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Infrared Thermometry and the Crop Water Stress Index. I. History, Theory, and Baselines

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Development of portable infrared thermometers and the definition of the Crop Water Stress Index (CWSI) have led to widespread interest in infrared thermometry to monitor water stress and schedule irrigations. But the CWSI concept is still new and poorly understood by many. The purpose of this paper is to review the definition of CWSI, and the determination and interpretation of the non-water-stressed baselines used to compute CWSI. The non-water-stressed baseline equation normalizes the canopy minus air temperature differential for variations in vapor pressure deficit. Non-water-stressed baselines can be determined empirically from measurements of canopy and air temperatures and vapor pressure deficit, made diurnally on a single day, or at a single time of day over many days, on well-watered plants. The value of the maximum canopy minus air temperature differential under maximum water stress should also be determined empirically. Causes for CWSI values falling outside of the defined 0 to 10 unit range are reviewed. Non-water-stressed baselines may shift with plant growth stage. Effective use of CWSI is dependent on understanding the definition of CWSI, and the proper determination and use of non-water-stressed baselines.

INFRARED THERMOMETRY was first used to measure temperatures of vegetative surfaces in the early 1960s (Fuchs and Tanner, 1966), and became more widely used during the 1970s with development of small, hand-held, portable infrared thermometers. During this period, the stress-degree-day parameter (the accumulation of positive values of the difference between canopy and air temperatures [dT]) was used to effectively quantify water stress. This worked well in wheat (*Triticum aestivum* L.) where it was observed that dT was negative when plants were well-watered, and positive when wheat was water-stressed (Jackson et al., 1977). But it is obvious from examination of the energy balance that variations in vapor pressure deficit have a significant effect on the magnitude of dT. This effect was observed in the early 1970s for cotton (*Gossypium hirsutum* L.) by Ehrler (1973). In the 1980s more routine use was made of infrared thermometry to quantify water stress in plants when Idso et al. (1981) and Jackson et al. (1981) defined and demonstrated the use of the CWSI. In the past 5 yr makers of infrared thermometers have incorporated software into instruments that automatically calculate CWSI for the user. Many growers, researchers, and extension agents use CWSI, but for many the concept is still new and poorly understood. The purpose of this paper is to review the definition of CWSI and the determination and interpretation of the non-water-stressed baselines used to compute CWSI.

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CWSI DEFINITION

CWSI was defined by Idso et al. (1981) as

$$\mathrm{CWSI} = \frac{\mathrm{dT} - \mathrm{MIN}}{\mathrm{MAX} - \mathrm{MIN}} \quad [1]$$

where

dT = Tc − Ta (°C)
Tc = crop temperature (°C)
Ta = air temperature (°C)
MIN = non-water-stressed baseline = A + B*VPD (°C)
VPD = vapor pressure deficit (kPa)
A = intercept of non-water-stressed baseline (°C)
B = slope of non-water-stressed baseline (°C kPa^{-1})
MAX = upper limit of dT (°C)

Tc is obtained from measurements made with an infrared thermometer. Ta and VPD have been obtained in several ways, including use of a psychrometer to get dry and wet bulb temperatures, or use of other temperature and humidity measuring devices and accompanying software built into an infrared thermometer and data logging system.

The value of CWSI can range from 0 (no stress) to 1 (maximum stress). Jackson et al. (1981) described this as "esthetically pleasing," since scientists studying plant-water relations often consider the ratio ET/ET_p, which similarly ranges from 1 (ample water) to 0 (no available water). Gardner and Shock (1989), on the other hand, described commercial development of infrared thermometry to monitor water stress and schedule irrigations, and reported that users of this technology did not readily accept the 0 to 1 scale of CWSI. Apparently users had difficulty interpreting the magnitude and significance of a change in CWSI that was reported in tenths or hundredths of a unit on a 0 to 1 scale. They reported that multiplying the scale by 10 to make a range from 0 to 10 was a practical improvement that allowed CWSI to be more easily understood and accepted.

