CHAPTER

27

Stress-Degree-Day Concept and Crop Water Stress Index

The stress-degree-day (SDD) procedure and crop water stress index (CWSI) are methods to evaluate water stress in plants. They were developed in the 1970s by scientists at the United States Department of Agriculture (USDA) Water Conservation Laboratory in Phoenix, Arizona (Jackson, 1982). The CWSI has been used widely since then (Anda, 2009; Agam et al., 2013). We now define SDD and the CWSI and show their application.

27.1 SDD PROCEDURE

The work of the Phoenix scientists began in 1976 (Dean, 1976). The SDD concept was developed before the CWSI. Let us follow the description of its development by Jackson et al. (1977). The water status of a plant is a primary determinant of grain yield. A means for evaluating water status by remote measurement could open the way to improved yield predictions and, in irrigated areas, to improved scheduling times. The temperature of a plant canopy can be measured remotely with lightweight, handheld infrared (IR) thermometers (see Chapter 26). The difference between the temperature of a plant canopy and the temperature of the surrounding air ($T_c - T_a$) may be an indicator of the water status of a crop because water stress causes partial stomatal closure, thus reducing transpiration and allowing sunlit leaves to warm above ambient air temperature. The Phoenix scientists introduced the concept of a stress-degree-day. SDD is a daily value of $T_c - T_a$ measured at the time of maximum surface temperature (generally 1–1.5 h after solar noon). SDD is defined as follows:

$$\mathrm{SDD} = \sum_{n=i}^{N} (T_c - T_a)_n, \tag{27.1}$$

which is the plant canopy temperature T_c minus the air temperature T_a 150 cm above the soil, summed over N days beginning at day i.

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(The SDD concept is similar to the growing-degree-day concept: $GDD = \Sigma\{[(T_M + T_m)/2] - T_t\}$, where GDD is growing-degree-day; T_t is the threshold temperature for growth; T_M and T_m are the daily maximum and minimum air temperatures, respectively, and the GDD values are summed over N days, the number of days under consideration (Lowry, 1969, p. 194). The threshold temperature varies with different crops.)

Jackson et al. (1977) evaluated water stress in plants (durum wheat, *Triticum durum* Desf. var. Produra) by using the SDD concept. They differentially irrigated the wheat. Plot 1 was the dry treatment (only enough irrigation water added to permit survival, a stressful condition in arid Phoenix, Arizona, where crops are usually amply watered, so they will grow). Plot 6 was the wet plot and was overwatered. Plots 2–5 received amounts of irrigation water that varied between the amounts added to Plots 1 and 6. Figure 27.1 shows their results. The greater the stress (lack of water), the greater was the value of the SDD. They began the summation of the SDD on day 83 (February 24, 1976), the day on which differential irrigation treatments were started. They ended the SDD summation on the day of harvest. Plot 6, which received an excessive

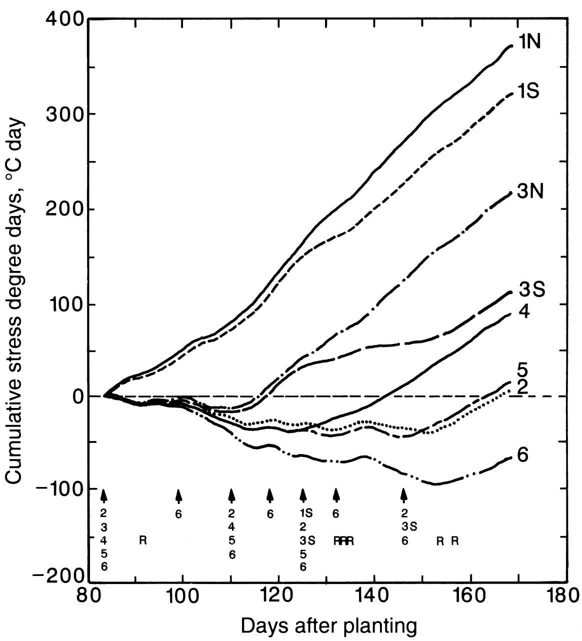

FIGURE 27.1 Stress-degree-days versus days after planting. Plot numbers are shown at the right. Arrows indicate irrigations, the numbers of the plots receiving the irrigation being shown below the arrows. R indicates rain. N indicates north side of a plot. S indicates south side of a plot. *From Jackson et al. (1977). American Geophysical Union. Reproduced by permission of American Geophysical Union.*

amount of irrigation water, had canopy temperatures that were consistently less than air temperatures, and the SDD became less than −100 during the latter part of the season.

