Canopy Temperature-Based Water Stress Indices: Potential and Limitations

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Abstract

Water stress in plant is associated with reduced availability of soil moisture under higher ambient temperature and wider vapour pressure deficit for a considerable period of time. Instruments like pressure chambers and porometers are being used to quantify crop water stress under field conditions, but their use is limited because of the numerous time-consuming measurements that must be made. The application of thermal indices involving canopy temperature for monitoring crop water stress and irrigation scheduling has been demonstrated by several researchers in the last five decades since the evolution of portable infrared thermometers in the 1960s. As the temperature of plant canopy is a manifestation of canopy energy balance, a water-stressed canopy is hotter than a well-watered one under the same environmental conditions. Infrared thermometer integrates the thermal radiation from all exposed surfaces in the field of view of the instrument that included the plant surface and exposed soil surfaces into a single measurement and converts it into temperature unit applying the principle of Stefan-Boltzmann law. However, different plant physiological as well as micro-climatic factors like solar radiation, turbulence, air temperature and humidity must influence the canopy temperature at the time of observation. Hence, stomatal conductance and transpiration rates cannot be estimated by canopy temperature alone. In other words, canopy temperature alone is not enough to make estimates of plant water status. For this reason many researchers have attempted to normalize the canopy temperature to account for the influence of other variable

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microclimatic parameters like vapour pressure deficit, air temperature, wind speed, solar radiation, etc.

In the past few decades, a number of thermal indices have been applied to estimate crop water stress under field condition. The difference between canopy temperature and air temperature (canopy-air temperature difference, CATD) was the first and one of the most commonly used thermal indices to quantify crop water stress. The summation of CATD over some critical period in the crop's life cycle was termed as stress degree day (SDD). Similarly, the difference between canopy temperature of stressed and non-stressed plants has been used as an index called temperature stress day (TSD). The "canopy temperature variability" (CTV) takes into account the spatial variability of canopy temperature in crop field which was found to be higher in stressed plant than that of non-stressed plant. The temperature-time threshold (TTT) method assumes that the stress is not occurring in the crop until the canopy temperature reaches certain threshold value and calculates the amount of time that canopy temperature is greater than temperature threshold to quantify moisture stress. The crop water stress index (CWSI) further normalizes the canopy-air temperature difference with vapour pressure deficit of air. The calculation of CWSI quantifies the moisture stress of a plant as a comparison of its canopy temperature with that of a non-water-stressed plant and a maximum stressed plant with respect to their differences from the ambient air temperature at a given vapour pressure deficit. Conceptually, CWSI of a non-stressed and fully stressed (non-transpiring) plant is 0 and 1, respectively. The water deficit index (WDI) integrated the percent vegetation coverage and canopy temperature to compensate the effect of soil background that interferes in the remote measurement of canopy temperature through infrared thermometry. The "Biologically Identified Optimal Temperature Interactive Console (BIOTIC)" is an irrigation protocol that provides irrigation scheduling based upon measurements of canopy temperatures and the temperature optimum of the crop species of interest. But some critical issues like impact of rapid fluctuation in radiation and wind speed on crop water stress, crop to crop variability in stress tolerance and the requirement of stress at particular phenophases of some crops have not been duly focused. Thus the canopy temperature-based water stress indices have limited application in irrigation scheduling at field scale. However, with advancement of satellite-based optical and thermal remote sensing in recent years, there is a renewed interest in thermal indices for crop stress monitoring.

14.1   Introduction

Water stress is one of the most common types of plant stress and is often associated with reduced availability water from soil and during periods of high evaporative demand of atmosphere associated with higher ambient temperature and vapour pressure deficit. The negative effects of water stress on crop yield are both cosmopolitan and substantial, reducing yields in all cropping systems and regions worldwide. Generally, the production is adversely affected when a crop undergoes longer period of stress during its life cycle, although some plants may require a period of water stress to initiate reproductive development. An increase in plant water stress (decreasing plant water potential) occurs when an imbalance exists between the amount of water absorbed by the roots and the amount lost through transpiration. The degree of stress that develops is a function of the plant's environment. Popular methods that include pressure chamber and porometer that are being adopted to quantify crop moisture stress under field conditions have relied observations on a single plant or plant part. The pressure chamber measures leaf water potential of sample leaves removed from the growing plant (Correia et al. 2001). Porometer is frequently used for in situ measurement of stomatal conductance using portable chamber system (Turner 1991). Both the methods have potential to characterize crop water stress under field condition. However, these methods require numerous time-consuming measurements that limit their large-scale field application. However, for small plot research, these and similar methods provide useful information (Reginato 1983). Since the last few decades, the use of canopy temperature has received much attention for characterizing plant water stress with evolution of portable infrared thermometer (Idso 1982; Jackson et al. 1977, 1981).

14.2   Basic Principle

The plant leaves absorb a certain fraction of the incident radiation and partition this energy into three outgoing streams: reradiation, convective heat exchange with the air and evaporation of water or transpiration. In case of plant leaf, the heat conduction is too small to be considered significant, and for steady-state situations, the energy storage term is zero. Whenever water is evaporated from a leaf, the latent heat of evaporation is drawn from the leaf, cooling it down. Under water deficit conditions, stomata of leaves close in response to loss of turgor pressure (Kramer 1983), causing a lowering of transpiration rate. The dissipation of energy through latent heat is reduced leading to a positive energy balance. As the temperature of plant canopy is a manifestation of canopy energy balance, a water-stressed canopy is hotter than a well-watered one under the same environmental conditions. Testi et al. (2008) was of the view that the temperature of a canopy deviates from air temperature, in a way that is strictly dependent on the rate of transpiration under the same environmental conditions.