Equation 1 is sometimes referred to as the empirical form of CWSI. Jackson et al. (1981) pointed out that CWSI is a crop-ET-based index defined by CWSI = 1 − (ET/ET_p), where ET is actual crop evapotranspira-

Abbreviation: CWSI, Crop Water Stress Index.

tion and ET_p is potential evapotranspiration. They derived an analytical form of CWSI based on the standard equation of the energy balance of a surface. This form contains terms which represent most of the environmental variables that affect crop temperature. A major problem with the routine use of the analytical form of CWSI is the difficulty in obtaining the necessary values of wind speed, net radiation, and correct estimates of aerodynamic resistance. The remainder of this paper deals with calculations and interpretations concerning the empirical form of CWSI. This form has the limitations of not compensating for changes in net radiation and wind speed. In practice, we have found that these are not serious limitations if well-defined sampling rules are followed. These rules are discussed in a companion paper (Gardner et al., 1992).

NON-WATER-STRESSED BASELINE EQUATION

The non-water-stressed baseline equation shows the dependency of Tc-Ta on VPD (Fig. 1). As VPD increases due to either increasing air temperature or declining atmospheric humidity, the crop temperature becomes cooler relative to the air temperature. This results because of the increase in transpiration rate that occurs under well-watered conditions when VPD increases, and the subsequent greater cooling of the plant that occurs.

The non-water-stressed baseline equation can be determined empirically from simultaneous measurements of Tc, Ta, and VPD. Non-water-stressed baselines appear to be crop specific (Idso, 1982). There is differing evidence regarding whether non-water-stressed baselines are location-specific or not (Idso, 1982; Nielsen, 1990). The easiest method of determining a non-water-stressed baseline equation is to conduct a diurnal study of a well-watered crop. With this approach, dT and VPD data are collected throughout a single day from about 10 a.m. to 4 p.m. so that a wide range of dT and VPD values is obtained. A linear regression is then fitted to the data. Non-water-stressed baseline equations determined in this manner have reported R^2 values greater than 0.95. Gardner and Shock (1989), on the other hand, found that this approach did not always produce reliable and useful non-

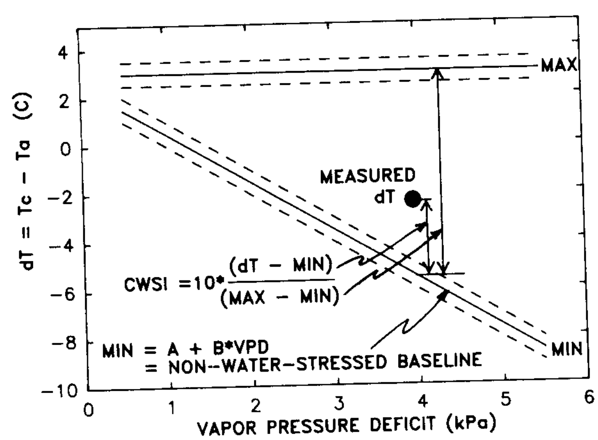

Fig. 1. Graphical depiction of the non-water-stressed baseline equation, MAX, and Crop Water Stress Index (CWSI). (Dashed lines represent variability of data used to determine MIN and MAX.)

water-stressed baselines. The following limitations should be recognized when diurnal data are used to determine non-water-stressed baselines:

1. Seasonal changes in canopy structure/architecture, stomatal response, and transpiration rate are not represented in the data. Data from a single day of measurement would not provide sufficient information to determine non-water-stressed baselines that change with crop growth stage.

2. Since the non-water-stressed baseline equation is the basis of an empirical model, its applicability is broader when the data defining the equation represent a range of naturally occurring variations in solar radiation, wind speed, air temperature, and VPD. The analytical CWSI calculation (Jackson, 1982) shows that the slope and intercept of a non-water-stressed baseline will be affected by variations in all of these parameters. Data collected during 1 d are unlikely to contain sufficient variation in all parameters, particularly VPD.

