant water status and canopy temperature. Agron. J. 76:553–557.

Pennington, D.A., and L. Heatherly. 1989. Effects of changing solar radiation on canopy-air temperatures of cotton and soybeans. Agric. For. Meteorol. 46:1–14.

Peterschmitt, J.M., and A. Perrier. 1991. Evapotranspiration and canopy temperature of rice and groundnut in southeast coastal India. Crop coefficient approach and relationship between evapotranspiration and canopy temperature. Agric. For. Meteorol. 56:273–298.

Pinter, P.J. 1983. Monitoring the effect of water stress on the growth of alfalfa via remotely sensed observations of canopy reflectance and temperature. p. 198-201. *In* Proc. 6th Conf. on Biometeorology and Aerobiology, Ft. Collins, CO. 26-28 April. Am. Meteorol. Soc., Boston.

Pinter, P.J., Jr., K.E. Fry, G. Guinn, and J.R. Mauney. 1983. Infrared thermometry: A remote sensing technique for predicting yield in water-stressed cotton. Agric. Water Manage. 6:385-395.

Pinter, P.J., Jr., and R.J. Reginato. 1982. A thermal infrared technique for monitoring cotton water stress and scheduling irrigations. Trans. ASAE 25:1651-1655.

Pinter, P.J., Jr., M.E. Stanghellini, R.J. Reginato, S.B. Idso, A.D. Jenkins, and R.D. Jackson. 1979. Remote detection of biological stresses in plants with infrared thermometry. Science (Washington, DC) 205:585-587.

Reginato, R.J. 1983. Field quantification of crop water stress. Trans. ASAE 26:772-775, 781.

Reginato, R.J., and J. Howe. 1985. Irrigation scheduling using crop indicators. J. Irrig. Drain. 111:125-133.

Reginato, R.J., S.B. Idso, and R.D. Jackson. 1978. Estimating forage crop production: A technique adaptable to remote sensing. Remote Sens. Environ. 7:77-80.

Reicosky, D.C., D.E. Deaton, and J.E. Parsons. 1980. Canopy air temperatures and evapotranspiration from irrigated and stressed soybeans. Agric. Meteorol. 21:21-35.

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

Reicosky, D.C., D.D. Warnes, and S.D. Evans. 1985b. Soybean evapotranspiration, leaf water potential and foliage temperature as affected by row spacing and irrigation. Field Crops Res. 10:37-48.

Robinson, F.E. 1984. Infrared analysis of sugar beet moisture stress due to root restriction and population. p. 17. *In* Agronomy abstracts. ASA, Madison, WI.

Sadler, E.J., and C.H.M. van Bavel. 1982. A simple method to calibrate an infrared thermometer. Agron. J. 74:1096-1098.

Saha, S.K., Ajai, A.K.S. Gopalan, and D.S. Kamat. 1986. Relationship between remotely sensed canopy temperature, crop water stress, air vapour pressure deficit and evapotranspiration in chickpea. Agric. For. Meteorol. 38:17-26.

Sammis, T.W., W.R. Riley, and D.G. Lugg. 1988. Crop water stress index of pecans. Appl. Eng. Agric. 4:39-45.

Sandhu, B.S., and M.L. Horton. 1978. Temperature response of oats to water stress in the field. Agric. Meteorol. 19:329-336.

Scherer, T.F. 1988. Canopy-air temperature differences as affected by soil textural class. Paper no. 88-2502, ASAE, St. Joseph, MI.

Shanahan, J.F., and D.C. Nielsen. 1987. Influence of growth retardants (anti-gibberellins) on corn vegetative growth, water use, and grain yield under different levels of water stress. Agron. J. 79:103-109.

Sharratt, B.S., D.C. Riecosky, S.B. Idso, and D.G. Baker. 1983. Relationships between leaf water potential, canopy temperature, and evapotranspiration in irrigated and nonirrigated alfalfa. Agron. J. 75:891-894.

Shock, C., E. Eldredge, and B. Gardner. 1987. Potato crop water stress index and tuber quality. p. 123. *In* Agronomy abstracts. ASA, Madison, WI.

Shock, C.C., T. Stieber, B. Gardner, and A. Bibby. 1989. Advances in evaluating stress. Potato Country. March, p. 26-29.

Sikkema, P.H., and J. Dekker. 1987. Use of infrared thermometry in determining critical stress periods induced by quackgrass (*Agropyron repens*) in soybeans (*Glycine max*). Weed Sci. 35:784-791.

Singh, P., and E.T. Kanemasu. 1983. Leaf and canopy temperatures of pearl millet genotypes under irrigated and nonirrigated conditions. Agron. J. 75:497-501.

Sithole, D.Y. 1987. Irrigation scheduling and crop water stress monitoring in potatoes. M.S. thesis. Washington State Univ., Pullman.