The energy budget of individual leaf in a plant canopy has been analysed in detail by Gates (1980). The empirical derivation of leaf temperature by Gates showed that for a leaf of characteristic dimension of 0.05 m and an internal resistance to water loss of 200 m s^{-1} at air temperature 30 °C, wind speed 1 m s^{-1} and relative humidity 50% the leaf temperature is 26 °C when the radiation absorbed by the leaf is 419 W m^{-2}. The leaf temperature is increased to 31.3 °C when the radiation absorption is 698 W m^{-2}, other conditions remaining similar. The non-transpiring leaf under similar conditions would have a temperature of 28.7 and 34.6 °C, respectively. Thus, the empirical analysis of Gates suggests that sunlit leaves would be warmer than air, whereas the lower-shaded leaves would be cooler than air, and transpiration was very important in the energy budget of plants.

14.3 Leaf Temperature Versus Canopy Temperature

The literature concerning leaf temperatures dates back at least to the early part of the eighteenth century. Jackson (1982) made a thorough review of the history of leaf temperature measurement and found that the leaf temperatures were higher than the air temperature in majority of the earlier reports. The earlier measurements involved clamping of sensors to the leaves or wrapping of un-detached leaves around the sensors. The major limitations in those measurements were that the leaves were not true representative of the whole canopy. The leaves were mostly near the top of plant under direct sunlight. As the quantity of absorbed radiation is the most influencing parameter in the energy budget of the leaf, the position of leaf in the plant stand (upper or lower leaf) is an important criterion in measurement of leaf temperature. Secondly, there was no standard location suggested for recording air temperature. Tanner (1963) was among the first researchers who studied canopy temperature with the help of infrared thermometry for monitoring plant water stress. Tanner was of the view that the temperature of individual leaf would fail to represent the status of the plant as a whole. A leaf with the surface normal to incident solar radiation will be at a substantially higher temperature than a leaf that has a large angle of incidence or one that is shaded. Thus, there is no single leaf temperature value that represents the plant to be useful for any given research problem. Nevertheless, the measurement of individual leaf temperature with contact thermometers is cumbersome and tedious. Furthermore, either attaching or inserting thermal sensors may affect the plant temperature that is to be measured. Hence, for studying response of crops to moisture stress, canopy temperature that represents the averaged condition of both sunlit and shaded leaves is a more acceptable parameter than that of leaf temperature.

14.4 Infrared Thermometry

Infrared thermometer integrates the thermal radiation from all exposed surfaces in the field of view (FOV) of the instrument that included the plant surface and exposed soil surfaces into a single measurement and converts it into temperature unit. Tanner

(1963) defined temperature measured with an infrared thermometer as the black-body temperature that would produce the radiation entering the instrument from plant parts in the field of view. However, the target surface may include soil surface exposed through the layers of vegetation.

14.4.1 Principles of Infrared Thermometry

The principle of infrared thermometer is based on the Stefan-Boltzmann law which states that the total energy radiated per unit surface area of a blackbody across all wavelengths per unit time (also known as the black-body *radiant emittance*) is directly proportional to the fourth power of the blackbody's thermodynamic temperature T:

$$\text{For blackbody,} \quad R_{\text{blackbody}} = \sigma\, T^4 \tag{14.1}$$

$$\text{For greybody,} \quad R_{\text{greybody}} = \varepsilon\, \sigma\, T^4 \tag{14.2}$$

The constant of proportionality σ is called the Stefan-Boltzmann constant. The value of the constant is $5.67 \times 10^{-8}\ \text{W m}^{-2}\ \text{K}^{-4}$. A blackbody absorbs all radiation incident upon it, and its emissivity is also maximum. For the blackbody absorptivity, (a) = emissivity (ε) = 1. An object that does not absorb all the incident radiation and emits less energy than a blackbody is known as grey body. These grey bodies are characterized by their emissivity. The conventional IR thermometers work in wavelength range of 8–14 micrometre, the range in which most of the earth objects have high emissivity ($\varepsilon = 0.94$ to 0.98).

14.4.2 Errors Associated with IR Thermometry

There are different types of error associated with the IR thermometry. The first error is due to interference of atmospheric radiation. According to Monteith and Szeicz (1962), the total upward long-wave radiation (R_T) from a surface with emissivity (ε) may be written as the sum of thermal infrared radiation emitted by the object and the part of atmospheric radiation reflected by it.

$$R_T = \varepsilon\, \sigma\, T_s^{\,4} + (1--\varepsilon)\, R_a = \varepsilon\, \sigma\, (T_s *)^4 \tag{14.3}$$

where T_s is the true temperature of the target surface, R_a is the atmospheric radiation received by the surface and T_s* is the apparent temperature of the surface assuming $\varepsilon = 1$.

The difference between the true temperature and apparent temperature has been derived by Monteith and Szeicz (1962) as

$$T_s - T_s{}^* \cong \frac{(R_T - R_s)(1 - \epsilon)}{4\,\epsilon\,\sigma\,T_s{}^3} \qquad (14.4)$$

The apparent radiative temperature was about 0.2 °C less than the true temperature for vegetation and water surface and as high as 1.5 °C less than the true temperature for a bare soil. Another possible source of error is due to the radiative flux divergence or the loss of radiation in the path for the surface to the sensor. Monteith and Szeicz (1962) opined that the surface temperature of turf may be underestimated by about 1 °C during the day and overestimated by about 0.2 °C during night. For bare soil, the difference may reach −2 to −3 °C during the day. The third source of variation of apparent surface temperature might be due to direction of measurement with respect to sun's position and angle of measurement. Here, solar zenith, measurement zenith and azimuth angle influence the measurement. Monteith and Szeicz (1962) studied the influence of measurement geometry and found that in the direction sun (azimuth = 0°), the radiometer saw patches of grass completely shaded by vertical irregularities of the canopy, whereas at azimuth = 180°, all visible leaves were fully illuminated and therefore relatively warm as the sunlit part of the canopy is expected to be warmer than the shaded part. The temperature of the surface also decreased at solar zenith >70°, showing that the grass blades were cooler at their tips than deeper in the cover.