An alternative approach to the diurnal determination of non-water-stressed baselines is to collect dT and VPD from well-watered plants several times a week throughout the growing season, making measurements during the same time each day. Measurements are usually made within 1 to 2 h after solar noon when VPD is maximum for the day. This is the time of day when water stress is likely to be highest and when irrigation scheduling with CWSI should be done. The disadvantage of this method is that it takes an entire growing season to collect the necessary data, and the regression of dT on VPD has R^2 values that are typically 0.6 to 0.7. The advantages to seasonal baseline data are:

1. The data represent a range of environmental conditions during the time of day when stress is likely to occur and during which routine measurements to quantify stress will be made during the growing season.
2. Seasonal changes in the crop canopy/architecture and transpiration rate are represented in the data.

Non-water-stressed baselines have been published for many different crops (Gardner et al., 1992), but most of these equations were determined using the diurnal method. Users of published non-water-stressed baselines should use some caution when applying these baselines in their specific situations, and are encouraged to test the baseline for applicability. Users of published non-water-stressed baselines should be aware of the environmental conditions occurring during the time of baseline determination, and not use a baseline outside the range of data used to define it.

Baselines that appear very different when comparing slope and intercept values may, over the range of actual data collected, be very similar. Table 1 shows two seemingly different non-water-stressed baselines for turfgrass developed in Indiana and Georgia (Carrow, 1987). Because of the differences in slope and intercept values, one might conclude that baselines for turfgrass are strongly location dependent, and perhaps species and variety de-

Table 1. Comparison of predicted crop-air temperature differences (dT) between non-water-stressed baselines (Carrow, 1987) determined in Indiana and Georgia. (Bold region shows vapor pressure deficit [VPD] range of original data collected at both locations.)

VPD	Indiana $dT=8.3-2.30*VPD$	Georgia $dT=4.7-0.86*VPD$	Difference between equations
(kPa)	°C (°F)		
0.0	8.3 (14.9)	4.7 (8.5)	3.6 (6.5)
1.0	6.0 (10.8)	3.8 (6.8)	2.2 (4.0)
2.0	**3.7 (6.7)**	**3.0 (5.4)**	**0.7 (1.3)**
2.5	**2.6 (4.7)**	**2.6 (4.7)**	**0.0 (0.0)**
3.0	**1.4 (2.5)**	**2.1 (3.8)**	**−0.7 (−1.3)**
4.0	−0.9 (−1.6)	1.3 (2.3)	−2.2 (−6.2)
5.0	−3.2 (−5.8)	0.4 (0.7)	−3.6 (−6.5)

pendent. One might also conclude that using CWSI in turfgrass is nearly a hopeless task due to the large number of varieties in use.

These conclusions are not justified however. The data for both these baselines were acquired in the 2 to 3 kPa VPD range. When predicted values of the two equations in Table 1 are compared in the 2 to 3 kPa VPD range, it can be seen that the two equations are, in fact, very similar in their prediction of dT. It is questionable whether the large predicted differences in the 0 to 1 and 4 to 5 kPa VPD ranges of these two equations have any significant physical meaning, since no data were collected in these ranges to test these equations. Again, the caution is that users be aware of the conditions from which non-water-stressed baselines were created, and not use them out of their range of applicability.

Development of a non-water-stressed baseline at a single location is often limited by the VPD range that occurs, thereby limiting the baseline's transportability to other locations. Gardner and Shock (1989) suggested that a VPD range of 1 to 6 kPa was necessary to define a baseline that could be used in many locations, and encouraged researchers from many locations to collaborate and combine data so that baselines valid over large VPD ranges could be developed.

After a non-water-stressed baseline has been defined, testing must be conducted to determine its validity and applicability. Non-water-stressed baseline validity can be tested by comparing the current baseline with data from other years and locations. To test a non-water-stressed baseline applicability. a user may conduct an independent irrigation scheduling experiment based on the CWSI values generated with the desired baseline, and determine if the results (generally crop yield) are economically satisfactory. At least two to three cropping seasons of such testing are required before a reliable baseline can be established, and the economic feasibility of using CWSI can be demonstrated (Gardner and Shock, 1989).

