

## Thermal Crop Water Stress Indices

[Note: much of the introductory material in this section is from Jackson (1982).]



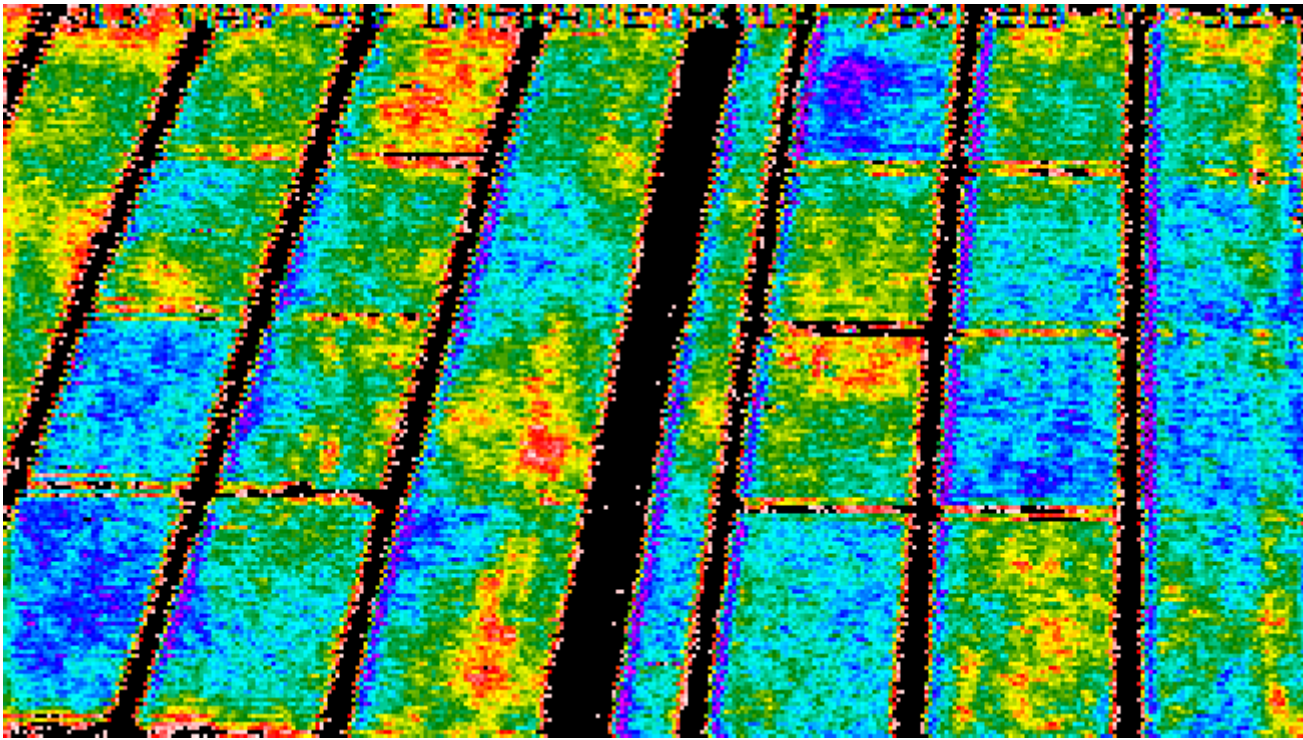
The most established method for detecting crop water stress remotely is through the measurement of a crop's surface temperature. The correlation between surface temperature and water stress is based on the assumption that as a crop transpires, the evaporated water cools the leaves below that of air temperature. As the crop becomes water stressed, transpiration will decrease, and thus the leaf temperature will increase. Other factors need to be accounted for in order to get a good measure of actual stress levels, but leaf temperature is one of the most important.

Infrared thermometers (hand-held or equipment-mounted) or thermal scanners (satellite or aircraft) are two instruments that can be used to measure a crop's surface temperature remotely. Both of these instruments measure the amount of radiation emitted from a surface and relate it to temperature by the Stefan-Boltzmann blackbody law:

$$R = M [ T_s^4 \quad \dots (1)$$

where R is the radiation emitted by the surface ( $W m^{-2}$ ), M is the emissivity of the surface, [ is the Stefan-Boltzmann constant ( $5.674 \times 10^{-8} W m^{-2} K^{-4}$ ), and  $T_s$  is surface temperature (K). The thermal infrared spectral region of 8 to 13  $\mu m$  is typically used for thermal remote sensing. This spectral range contains the maximum thermal emission for temperatures in the range found at the earth's surface and is less subject to absorption by atmospheric gases. Emissivity in the above equation represents how efficiently the surface emits energy. A perfect emitter (called a "blackbody") has an emissivity of 1, and plant leaves have emissivity values that typically range between 0.97 - 0.98. Assuming an emissivity of 1 for plants will usually result in less than 1°C error; however, some soil surfaces can have emissivity of 0.93, which can result in more significant errors in apparent temperature.