Kimes et al. (1980) opined that the thermal infrared sensor response to emissions from vegetation canopies may deviate significantly from that expected for a Lambertian surface (ideal diffusion surface). They obtained a difference of as great as 13 °C, when going from a viewing zenith angle of 0° to one of 80° for wheat canopy of leaf area index 1.5. The measured difference at different measurement zenith angle was function of vegetation canopy geometry and the vertical temperature distribution of the canopy components.

The errors associated with IR thermometry are appeared to be highly variable with respect to time of measurement (solar angle), measurement geometry (angle, direction and distance of measurement) and field of view (FOV). Kirkham (2005) opined that the overall error generally varied from 0.5 to 1.5 °C. By viewing the target obliquely, one would ensure that maximum amount of vegetation remains within the FOV of the IR sensor. Furthermore, the influence of the sun's angle that would affect the target temperature may be minimized by taking readings from different directions. Jackson et al. (1981) took eight measurements four facing the east and four facing the west between 1340 and 1400 local time at an angle of 30° to represent the canopy temperature of wheat. Kirkham (2005) also preferred the same viewing angle, and they held the thermometer 1.2 m away from the crop (corn) canopy.

14.5   Application of Infrared Thermometry in Stress Monitoring

The energy budget of plant leaf involves three modes of heat transfer, i.e. by radiation, convection and transpiration. Aston and Van Bavel (1972) used infrared thermometry to record an increase in canopy temperature as a result of increased short-wave and long-wave radiant loads on leaf arrays. They compared temperature increase of different surfaces and reported that the surface temperature increased by 2.5, 0.5 and 2.0 °C in dry blotting paper, wet blotting paper and leaves of the southern pea (*Vigna sinensis*), respectively. Such increase in temperature of artificial and real leaves has also been predicted by the leaf energy balance-soil water depletion model with an accuracy of 1 and 5% for the artificial and real leaves, respectively. Gates (1980) gave a detailed account of energy budget of leaf and derived that the leaf temperature is influenced by cooling produced by the evaporation of liquid water to water vapour in the mesophyll and its diffusion through the stomata and across the boundary layer to the free air beyond the leaf. Thus, the canopy temperature that represents the average condition of all the leaves of the plant would indicate the transpiration status of the plant as a whole.

Complications arise while interpreting canopy temperature recorded from field measurement because of plant physiological as well as microclimatic factors like radiation, turbulence, air temperature and humidity that influence the canopy temperature at any particular time of observation in crop field. Thus, the stomatal conductance and transpiration rate that represent plant water status cannot be estimated by measuring the canopy temperature alone. Hence, many researchers attempted to normalize leaf and canopy temperature to account for the influence of the environmental condition during the period of measurement.

14.5.1 Canopy-Air Temperature Difference (CATD) and Stress Degree Day (SDD)

One of the most widely used parameters for normalization of environmental factors in canopy temperature-based stress monitoring approach is air temperature. Erhler (1973) was among the first few researchers who described the relation between leaf-air temperature difference and plant water stress. He used fine wire thermocouples imbedded in cotton leaves to measure leaf temperature on well-watered plants and concluded that within an irrigation cycle, main long-term changes in cotton (*Gossypium*) are progressive leaf dehydration and consequent stomatal closure. During this drying period, if the leaf continues to absorb the same amount of energy throughout the cycle, it will heat up gradually. Consequently, a long-term measurement of leaf temperature (T_L) is an indirect guide to stomatal aperture and might serve as an indicator of the need for irrigation. A simultaneous measurement of air temperature (T_A) would help computing leaf-air temperature differences ($\Delta T = T_L - T_A$). These differences could be related to soil water depletion. But he also opined that other factors like air temperature, vapour pressure, wind speed, radiation and leaf resistance would be intimately related to transpiration and stomatal aperture and

thus could regulate leaf temperature (T_L). It was evident from the study of Linacre (1967) that the leaf and air temperature are highly correlated. He suggested that the plants had an optimum temperature for growth. When the air temperature falls below the optimum temperature, the plant canopy will become warmer than air. If the air temperature is above the optimum value, the plant canopy will be cooler than air. Several authors have referred it as "equality temperature" or "crossover temperature". Blad and Rosenberg (1976) observed that the crossover temperature varies widely under advective conditions in case of alfalfa and corn. The effects of environmental factors on T_L must be determined or held constant before T_L or ΔT data can be used for irrigation scheduling.

Quantification of plant stress through infrared thermometry was first demonstrated by Idso et al. (1977) and Jackson et al. (1977). They proposed that the difference between the temperature of a plant canopy and the temperature of the surrounding air ($T_C - T_A$) might be an indicator of the water status of wheat, since water stress induces partial closure of stomata and reduces transpiration. This allows sunlit leaves to warm above ambient air temperature as it absorbs energy from the sun. They quantified the crop water stress in terms of stress degree day (SDD) which may be defined as the summation of canopy-air temperature difference ($T_C - T_A$) over some critical period in the life cycle of crop much like the concept of growing degree day (GDD).

$$\text{SDD} = \sum\nolimits_{n=i}^{N} (T_c - T_c)_i \tag{14.5}$$

where "i" to "N" is the period under study. The $T_C - T_A$ should be recorded during mid-afternoon (about 2 p.m.), and the air temperature was defined as the temperature measured at 150 cm above the soil.