Sivakumar, M.V.K. 1986. Canopy-air temperature differentials, water use and yield of chickpea in a semi-arid environment. Irrig. Sci. 7:149-158.

Slack, D.C. 1988. Effects of non-water stressed stomatal control mechanisms on the crop water stress index of ryegrass turf. Paper no. 88-104, ASAE, St. Joseph, MI.

Slack, D.C., Jalali-Farahani, H., D.M. Kopec, and A.D. Matthias. 1986. Predicting turfgrass evapotranspiration from canopy temperature. Paper no. 86-2521, ASAE, St. Joseph, MI.

Smith, R.C.G., H.D. Barrs, and W.S. Meyer. 1989. Evaporation from irrigated wheat estimated using radiative surface temperature: An operational approach. Agric. For. Meteorol. 48:331-344.

Smith, R.C.G., H.D. Barrs, J.L. Steiner, and M. Stapper. 1985. Relationship between wheat yield and foliage temperature: Theory and its application to infrared measurements. Agric. For. Meteorol. 36:129-143.

Stark, J.C., and J.L. Wright. 1985. Relationship between foliage temperature and water stress in potatoes. Am. Potato J. 62:57-68.

Steiner, J.L., R.C.G. Smith, W.S. Meyer, and J.A. Adeney. 1985. Water use, foliage temperature and yield of irrigated wheat in southeastern Australia. Aust. J. Agric. Res. 36:1-11.

Stone, L.R., and M.C. Horton. 1974. Estimating evapotranspiration using canopy temperatures: Field evaluation. Agron. J. 66:450-454.

Stone, L.R., E.T. Kanemasu, and M.L. Horton. 1975. Grain sorghum canopy temperature as influenced by clouds. Remote Sens. Environ. 4:177-181.

Tanner, C.B. 1963. Plant temperatures. Agron. J. 55:210-211.

Temple, P.J., and L.F. Benoit. 1988. Effects of ozone and water stress on canopy temperature, water use, and water use efficiency of alfalfa. Agron. J. 80:439-447.

Throssell, C.S., R.N. Carrow, and G.A. Milliken. 1987. Canopy temperature based irrigation scheduling indices for Kentucky bluegrass turf. Crop Sci. 27:126-131.

Tormann, H. 1986. Canopy temperature as a plant water stress indicator for nectarines. S. Afr. J. Plant Soil 3:110-114.

Tripathis, R.P., K.R.S. Bohra, A. Kumar, and H.S. Kushwaha. 1985. Assessing crop water stress by infrared thermometry and pressure chamber for scheduling irrigation of wheat. Int. J. Ecol. Environ. Sci. 11:69-79.

Tubaileh, A.S., T.W. Sammis, and D.G. Jugg. 1986. Utilization of thermal infrared thermometry for detection of water stress in spring barley. Agric. Water Manage. 12:75-85.

Turner, N.C., J.C. O'Toole, R.T. Cruz, O.S. Namuco, and S. Ahmad. 1986. Responses of seven diverse rice cultivars to water deficits. I. Stress development, canopy temperature, leaf rolling and growth. Field Crops Res. 13:257-271.

Van Zyl, J.L. 1986. Canopy temperature as a water stress indicator in vines. S. Afr. J. Enol. Vitic. 7:53-60.

Walker, G.K., and J.L. Hatfield. 1979. Test of the stress-degree day concept using multiple planting dates of red kidney beans. Agron. J. 71:967-971.

Walker, G.K., and J.L. Hatfield. 1983. Stress measurement using foliage temperatures. Agron. J. 75:623-629.

Wanjura, D.F., J.L. Hatfield, and D.R. Upchurch. 1990. Crop water stress index relationships with crop productivity. Irrig. Sci. 11:93-99.

Wanjura, D.F., C.A. Kelly, C.W. Wendt, and J.L. Hatfield. 1984. Canopy temperature and water stress of cotton crops with complete and partial ground cover. Irrig. Sci. 5:37-46.

Wiegand, C.L., and L.N. Namken. 1966. Influence of plant moisture stress, solar radiation, and air temperature on cotton leaf temperature. Agron. J. 58:582-586.

Williams, L., and D. Grimes. 1986. Modelling vine growth—Development of a data set for a water balance subroutine. Kearney Agric. Cent. Exp. Stn. Rep. D-LAW 3065-H, Parlier, CA.

Zipoli, G., P.J. Pinter, Jr., R.J. Reginato, R.D. Jackson, and S.B. Idso. 1987. Canopy temperatures for assessing water use and yield performance of wheat cultivars exposed to drought stress. p. 93-97. *In* R.J. Hanks and R.W. Brown (ed.) Proc. Int. Conf. on Measurement of Soil and Plant Water Status, Logan, UT. 6-10 July. Utah State Univ., Logan.