The following is a thermal image of a cotton canopy that was part of a water and nitrogen study in Arizona. Blues and greens represent lower temperatures than yellow and orange. The image was acquired with a thermal scanner on board a helicopter. Most of the blue rectangles (plots) in the image correspond to high water treatments. However, note that many of the patterns do not correspond to the treatment plots, but represent the natural variability in soil conditions across the field.



If the field above were irrigated uniformly, some areas of the field would receive more water than the plants need, while other areas would not receive enough. Therefore, varying the application across the field could reduce water use without significant impact on crop yield.

### Quantifying Water Stress

The previous image illustrates the variability of surface temperature across the field, but it still does not tell us if we need to irrigate or not. One method used to apply thermal data to irrigation is the Crop Water Stress Index (CWSI):

$$\text{CWSI} = (dT - dT_l) / (dT_u - dT_l) \quad \dots (2)$$

where,

$dT$  is the measure difference between crop canopy and air temperature,  
 $dT_u$  is the upper limit of canopy minus air temperature (non-transpiring crop), and  
 $dT_l$  is the lower limit of canopy minus air temperature (well-watered crop).

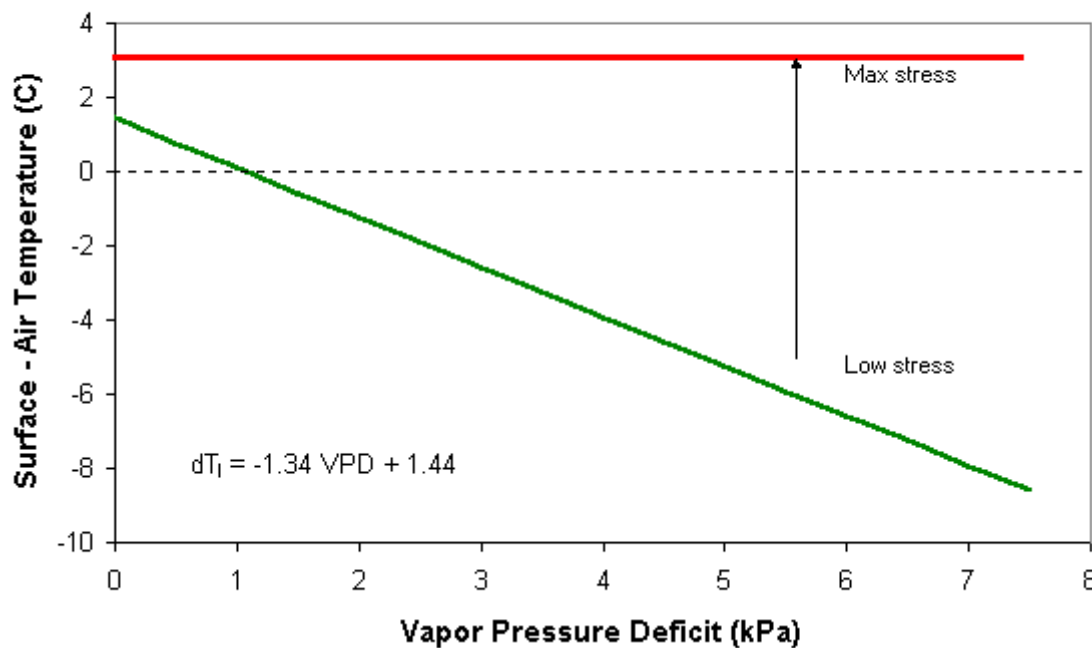
A CWSI of 0 indicates no water stress, and a value of 1 represents maximum water stress. The crop-water stress that signals the need for irrigation is crop specific and should consider factors such as yield response to water stress, probable crop price, and water cost. Reginato and Howe (1985) found that cotton yield showed the first signs of decline when the CWSI average during the season was greater than 0.2.