Idso et al. (1977, 1978) applied the concept of SDD to yield prediction. They have considered the period between the appearance of heads and awns to the end of plant growth as the critical period for SDD summation for grain crop like wheat, while for a forage crop such as alfalfa, the dry matter production per unit leaf area was a linear function of SDD summed over the entire period of vegetative growth.

Jackson et al. (1977) applied the concept of SDD to irrigation scheduling and provided the framework for possible automation of irrigation scheduling applying the concept of SDD over larger areas by using airborne thermal scanner measurements.

Reginato et al. (1978) successfully applied the concept of stress degree day to alfalfa, for predicting its forage yield as well as grain yield. Walker and Hatfield (1979) obtained an inverse relationship between SDD and final yield of beans. Helyes et al. (2006) also observed that the accumulated SDD during flowering season had inverse relationship with the yield of snap bean. They opined that each 1 degree higher SDD might cause 90–130 kg ha^{-1} yield loss. All these studies showed that the SDD model illustrated the effect of moisture stress on eventual yield of crop.

Idso et al. (1981) presented $T_C - T_A$ and vapour pressure deficit (VPD) data for several crops and showed that the relationship between $T_C - T_A$ and VPD, for well-watered crops under clear-sky conditions, was linear. Diaz et al. (1983) noted that evapotranspiration was inversely and linearly related to the cumulative SDD values for a variety of crops grown under water-stressed conditions. Canopy to air temperature difference is also correlated to soil moisture content and stem water potential of peach orchards (Wang and Gartung 2010).

14.5.2 Temperature Stress Day (TSD)

The difference between canopy temperature of stressed and non-stressed plants has also been used as an index to quantify moisture stress. The earlier studies of Tanner (1963) revealed a possible maximum temperature difference of 3 °C between irrigated and unirrigated potatoes (*Solanum tuberosum* L.) due to stomatal closure. Gardner et al. (1981a) suggested that a relative measure of plant water status can be obtained from the temperature difference between a well-watered plot and a stressed plot. They referred this temperature difference to as "temperature stress day" (TSD). Irrigations could be initiated when the stress plot reached a predetermined temperature above the well-watered crop. They found parabolic curve between difference in leaf water potential ($\Delta\psi$) and difference in canopy temperature between stressed and non-stressed plant (TSD) of grain sorghum. During initial phases of moisture stress, the transpiration is reduced leading to increase in canopy temperature and thereby increase in TSD up to a value of about 4 °C. Beyond that point, transpiration from the stressed plants is restricted sufficiently to cause a slight increase in the leaf water potential (ψ), but at the same time, TSD continued to increase because transpiration was restricted and more of the absorbed radiation caused heating of the plant. However, the stress was not always indicated in sorghum whenever the TSD was greater than 0, since the TSD of non-stressed crop varied about mean 0 and standard deviation of 0.3. Clawson and Blad (1982) used TSD values of 1.0–3.0 to initiate irrigation of corn. Gardner et al. (1981b) also correlated corn grain yields with TSD of plants grown under several irrigation regimes and successfully used daily midday TSD values during the pollination and grain-filling stages to predict grain yield with an accuracy of $\pm10\%$.

The appealing simplicity of the TSD was that it only required simultaneous measurement of canopy temperatures of a stressed and a well-watered field of same crop and soil type. No other measurements of other atmospheric or plant parameters were required to calculate TSD. However, Clawson et al. (1989) suggested that the TSD is not an environmentally independent index, it has strong dependency with the vapour pressure deficit of air, and thus it cannot be universally applied.

14.5.3 Canopy Temperature Variability (CTV)

Studies on canopy temperature have revealed that the spatial variability of canopy temperature in water-stressed crop was higher than that of non-stressed crop (Gardner et al. 1981b; Clawson and Blad 1982; Nielsen and Gardner 1987). This formed the basis of the "canopy temperature variability" (CTV) approach as a tool for determining crop water stress. However, the CTV approach was originally suggested by Aston and Van Bavel (1972). They found that the standard deviations of the canopy temperature were 0.3 °C for well-watered corn plots, while it was about 4.2 °C for water-stressed plots. The large variation in canopy temperature as a result of changing environmental factors (e.g. air temperature and radiation) suggested the use of in-field temperature variations due to differential drying of non-homogeneous soil as an indicator of plant water status.

Gonzalez-Dugo et al. (2006) made a detailed study on applicability of CTV concept to different levels of moisture stress and observed that at low moisture stress CTV in field was relatively small, whereas at moderate stress level, CTV was highly sensitive to water stress. However, at high stress level, assessment of moisture stress from CTV was poor and not recommendable. The major limitation of CTV concept is that the degree of uniformity of the root zone water availability of the field might differ from one another. This makes the application of threshold value (of CTV) or its empirical relationship with other stress indices difficult.

14.5.4 Time-Temperature Threshold (TTT)

The TTT method assumes that stress is not occurring in the crop until it reaches the temperature threshold or $T_{critical}$ and calculates the amount of time that canopy temperature (T_c) is greater than $T_{critical}$. Upchurch et al. (1996) received US patent no. 5,539,637 for an irrigation management system that was based on this optimal leaf temperature for enzyme activity and a climate-dependant time threshold. They termed it as "temperature-time threshold" (TTT) method of irrigation scheduling. In this approach, every minute the canopy temperature exceeds, the threshold temperature is added up to get cumulative value of TTT. An irrigation of a fixed depth is scheduled when the TTT exceeds the time threshold at the end of the day. The TTT approach can be mathematically expressed as

$$TTT = \sum_{h=0}^{24} h, \quad when \ T_c > T_{critical} \quad (14.6)$$

The TTT approach has been successfully applied as a precision irrigation scheduling tool. The "Biologically Identified Optimal Temperature Interactive Console (BIOTIC)" is an irrigation protocol that provides irrigation scheduling based upon measurements of canopy temperatures and the temperature optimum of the crop species of interest. The BIOTIC protocol has been demonstrated to be an effective irrigation scheduling method for several crop species in both semiarid and humid

environments (Mahan et al. 2005). However, it requires real-time monitoring of canopy temperature and judicious selection of critical temperature which is expected to be crop, climate and growth specific. Wanjura et al. (1995) described three methods for the determination of time thresholds: (1) empirical method based on field testing of multiple time thresholds for irrigation and the selection of the threshold that optimized crop performance, (2) empirical analysis of historical crop canopy temperatures for a crop grown under well-watered conditions and (3) theoretical determination of canopy temperatures of well-watered crop from energy balance analysis.