Small errors in non-water-stressed baseline determination can potentially cause large errors in calculated CWSI. For example, using the baselines given in Table 1, the 0.7 °C (1.26 °F) difference in dT predicted by the two baselines at VPD = 2 kPa gives CWSI = 1.3 (Indiana baseline) and CWSI = 3.3 (Georgia baseline) [assuming dT = 4 °C (7.2 °F), MAX = 6 °C (10.8 °F), and a CWSI range of 0 to 10]. At VPD = 3 kPa the calculated CWSI using the Indiana baseline is 5.7, while the Georgia baseline gives CWSI = 4.9. Determination and use of the correct non-water-stressed baseline is critical to the successful use of the empirical CWSI method.

DETERMINATION OF MAX

The value of MAX in Eq. 1 and Fig. 1 is the value of dT that occurs when no transpiration is occurring in the plant such that the radiant and convective heat exchange terms dominate in the energy balance of the canopy. Idso et al. (1981) showed that MAX is a function of air temperature, but variation of MAX was small within the limits of typical midday temperatures during the crop growing season. Choosing a constant value of MAX for all values of Ta introduces only a small error into the calculation of CWSI. We suggest the following method for determining MAX:

1. MAX should be based on field observations of an extremely water stressed crop that has not had major changes in canopy structure and architecture due to wilting and leaf abscission.
2. The severity of water stress imposed should be evaluated through a combination of physiological measurements (such as stomatal resistance, leaf relative water content, leaf water potential) and soil water measurements. MAX should be selected on the basis of yield/quality considerations rather than solely on cessation of transpiration since the value of dT at which crop yield/quality is maximally affected may be different than the value at which transpiration is totally eliminated.

VALUES OF CWSI OUTSIDE THE 0–10 RANGE

As stated earlier, Eq. 1 (multipled by 10) should generate values of CWSI which fall in the range of 0 to 10. Since there is variability associated with the measurement of ambient temperature and humidity conditions, as well as with crop temperature, there is variability associated with the determination of the non-water-stressed baseline equation and MAX, as noted by the dashed lines in Fig. 1. Consequently, there may be times when measurements give values of dT that are less than MIN and greater than MAX, which would result in values of CWSI less than 0 and greater than 10, respectively. This is the primary cause of negative CWSI values. Other causes of out-of-range CWSI include:

1. Evaporation from wet plant and soil surfaces following dew deposition, rain, or irrigation adds to evaporative cooling beyond what is accounted for by the non-water-stressed baseline.
2. The solar radiation level is too low due to clouds or dense haze in front of the sun, or from measurements taken more than 2 hr before or 2 hr after solar noon.
3. Wind speed is higher than occurred during determination of the non-water-stressed baseline.
4. Shaded leaves/canopy were measured instead of sunlit leaves/canopy.

5. Air temperature is much cooler than the conditions that existed at the time of non-water-stressed baseline determination, resulting in an unusually cool canopy even in the presence of high solar radiation.
6. Air temperature readings are anomously high due to the air temperature sensor not having sufficient time to equilibrate to the ambient air temperature.
7. Soil surface was viewed by the IRT due to low leaf area.
8. The non-water-stressed baseline equation being used is in error. Generally this is not a problem once a baseline has been tested and used enough to determine that it is correct for a given crop in a given location.

More details on the effects of radiation, wind speed, leaf orientation to the sun, and low leaf area are given in the companion paper (Gardner et al., 1992).

If it is known through experience that the non-water-stressed baseline equation is correct, that proper procedures of data collection have been used (Gardner et al., 1992), that wet plant and soil surfaces are not present, and that solar radiation is high, then occasional negative CWSI values do not represent a problem, and can be considered a result of the variability associated with collection of field data and the empirical method of non-water-stressed baseline determination. Occasional negative CWSI values under these circumstance can be assumed to represent a non-water-stressed condition.

From Eq. 1 and Fig. 1 it can be seen that if the estimated value of MAX is too low, values of CWSI greater than 10 will frequently result. Again, because of the natural variability associated with field measurements, an occasional CWSI value greater than 10 under extremely water-stressed conditions should not be a cause for concern. If, as suggested earlier in this paper, MAX is estimated based on yield/quality considerations rather than transpiration cessation, then there may be frequent occurrences of CWSI greater than 10 under severe water stress conditions. This should not be a problem in interpretation, for it means that CWSI = 10 is the point at which maximum damage to crop yield/quality occurs, and values greater than 10 indicate further reduction in transpiration.