There are several methods to determine the upper and lower limits in the CWSI equation. One method developed by Idso et al. (1981) accounts for changes in the upper and lower limits due to variation in vapor pressure deficit (VPD). VPD is calculated as:

$$\text{VPD} = \text{VP}_{\text{sat}} - \text{VP} \quad \dots (3)$$

where  $VP_{sat}$  is the maximum vapor pressure for a given air temperature and pressure (the maximum water vapor the air can hold) and  $VP$  is the actual vapor pressure (partial pressure of water vapor in the atmosphere). Therefore, a VPD of 0 indicates that the air is holding as much water vapor as possible (this also corresponds to a relative humidity of 100%). The lower limit in the CWSI will change as a function of vapor pressure because at lower VPDs, moisture is removed from the crop at a lower rate, thus the magnitude of cooling is decreased. Idso (1982) demonstrated that the lower limit of the CWSI is a linear function of VPD for a number of crops and locations. The following is an example for soybeans:

### Example of VPD Baseline for Soybeans



The green line is the non water-stressed baseline (i.e., the difference between canopy and air temperature of well-watered soybeans at different VPDs). The red line is the canopy air temperature difference for a non transpiring crop. The red line does not fall exactly on the intercept value, as transpiration can still occur at a VPD of 0. Note that in this example, for VPDs < 1, there is less than a 3°C difference between a well-watered plant and one that is completely stressed. Therefore, the CWSI is not appropriate for humid regions (of course, drought stress is usually not a concern under these conditions).

Slope and intercept values have been determined for a number of crops as shown in the table below.

#### Baseline parameters for various crops - sunlit conditions (from Idso, 1982).

Crop	Intercept	Slope
Alfalfa	.51	-1.92
Barley (pre-heading)	2.01	-2.25
Barley (post-heading)	1.72	-1.23
Bean	2.91	-2.35
Beet	5.16	-2.30
Corn (no tassels)	3.11	-1.97

Cowpea	1.32	-1.84
Cucumber	4.88	-2.52
Lettuce, leaf	4.18	-2.96
Potato	1.17	-1.83
Soybean	1.44	-1.34
Tomato	2.86	-1.96
Wheat (pre-heading)	3.38	-3.25
Wheat (post-heading)	2.88	-2.11

Using the parameters in the above table, the canopy air temperature difference for a well-watered crop (lower limit) and severely stressed crop (upper limit) can be calculated for equation 2 as

$$dT_1 = \text{Intercept} + \text{Slope (VPD)} \quad \dots (4a)$$

$$dT_u = \text{Intercept} + \text{Slope (VP}_{\text{sat}}\{T_a\} - \text{VP}_{\text{sat}}\{T_a + \text{Intercept}\}) \quad \dots (4b)$$

where VPD has units of kPa,  $\text{VP}_{\text{sat}}\{T_a\}$  is the saturation vapor pressure at air temperature (kPa), and  $\text{VP}_{\text{sat}}\{T_a + \text{Intercept}\}$  is the saturation vapor pressure at air temperature plus the Intercept value for the crop of interest. Thus, with a measure of humidity (relative humidity, wet bulb temperature, etc.), air temperature, and canopy temperature, it is now possible to determine CWSI. The slope and intercept parameters in the previous table were determined from experimental data, so the CWSI calculated using this method is often referred to as the "empirical" CWSI.

For information on calculating saturation vapor and relative humidity from wet and dry bulb temperatures, see the [relative humidity equations](#) page on this site.