14.5.5 Crop Water Stress Index (CWSI)

The canopy temperature-based variables, namely, CATD (or SDD), CTV or TSD, as discussed earlier are aimed at normalizing canopy temperature with the air temperature. However, the evapotranspirative demand that determines the water stress in crop plant to a considerable extent is regulated by vapour pressure deficit of ambient air. The crop water stress index (CWSI) is a promising tool that further normalizes CATD with vapour pressure deficit (VPD) to quantify crop water stress (Jackson et al. 1981; Idso et al. 1981; Idso 1982; Jackson 1982). The calculation of CWSI is based on two baselines: the non-water-stressed baseline represented by a fully watered crop and the maximum stressed baseline, which corresponds to a non-transpiring crop where the stomata are assumed to be fully closed. The crop water stress index (CWSI) is conceptualized as the ratio of the distance of an actual T_c–T_a data point above the non-stressed baseline to the distance from the baseline to the upper limit, at a given VPD. Thus, a non-stressed plant had a CWSI value equals to 0, while that of a fully stressed non-transpiring crop had a CWSI value of 1.0.
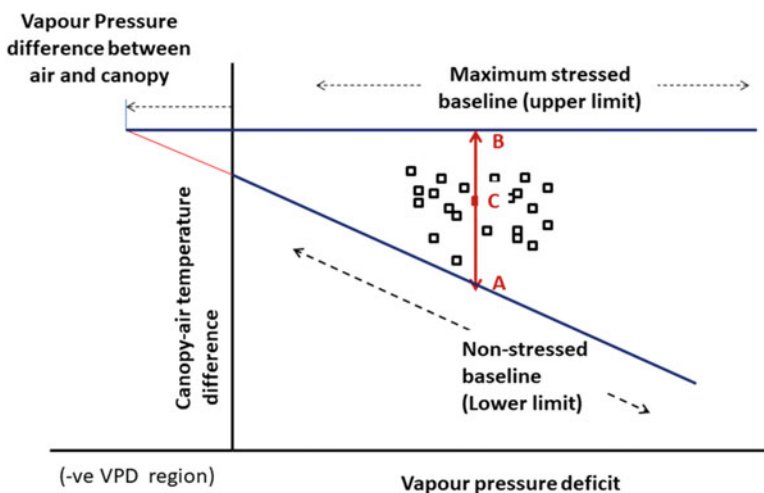
According to Idso's definition (Idso et al. 1981), the CWSI can be expressed as

$$\text{CWSI} = \frac{(T_c - T_a) - D_2}{D_1 - D_2} \tag{14.7}$$

where D_1 is the maximum value of canopy and air temperature difference for a fully stressed crop (the maximum stressed baseline), D_2 the lower limit canopy and air temperature difference for a well-watered crop (the non-water-stressed baseline), T_c the measured canopy surface temperature (°C) and T_a the air temperature (°C).

There are two popular approaches to define non-water-stressed baselines for determination of CWSI. One is the empirical approach given by Idso et al. (1981), in which the empirical relationship between the canopy-air temperature differences $(T_c - T_a)$ and the vapour pressure deficit (VPD) is established from field measurements under different environmental conditions for a well-watered crop. The other approach by Jackson (1982) is based on the theoretically derived relationship between $T_c - T_a$ and VPD following one-layer canopy energy balance model.

14.5.5.1 Empirical Approach

Following Idso's approach, the empirical formula for non-water-stressed baseline is represented as

$$D_2 = A + B.\text{VPD} \tag{14.8}$$

where VPD is the air vapour pressure deficit (in Pa), *A* is the intercept and *B* is the slope of the linear regression equation of the lower limit canopy and air temperature difference and the vapour pressure deficit. Idso (1982) has given the regression coefficients of non-water-stressed baselines for 26 different plant species for clear-sky conditions and for 6 of these plants, including one aquatic species he had also given the regression coefficients under cloudy or shaded conditions.

The water-stressed baseline (D1) is a line plotted parallel to the x-axis with the assumption that the CATD remains unaltered by the changes in VPD under maximum possible stress when the transpiration is completely stopped. It has been observed from VPD vs CATD regression line given by several researchers for different crops that the canopy temperature is equal to the atmospheric temperature when the atmosphere is completely saturated (i.e. VPD = 0) as implied by positive value of the intercepts in the regression lines. This prompted Idso et al. (1981) to assume that even under completely saturated atmospheric condition, a positive vapour pressure gradient will exist between the foliage and the air, and thus, the transpiration from the plant canopy will not be fully suppressed. They have suggested extrapolating the VPD-CATD regression line beyond the atmospheric saturation level into the negative VPD zone until it reaches the point where atmospheric vapour pressure is equal to the canopy vapour pressure. The CATD at that point is referred to as the water-stressed baseline.

14.5.5.2 Theoretical Approach

The computation of CWSI according to Jackson et al. (1981) is based on theoretically derived relationship between Tc − Ta and VPD based on the one-layer canopy energy balance model. Jackson's derivation of CWSI is explained here for detailed understanding.