SEASONAL SHIFTS IN NON-WATER-STRESSED BASELINES

The slope and intercept of the non-water-stressed baseline equation are affected by such factors as plant structure (leaf size, shape, orientation; presence of reproductive structures such as heads, ears, tassels; amount of canopy cover) and variation of potential transpiration rate with plant age. For many crops, a single baseline has been used successfully over an entire growing season. It has been found, however, that for a crop such as winter wheat, distinctly different baselines should be employed for prehead and for posthead wheat (Idso, 1982). Not all crops have exhibited such well-defined shifts in baselines with an easily identified stage change, such as heading in wheat. Consequently, the routine use of CWSI becomes more complex if a user must change baselines based on plant development.

Gardner and Shock (1989) suggested an alternative method to using multiple baselines. They advocated defining a single baseline for a particular crop, using that baseline the entire growing season, and adjusting the target CWSI for irrigation scheduling based on tabulated or graphical values that accounted for the seasonal shift in baselines. With this procedure, target CWSI values do not remain near 0 during the entire growing season, but vary with seasonal crop requirements and canopy structure. This can be the case early in the growing season before full canopy cover occurs, and late in the season as leaves begin to senesce. Practical CWSI values for irrigation decisions might decline then rise, as in Fig. 2. In practice, a grower would irrigate when CWSI exceeds a reference CWSI value for a particular part of the season instead of irrigating at the same predetermined CWSI value for the entire season. The major advantage is that the grower need not decide when to change a baseline. The determination of a set of seasonally varying minimum CWSI values, such as those idealized in Fig. 2, must be obtained from a user's experience with CWSI. Data would be collected from well-watered areas throughout the growing season, and then plotted against date or crop growth stage. A single non-water-stressed baseline equation would be determined during midseason when maximum crop cover existed.

INTERPRETIVE SUMMARY

Infrared thermometry and the CWSI are valuable tools for monitoring and quantifying water stress, and for scheduling irrigations. Effective use of CWSI is dependent on understanding the definition of CWSI and the proper determination and use of non-water-stressed baselines. Non-water-stressed baselines should be determined empirically from simultaneous measurements of dT and VPD made diurnally or at a single time of day over many days on well-watered plants. Non-water-stressed baselines should not be used to calculated CWSI under VPD conditions outside of the range used to define the baseline. The value of MAX should also be determined empirical-

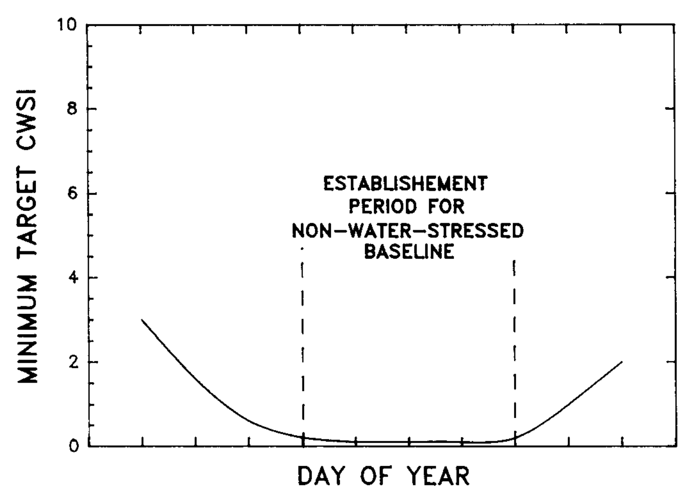

Fig. 2. Variation in minimum target Crop Water Stress Index (CWSI) with time due to using a single non-water-stressed baseline over the entire growing season.

ly as the dT value from maximally water-stressed plants with regard to yield/quality considerations. Non-water-stressed baselines may shift with plant growth stage due to plant developmental changes affecting plant structure and potential transpiration rate. Understanding the definition of CWSI, the determination of non-water-stressed baselines, and conditions that can cause CWSI to fall outside of the defined 0 to 10 unit range can help users avoid making measurements under unacceptable conditions and can increase the usefulness of CWSI data collected.

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