## Surface Energy Balance

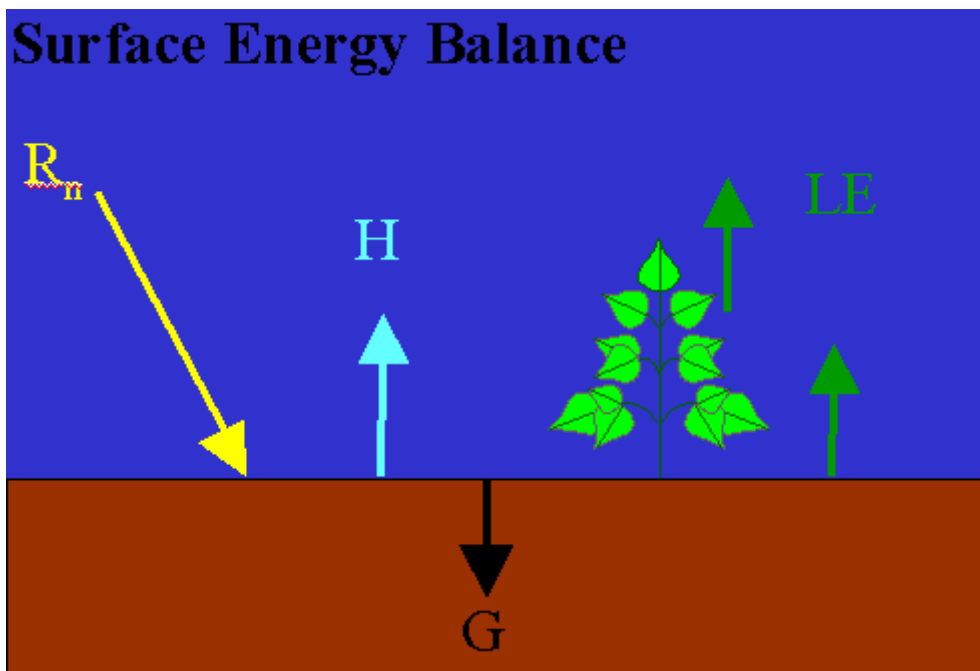
It is important to note that environmental factors other than air temperature and humidity impact a crop's temperature. For example, the parameters in the previous table are based on sunlit conditions (i.e., no clouds), and different parameters would be needed for shaded conditions. To include more environmental factors, a theoretical approach was taken to calculate the canopy temperature of a well-watered and stressed crop for use with the CWSI (e.g., Jackson et. al., 1981; Jackson, 1988).

The approach is based on the conservation of energy (energy balance) for a cropped surface. The energy balance equation can be written as

$$R_n + G + H + SE + M = 0 \quad \dots (5)$$

where  $R_n$  is net radiation,  $G$  is soil heat flux,  $H$  is sensible heat flux (exchange between the surface and air),  $SE$  is the latent heat flux (energy transfer due to evaporation or condensation), and  $M$  represents the energy transfer in miscellaneous such as respiration or heat storage, all with units of  $\text{W m}^{-2}$  (Rosenberg et. al., 1983, provide a detailed review of the energy balance as it applies to biological systems). The energy associated with the processes represented by  $M$  is very small compared to the other terms, and it is usually ignored. Equation 5 is illustrated in the figure below.

Note that any of the terms in equation 5 can be negative as energy can be transferred to or from the surface.



### Net Radiation

Net radiation be partitioned into differ components as

$$R_n = R_{s\_in} - R_{s\_out} + R_{lw\_in} - R_{lw\_out} \quad \dots (6)$$

where the subscript **s** indicates shortwave radiation, **lw** longwave radiation, **in** is radiation towards the surface and **out** is away from the surface. The shortwave component can be calculated if the total solar shortwave incoming radiation is measured as

$$R_{s\_in} - R_{s\_out} = (1-\alpha) R_{s\_in}$$

where alpha is the shortwave albedo. With the growing number of weather stations across the country, measurements of  $R_{s\_in}$  are usually available. The albedo represents the fraction of radiation reaching the surface reflected back into space. Albedo can be measured by downward-looking wide spectral band radiometer or by applying weighting factors to measurements of reflected radiation in discrete portions of the spectrum. Albedo for full cover field crops ranges from about 0.2 to 0.25 (Jensen et. al., 1990).

The incoming longwave radiation can be estimated as a function of air temperature using a form of equation 1:

$$R_{lw\_in} = M_a [T_a]^4 \quad \dots (6)$$

where  $T_a$  is air temperature (K), and  $M_a$  is clear sky emittance. Various equations have been developed to estimate  $M_a$  as a function of temperature and humidity. Idso (1981) determined

$$M_a = 0.70 + (59.5/10^5) VP \exp(1500/T_a) \quad \dots (7)$$

where VP is vapor pressure in kPa. Similarly, the outgoing longwave radiation ( $R_{lw\_out}$ ) can be calculated using equation 1. Net radiation can also be measured directly using a net radiometer.

Ideally the radiometer absorbs all of the radiation from all wavelengths to the surface and away from it. Typically this is accomplished with two sets of thermopiles.

### Soil Heat Flux

The rate at which heat is transferred to the soil will depend on the soil's thermodynamic properties and moisture content, temperature distribution of the soil profile, and the amount of crop cover. One method to calculate soil heat flux is to apply the first law of heat conduction (Fourier's Law) that says heat flux is the direction of and proportional to the temperature gradient. Stated as a formula in one dimension

$$G = k \, dT/dz \sim k (T_s - T_g) / z \quad \dots (8)$$

where  $k$  is thermal conductivity and  $T_g$  is the soil temperature at depth  $z$  below the soil surface. The thermal conductivity will vary based on soil type and moisture content.