The energy balance of a crop canopy is explained according to Monteith (1973) as

$$Rn = G + H + \lambda E \tag{14.9}$$

where Rn = net radiation, G = ground heat flux, H = sensible heat flux and E = latent heat flux (all expressed in W m^{-2}).

The storage energy is neglected in the present derivation. The flux components H and E can be expressed in simple forms as

$$H = \rho C_p \frac{T_c - T_a}{r_a} \tag{14.10}$$

$$\lambda E = \frac{\rho C_p}{\gamma} \frac{e_c^* - e_a}{(r_a + r_c)} \tag{14.11}$$

where ρ = air density (kg m^{-3}), C_p = heat capacity of air (J kg^{-1} °C^{-1}), T_C = surface (canopy) temperature (°C), T_a = air temperature (°C), e_c^* = saturated vapour pressure (Pa) at T_c, e_a = vapour pressure (Pa) of air, r_a = aerodynamic resistance (s m^{-1}) and r_c = canopy resistance (s m^{-1}) to vapour transport. Combining Eqs. (14.9), (14.10) and (14.11), assuming G is negligible and defining Δ = slope of saturation vapour pressure temperature relation $(e_c^* - e_a^*)/(T_c - T_a)$ expressed in Pa °C^{-1}, the canopy-air temperature difference can be written as

$$T_c - T_a = \frac{r_a Rn}{\rho C_P} \cdot \frac{\gamma(1 + r_c/r_a)}{\Delta + \gamma(1 + r_c/r_a)} - \frac{VPD}{\Delta + \gamma(1 + r_c/r_a)} \tag{14.12}$$

where VPD = vapour pressure deficit of air = saturated vapour pressure (e_a^*) − actual vapour pressure (e_a) of air.

Equation 14.12 relates $T_c - T_a$ to the vapour pressure deficit of air. The upper limit of $T_c - T_a$ (water-stressed baseline) can be obtained from Eq. (14.4) by setting $r_c \to \infty$ as

$$D_1 = \frac{r_a Rn}{\rho C_P}. \tag{14.13}$$

The lower limit of $T_c - T_a$ (non-stressed base line) may be defined from Eq. (14.12) by setting $r_c = r_{cp}$. The canopy resistance at potential evapotranspiration (r_{cp}) is probably not zero (van Bavel and Ehrler 1968). Thus the lower limit (non-stressed baseline) is defined as

$$D_2 = \frac{r_a R_n}{\rho . C_p} \cdot \frac{\gamma\left(1 - r_{cp}/r_a\right)}{\Delta + \gamma\left(1 - r_{cp}/r_a\right)} - \frac{VPD}{\Delta + \gamma\left(1 - r_{cp}/r_a\right)} \qquad (14.14)$$

Equation 14.14 represents the linear relation between vapour pressure deficit of air ($e_a^* - e_a$) and canopy-air temperature difference ($T_c - T_a$) under certain values of r_{cp} and r_a. Since Δ appears in intercept and slope, both the terms are temperature dependent. Thus, the lower limit is temperature dependent.

For simplifying the derivation of CWSI, Jackson et al. (1981) used a measure of the ratio of actual to potential evapotranspiration (E/E_p) taking into consideration of the Penman-Monteith equation of potential evapotranspiration (E).

$$\lambda E = \frac{\Delta Rn + \rho C_p\left(e_a^* - e_a\right)/r_a}{\Delta + \gamma(1 + r_c/r_a)} \qquad (14.15)$$

The ratio of actual and potential evapotranspiration, thus, can be written as

$$\frac{E}{E_p} = \frac{\Delta + \gamma\left(1 + r_{cp}/r_a\right)}{\Delta + \gamma(1 + r_c/r_a)} \qquad (14.16)$$

where r_{cp} is canopy resistance at the rate of potential evapotranspiration. The value of E/E_p ratio is assumed to vary from 0 (no available water where $r_c \to \infty$) to 1 (ample available water where $r_c = r_{cp}$). Thus the CWSI is defined as

$$CWSI = 1 - \frac{E}{E_p} = \frac{\gamma(1 + r_c/r_a) - \gamma\left(1 + r_{cp}/r_a\right)}{\Delta + \gamma(1 + r_c/r_a)} \qquad (14.17)$$

Now for calculation of *CWSI*, it is important to quantify the resistance terms r_a, r_c and r_{cp}. The r_a is calculated by the following Monteith (1973) equation when the wind speed is >2 ms^{-1}.

$$r_a = \left\{ \frac{\ln\left[(z - d)/z_0\right]/K\}^2}{u} \right. \qquad (14.18)$$

When the winds peed is ≤ 2 ms^{-1}, r_a is calculated following Thom and Oliver (1977) wind function derived for the Penman's evaporation equation.

$$r_a = 4.72 \left[\frac{\ln\left(z - d\right)/z_0]^2}{1 + 0.54u}\right. \qquad (14.19)$$

where z is the reference height (2 m), d the displacement height (m), z_0 the roughness length (m), k the von Karman constant (0.41) and u the wind speed (m s^{-1}). The roughness length and zero plane displacement can be derived as functions of the crop height (h). A convenient value of d and z_0 may be assumed as $0.56\,h$ and $0.13\,h$, respectively, following Legg and Long (1975).

Equation 14.9 requires the value of r_c/r_a which can be obtained by rearranging Eq. 14.4 as follows:

$$\frac{r_c}{r_a} = \frac{\gamma r_a Rn/(\rho C_P) - (T_c - T_a)(\Delta + \gamma) - VPD}{\gamma \left[(T_c - T_a) - r_a Rn/(\rho C_P) \right]} \tag{14.20}$$

The canopy resistance at potential evapotranspiration (r_{cp}) is approximated by Jackson et al. (1981) iteratively by adjusting r_{cp} until the CWSI value obtained near zero after a fresh irrigation. This was a one-time approximation.