$G$  can also be measured with a "soil heat flux plate" buried near the soil surface. However, for crops that are near full cover, soil heat flux is a very small component of the energy balance. Under full cover conditions,  $G$  is typically only 10% of the net radiation, so for these conditions  $R_n - G \sim .9 R_n$ .

### Sensible Heat Flux

Sensible heat flux describes the transfer of energy from objects that are warmer than their surroundings to the air or conversely, heat transferred from the air to cooler objects. The heat can be transferred by laminar (conduction or diffusion) or turbulent (wind) processes. A "resistance" approach is often used to calculate sensible heat. That is, similar to Ohm's law in electrical circuits (voltage = current x resistance =>  $V=IR$  or  $I = V/R$ ), the rate of heat transfer is determined by the driving force (difference in temperature) and the resistance to the movement of heat. Thus,  $H$  can be calculated as

$$H = Y C_p (T_s - T_a) / r_a \quad \dots (9)$$

where  $Y$  is the density of air ( $\text{kg m}^{-3}$ ),  $C_p$  the heat capacity of air ( $\sim 1013 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$ ),  $T_s$  is the surface temperature ( $^\circ\text{C}$ ), and  $r_a$  is aerodynamic resistance ( $\text{s m}^{-1}$ ). Air density can be approximated as a function of elevation by

$$Y = 1.23 - .000112 * \text{Elv} \quad \dots (10)$$

where  $\text{Elv}$  is the elevation above sea level (m). Estimation of aerodynamic resistance is more complicated. The resistance to heat transfer will be a function of wind speed and surface roughness (rougher surfaces create more mixing of the air with the surface). One equation from used to calculate resistance ( $\text{s m}^{-1}$ ) is

$$r_a = \{ \ln[(z-d)/z_0] / k \}^2 / U \quad \dots (11)$$

where  $z$  is the height of wind speed measurements,  $d$  is the displacement height (m),  $z_0$  is the roughness length (m),  $k$  is the von Karman constant ( $\sim 0.4$ ), and  $U$  is wind speed ( $\text{m s}^{-1}$ ). For plant canopies with full cover, estimates of  $z_0$  and  $d$  can be obtained by:

$$z_o = 0.13 h \quad \dots (12a)$$

$$d = 0.63 h \quad \dots (12b)$$

where  $h$  is canopy height (m). Displacement height is the height at which wind speed becomes essentially zero in the plant canopy, and the roughness length represents the remaining area of the canopy that contributes to turbulent mixing.

Equation 10 is based on several assumptions

1. Neutral atmospheric conditions (i.e., surface temperature is close to air temperature),
2. Heat and momentum are transferred at the same locations in the canopy,
3. Wind speeds are sufficient to create turbulent transfer processes.

For full cover crop canopies, assumptions 1 and 2 do not introduce too much error; however, low wind speeds can create more significant errors. Note, that in equation 10, as wind speed approaches 0, the resistance to heat transfer approaches infinity (no longer a turbulent transfer process) A semi-empirical equation for resistance that is more robust under low wind speed conditions is:

$$r_a = 4.72 \{ \ln[(z-d)/z_o] / k \}^2 / (1+0.54 U) \quad \dots (13)$$

Note that this equation will not tend to infinity as wind speed approaches 0. When trying to apply this approach to sparse cover or bare soil conditions, more rigorous treatment of the resistance term is needed. For more discussion and references on this topic, see Jackson et al. (1988).

#### Latent Heat Flux (Evapotranspiration)

For irrigation management, latent heat flux is the component of the energy balance in which we are ultimately interested. Many equations have been developed to predict the rate at which water can be transferred to the atmosphere when water at the surface is not limited (potential evapotranspiration or PET). However, few methods exist to predict actual evapotranspiration (ET), that is the amount of water lost by the plant when water is limited. Building on the work of Penman (1948) and Monteith and Szeicz (1962), and Jackson et al. (1981) determine

$$SE = Y C_p (VP_c^* - VP) / [K (r_a + r_c)] \quad \dots (14)$$

where  $VP_c^*$  is the saturated vapor pressure of the air at the temperature of the canopy (kPa),  $K$  is the psychrometric constant ( $kPa \text{ } ^\circ C^{-1}$ ),  $r_c$  is the canopy resistance to water loss ( $s \text{ } m^{-1}$ ), and other terms were previously defined in equations 3 and 5. This equation also uses the "resistance" concept, where the driving force is the vapor pressure gradient from the leaf to the surrounding air, and the resistance of water movement from the canopy has been added to the aerodynamic resistance.