Later on, a baseline was proposed by Alves and Pereira (2000), which evaluated the radiometric surface temperature of fully transpiring crop in Jackson's definition as a "surface wet bulb temperature" and thus avoided the use of the surface resistances of crop. They assumed that the infrared surface temperature of fully transpiring crops can be regarded as a surface wet bulb temperature (T_{sw}) expressed as follows:

$$T_{sw} = \frac{\gamma}{\Delta + \gamma} \cdot \frac{r_a (R_n - G)}{\rho.C_p} + T_w \tag{14.21}$$

where T_w is the wet bulb air temperature (°C).

So, the non-water-stressed baseline can be expressed as

$$D_2 = \frac{\gamma}{\Delta + \gamma} \cdot \frac{r_a (R_n - G)}{\rho.C_p} + T_w - T_a \tag{14.22}$$

Equation 14.22 can be written as

$$D_2 = \frac{\gamma}{\Delta + \gamma} \cdot \frac{r_a (R_n - G)}{\rho.C_p} + \frac{VPD}{\Delta + \gamma} \tag{14.23}$$

Comparing Eq. 14.23 with Eq. 14.14, it can be found that the contribution of ground heat flux (G) is ignored in Jackson's approach and that in Alves' definition, the crop minimum surface resistance (r_{cp}) is set to zero.

14.5.5.3 Field Application of CWSI

The preliminary evaluation of CWSI based on field data of winter wheat (Jackson et al. 1981) showed that after each irrigation, the CWSI gradually increased with time roughly in parallel with the trend of extractable water used. They found that the CWSI did not reach its lowest value immediately after irrigation. Instead, it required 5–6 days for CWSI to reach minimum value implying that the stressed wheat required some time to recover. Again, at the senescence stage, the canopy temperature remained high even though the extractable water used were low.

Hatfield (1983) obtained extremely good fit while studying the relation of accumulated CWSI values with available water extracted by grain sorghum and

concluded that canopy temperature can be correlated with soil-water availability in some circumstances without additional data such as spectral reflectance. Keener and Kircher (1983) studied the relationship of SDD, CWSI (empirical) and CWSI (theoretical) with yield and kernel number of maize and found that in the humid condition, the SDD index showed no relationship with yield, whereas the CWSI (theoretical) gave the best relation with both yield and kernel number.

However, Kelly (1989) found poor correlation of CWSI (theoretical) with the water use by turf grass in the lysimetric study, and he attributed the mismatch to the measurement constraint associated with smaller field of view of the IR thermometer, rapid fluctuation of environmental parameters like net radiation, air temperature, wind speed and VPD and the probable error in estimation of aerodynamic resistance.

Taghvaeian et al. (2012) applied the CWSI model to predict the moisture content of the thin layer of topsoil of irrigated maize and obtained strong relationship between them with a high coefficient of determination. The empirical CWSI approach was accurate in computing crop water use as the physically based and more computationally intense remotely sensed surface energy balance (RSEB) model implemented in this study.

Agam et al. (2013) compared the theoretical and empirical CWSI models in their study on olive tree. The empirical CWSI differentiated between the well-watered and the stressed trees and depicted the water status dynamics both during the drought and recovery periods and on a diurnal scale. In contrast, the theoretically derived CWSI failed to capture the dynamics on both time scales. They attributed the failure of theoretical CWSI to the misrepresentation of the aerodynamic resistance to sensible heat transport in olive.

Alderfasi and Nielsen (2001) demonstrated the application of CWSI (empirical) to irrigation scheduling of wheat. However, they found that the data from a single-day measurement might not be enough to determine non-water-stressed baselines and proposed that for wheat crop, a distinctly different baseline should be used for pre-head and for post-head growth stages.

Çolak et al. (2015) used CWSI for irrigation scheduling of eggplant and concluded that the eggplant should be irrigated at CWSI values between 0.18 and 0.20 for high and good quality yields. They also found significant linear relations between the yield and CWSI under different irrigation treatments.

Colak and Yazar (2017) applied the CWSI approach for irrigation scheduling of grape vine. They determined lower (non-stressed) and upper (stressed) baselines empirically from measurements of Tc, Ta and VPD values and calculated the CWSI for each irrigation treatment. They found significant linear relations between the grapevine yield and CWSI and concluded that grapevine should be irrigated at CWSI values between 0.20 for high- and good-quality yields.

14.5.5.4 Critical Issues in Application of CWSI Approach

The CWSI has been considered as a promising tool for the quantification of crop water stress (Jackson et al. 1981). However, there are some critical issues which must be addressed for successful application of CWSI model at field scale.

14.5.5.4.1 Measurement Complexity

Even though CWSI seems to be scientifically sound, the greatest limitation of its application by any of the approach is the concurrent measurement of air temperature and humidity (in Idso's approach) and additional parameters like wind speed, net radiation (in Jackson or Alves and Pereira approach) and then estimation of the baselines. The whole process is too complex to be applied at farmers' level.

14.5.5.4.2 The Resistance Terms

Jackson's approach requires aerodynamic and canopy resistance among other parameters. Précised estimation of canopy and aerodynamic resistance is difficult. The aerodynamic resistance is highly variable with time and space, and it depends on both wind speed and temperature profile, specifically in a thermally stratified layer. However, for practical purpose, such complexity has been avoided by Alves and Pereira in the modified form of Jackson's approach. Alves and Pereira (2000) have simplified Jackson's approach by assuming crop minimum surface resistance at potential evapotranspiration (r_{cp}) to be zero. Though this assumption seems to be an oversimplification, it helps to avoid the difficulty of estimating the critical parameter r_{cp}.