Equation 14 is subject to the same assumptions as those that apply to sensible heat flux, and when applied to a crop canopy, an additional assumption is that the source of latent and sensible heat is primarily from the vegetation, not the soil.

The psychrometric constant is not really "constant" and with units of ( $kPa \text{ } ^\circ C^{-1}$ ) can be calculated as

$$K = (C_p P) / (0.622 S) \quad \dots (15)$$

where  $C_p$  is the heat capacity of air ( $\sim 1013 \text{ J } kg^{-1} \text{ } ^\circ C^{-1}$ ),  $P$  is atmospheric pressure (kPa), and  $S$  is the latent heat of vaporization ( $\text{J } kg^{-1}$ ). A sufficient estimate of air pressure can be determined from

elevation. For an estimate in kPa

$$P = 101.3 - 0.01055 \text{ Elv} \dots (16)$$

where Elv is elevation above mean sea level (m).

S is not very sensitive to pressure, but it will vary with temperature and can be calculated as ( $\text{J kg}^{-1}$ )

$$S = 2.501 \times 10^6 - 2.361 \times 10^3 T_a \dots (17)$$

where  $T_a$  is air temperature ( $^{\circ}\text{C}$ ).

[Note equations 10 and 15-17 are taken from information summarized by Jensen et. al. (1990).]

### "Theoretical" CWSI

By rearranging terms of the surface energy balance, Jackson et al. (1981) were able to develop an equation to predict the canopy minus air temperature difference ( $T_c - T_a$ ,  $^{\circ}\text{C}$ ):

$$T_c - T_a = X_1 X_2 - X_3 \dots (18a)$$

$$X_1 = r_a (R_n - G) / (Y C_p) \dots (18b)$$

$$X_2 = [K(1+r_c/r_a)] / [- + K(1 + r_c/r_a)] \dots (18c)$$

$$X_3 = \text{VPD} / [- + K(1 + r_c/r_a)] \dots (18d)$$

where all the terms are as previously defined, and

$$- = (\text{VP}_c^* - \text{VP}_{\text{sat}}) / (T_c - T_a)$$

where  $-$  is the slope of the saturated vapor pressure-temperature relation ( $\text{kPa } ^{\circ}\text{C}^{-1}$ ). Jackson et al. (1988) found that  $-$  could be sufficiently represented by

$$- = (45.03 + 3.014 T_{ca} + 0.05345 (T_{ca})^2 + 0.00224 (T_{ca})^3) \times 10^{-3} \dots (19)$$

where  $T_{ca}$  is the average of the canopy and air temperature ( $^{\circ}\text{C}$ ). Even with the simplification of equation 19, air and canopy temperature still appear on both sides of equation 18, so iteration is needed to obtain a solution.

Equation 18 can now be used to obtain the upper and lower bounds for the CWSI. In the case of the upper limit (non transpiring crop), canopy resistance will approach infinity, so equation 18 reduces to

$$dT_u = r_a (R_n - G) / (Y C_p) \dots (20)$$

In the case of a non water stressed crop, assuming  $r_c$  is essentially 0:

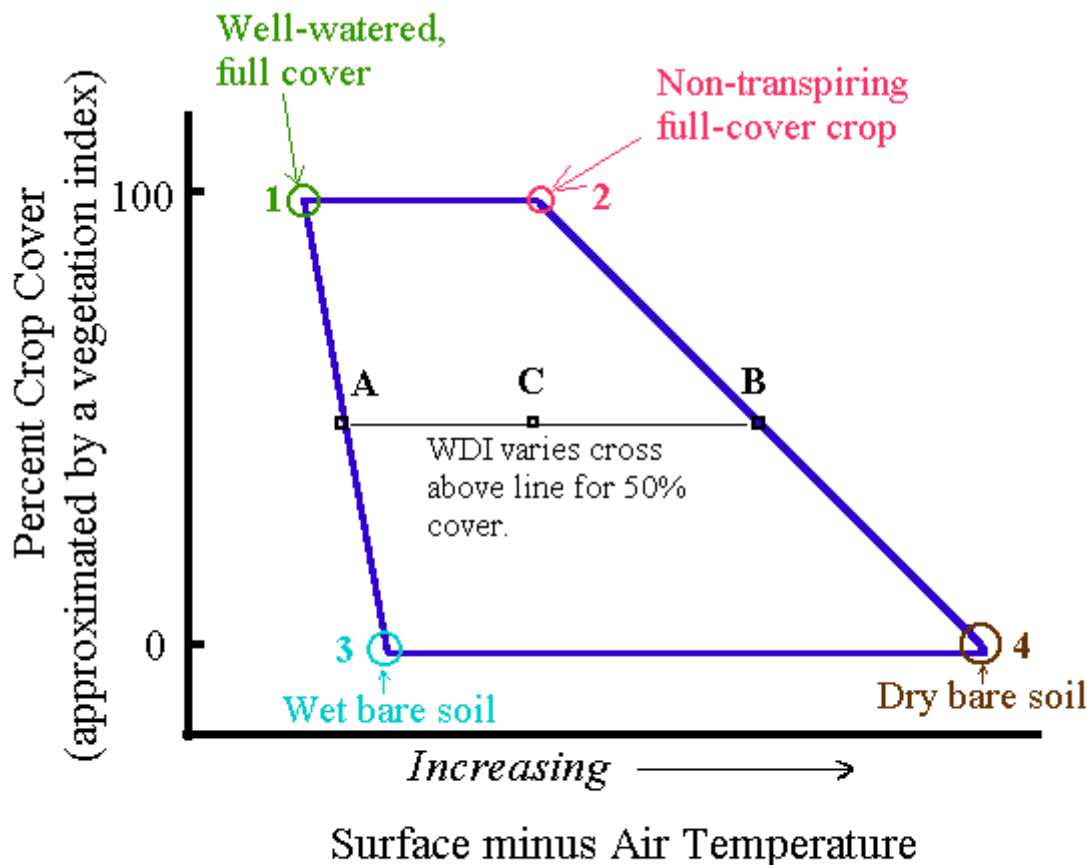


$$dT_1 = [r_a (R_n - G) / (Y C_p)] [K / (- + K)] - [VPD / (- + K)] \dots (21)$$

Now equations 20 and 21 can be used to determine the CWSI as given in equation 2. In some cases measurements of soil heat flux are not available, so under conditions of complete canopy closure, 10 percent of net radiation is assumed to be transferred to the soil or  $(R_n - G) = 0.9R_n$ .

### The Water Deficit Index (WDI)

The previous discussions of the CWSI have assumed that a measure of canopy temperature was available or that the crop completely covered the soil surface. This is not the case during the early season for all annual crops and may never occur in some cropping systems. A soil background included in the surface temperature measurement can lead to false indications of water stress, as a dry soil is often much warmer than air temperature. To overcome this limitation, Moran et al. (1994) developed the water deficit index (WDI) that uses both surface minus air temperature and a vegetation index to estimate the relative water status of a field. The concept of the WDI is illustrated in the figure below.



### Illustration of the water deficit index trapezoid.

The distribution of surface minus air temperature at a particular time was found to form a trapezoid when plotted against percent cover. Note that for many crops, there is a linear relationship between percent cover and a vegetation index (such as the normalized difference vegetation index  $(NDVI = [NIR-Red]/[NIR+Red])$ ), so the index can be used in place of a direct measure of percent cover. The upper left of the trapezoid corresponds to a well-watered crop at 100 percent cover and the upper right to a non transpiring crop at 100 percent cover (points 1 and 2, respectively). These two points are the same as those as the upper and lower limits for the standard CWSI and can be estimated

using the same techniques. The lower portion of the trapezoid (bare soil) is bound by a wet and dry soil surface. These points can also be calculated using the energy balance concepts previous discussed; however, the calculation of the resistance terms needs to be more rigorous, particularly in the case of a dry bare soil, as the assumption of atmospheric stability is usually not valid and can introduce large errors. Details on calculating the soil corners are not presented here, but are explained by Moran et al. (1994).