14.5.5.4.3 Definition of Baseline

Defining water-stressed and non-stressed baseline has been the most critical step in CWSI approach. Alves and Pereira (2000) were of the view that the Idso's baseline has to be determined experimentally, which precludes its applicability to different climatic conditions (other places, other times of the day). Several other workers have recommended that the non-stressed baseline of Idso's empirical approach is specific to crop, growth stage and climate (Alderfasi and Nielsen 2001; DeJonge et al. 2015).

Jackson's approach on the other hand is based on the theoretical relationship among the microclimatic parameters in respect of vapour diffusion at stomata level to transport of vapour in the lower boundary layer, both driven by energy balance and aerodynamic process as well as supply of soil moisture. There are set of parameters either to be measured or estimated or assumed to be constant. Yuan et al. (2004) compared the CWSI computed by Idso's approach with that of Jackson's approach and Alves' approach in their study on winter wheat in China. They are of the view that the empirical CWSI based on Idso's approach may not be always applicable for evaluating water stress of winter wheat as the CWSI showed large fluctuations and frequently recorded the value outside the range of 0.0–1.0. The Jackson's approach was shown to be more reasonable to quantify the crop water stress, while the Alves' approach would be more practical for determining CWSI because it did not require the estimation of the crop canopy surface resistance. Again, because CWSI values based on Jackson's definition were different from that of Alves' definition for the same water stress degree, appropriate threshold CWSI should be considered when they are used for irrigation scheduling.

14.5.5.4.4 Vegetation Fraction and Exposure of Soil Surface

The system of canopy temperature measurement is applied for the crop canopy that fully covered the background soil. However, the soil surface often dries up after few days of irrigation and offers a warmer surface though the sub-surface has abundant moisture to support evapotranspiration at a rate reasonably close to potential evapotranspiration. Thus, the soil background included in surface temperature measurement can lead to false indication of water stress, especially when the surface soil is dried up.

14.5.6 Water Deficit Index (WDI)

To overcome the limitation of CWSI under fractional canopy coverage, Moran et al. (1994) conceptualized water deficit index (WDI) that uses surface-air temperature difference and vegetation index to estimate relative water status of a field. They assumed a trapezoid by taking four vertices as well-watered full canopy-covered crop, wet bare soil, non-transpiring fully covered crop (fully stressed) and dry bare soil in a scattered plot of percentage canopy cover versus surface-air temperature difference. The WDI was computed similar that of CWSI as the ratio of the displacement of CATD of the target plot from fully stressed line to the difference between fully stressed and non-stressed line as demonstrated in the given diagram. The possible error due to exposure of soil background, whose temperature would be different from that of the plant surface, is overcome in WDI approach. The concept of water deficit index is illustrated in the figure.

P- Non-stressed, Full canopy cover
Q- Fully-stressed, Full canopy cover
R- Dry bare soil
S- Wet bare soil
PS- Non-stressed line
QR- Fully stressed line
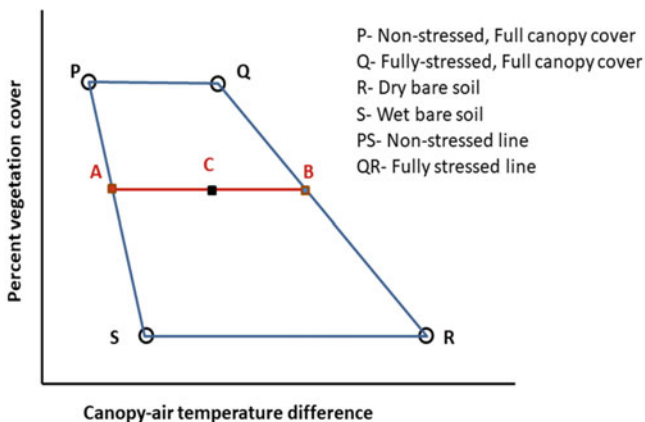
The WDI concept is being widely used for satellite-based determination of crop water stress, where the vegetation cover is approximated by the remote sensing-based vegetation indices like normalized difference vegetation index (NDVI) or soil-adjusted vegetation index (SAVI) or surface albedo. Both canopy temperature (land

surface temperature, LST) and air temperature can also be derived from thermal remote sensing (Moran et al. 1994; Petropoulos et al. 2009).

14.6   Conclusion

The application of thermal indices involving canopy temperature for monitoring crop water stress and irrigation scheduling has been demonstrated by several researchers in the last four decades since the evolution of portable infrared thermometers in the 1960s. The researchers have developed different scientific tools for normalizing the influence of other variable microclimatic parameters like vapour pressure deficit, air temperature, wind speed, solar radiation, etc. While the simple indices like stress degree day (SDD), temperature stress day (TSD), canopy temperature variability (CTV), etc. provide quick and non-destructive assessment of crop water stress, the crop water stress index (CWSI) has been demonstrated as a promising tool to give crop moisture stress with due consideration of energy balance and evaporative demand of the atmosphere. These indices have shown good correlation with crop yield. The integration of percent vegetation coverage and canopy temperature as demonstrated in water deficit index (WDI) compensates the effect of soil background that interferes in the remote measurement of canopy temperature through infrared thermometry. However, few issues like the requirement of stress at particular phenophases of some crops, crop to crop variability in stress tolerance and rapid fluctuation in radiation and wind speed have limited the large-scale application of these tools in irrigation scheduling. The thermal indices have wide scope of application as precision irrigation scheduling tools. With advancement of satellite-based optical and thermal remote sensing, the importance of thermal indices for stress monitoring has increased in recent years.

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