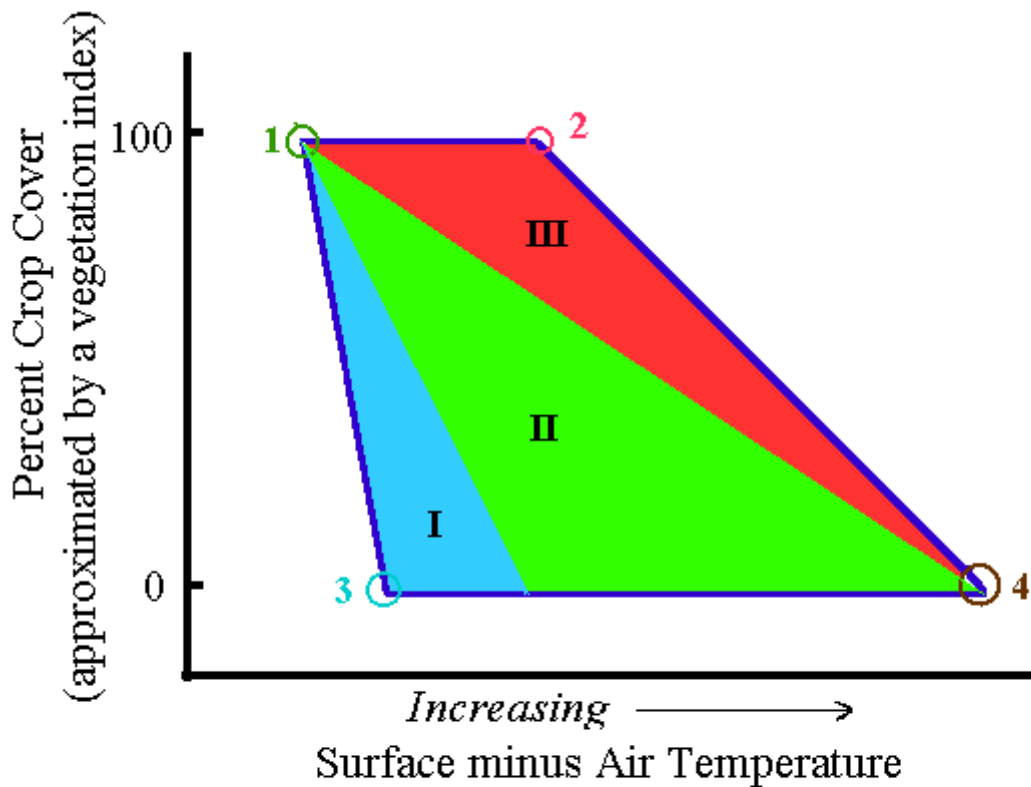
With corners of the trapezoid, the WDI for a measure percent cover becomes

$$\text{WDI} = (dT - dT_{L13}) / (dT_{L24} - dT_{L13}) \quad \dots (22)$$

where  $dT$  is the measure of surface minus temperature at a particular percent cover,  $dT_{L13}$  is the surface minus air temperature determined by the line from points 1 to 3 for the percent cover of interest ("wet" line), and  $dT_{L24}$  is the temperature difference on the line formed between points 2 and 4 ("dry" line). Graphically, the WDI can be viewed as the ratio of the distances AC to AB in the previous figure. As the WDI considers both evaporation from a soil surface as well as the crop, it can be interpreted as a measure of the amount of evapotranspiration (ET) actually occurring relative to the potential ET (PET) or

$$\text{WDI} = 1 - \text{ET} / \text{PET} \quad \dots (23)$$

While WDI can be used to estimate ET, it does not provide a direct measure of crop water stress, as the index will vary based on soil-water evaporation as well as crop transpiration. For example, at 50 percent cover the WDI may vary from 0 to 0.5 as the soil surface dries, but the crop transpiration rate could remain near the potential level the entire time. The crop begins to experience some level of stress when the WDI falls to the right of a line formed between points 1 and 4 as illustrated by the area shown in red below (Clarke, 1997).



Descriptive zones within the trapezoid:

- I - nonstressed plants with a wet soil background
- II - nonstressed plants with a drying soil background
- III - some degree of water stress and completely dry soil background.

Clarke (1997) developed an approach that uses measurements of wet and dry soil surfaces to define the corners of the trapezoid. If imagery is collected over a farm, there are often areas with wet soils from a recent irrigation and other fields with a dry soil present, so the measured surface temperatures over these locations can be used to determine points 3 and 4, respectively. Additionally, point 1 can be "measured" if there is a field that has been recently irrigated and has full cover. Point 2 could be approximated by canopy temperature measurements over a field known to be experiencing extreme water stress. Alternatively, the stems of adjacent plants can be cut and measured with an infrared thermometer until the difference between leaf and air temperatures become asymptotic to define point 2.

### Taking Measurements

The time that measurements are taken to determine crop water stress is very important. During the night, water in the soil has time to become redistributed around the roots, so in the morning the plants may show no signs of water stress even if the soil moisture reserve is very low. Therefore, it is best to take measurements in the afternoon, ideally at the same time each day. Additionally, under cloudy conditions, crop water demand is low, and again, the crop may show no signs of water stress. When applying the traditional CWSI it is important that the surface temperature measurements are not influenced by the soil background.

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