In general, if a plant has adequate water, $T_c - T_a$ will be near zero or negative; if it is water stressed, $T_c - T_a$ will be greater than zero. Thus, the sum of the positive values of $T_c - T_a$ may serve as an index of when to irrigate. Jackson et al. (1977) defined a positive SDD as follows:

$$\mathrm{SDD_{pos}} = \sum_{n=i}^{N} (T_c - T_a)_n \tag{27.2}$$

in which values of $T_c - T_a$ less than zero are set equal to zero. The index i is the first day after irrigation, and N is the number of days required for $\mathrm{SDD_{pos}}$ to reach a prescribed value.

Figure 27.2 shows $\mathrm{SDD_{pos}}$ and soil water depletion (measured using a neutron probe) for two of the plots in the experiment of Jackson et al. (1977). Cloudiness and other climatic conditions can cause abrupt changes in the slope of the $\mathrm{SDD_{pos}}$ versus time graph (Figure 27.2) during the first few days after irrigation. As water depletion increases, $T_c - T_a$ is always positive, the slope rapidly increases, and the effect of climatic factors diminishes.

Jackson et al. (1977) proposed an $\mathrm{SDD_{pos}}$ 10 as an index for the time to irrigate wheat in Arizona. They recognized that this value is somewhat

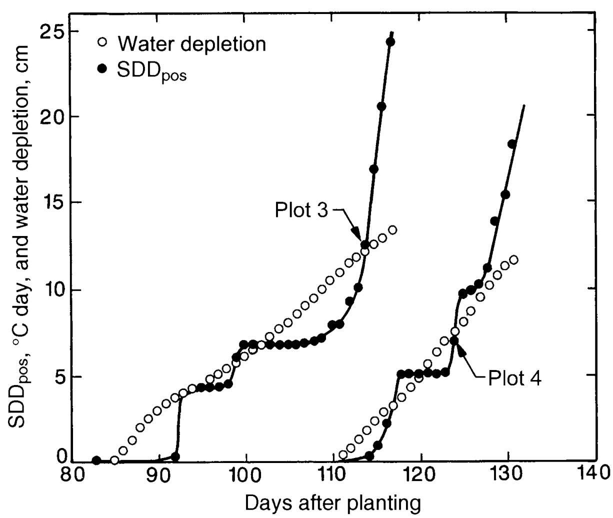

FIGURE 27.2 Positive stress-degree-days and water depletion for two plots, beginning after the last irrigation. Numerical values on the ordinate are the same for both factors. *From Jackson et al. (1977). American Geophysical Union. Reproduced by permission of American Geophysical Union.*

dependent on the means used to measure T_c and T_a (for example, the height at which T_a is measured), that it may be soil and crop specific (they used a loam soil), and that it may be different under other climatic conditions. Nevertheless, the SDD_{pos} appears to provide a possible means to develop irrigation scheduling based on remotely sensed plant canopy temperatures.

27.2 CANOPY-MINUS-AIR TEMPERATURE AND EVAPOTRANSPIRATION

Let us now turn to the relation between $T_c - T_a$ and evapotranspiration. One approach to estimating the amount of water depleted from the root zone is to use an evapotranspiration equation based on the temperature difference $T_c - T_a$, such as the following equation (Jackson et al., 1977):

$$ET = R_n - G - f(u)C(T_c - T_a), \tag{27.3}$$

in which ET is evapotranspiration, R_n is net radiation, G is soil heat flux, $f(u)$ is a function of wind speed, and C is the volumetric heat capacity of air. This equation is a reliable predictor of crop evapotranspiration (Stone and Horton, 1974). Stone and Horton (1974) used Eqn (27.3) for the same purpose that Jackson et al. (1977) were concerned with—to develop a method of predicting water use over large areas by using remotely sensed parameters.

To use Eqn (27.3), Jackson et al. (1977) made some simplifying assumptions. They found that for their experimental conditions, wind was not of major importance in the calculation of ET using Eqn (27.3). (This may not be true for locations with persistent winds and higher wind speeds than those recorded in Phoenix, Arizona.) They were not concerned with hourly values of ET, but wanted to calculate daily values of actual ET, using a minimum of input data and a one-time-of-day measurement of $T_c - T_a$. For 24-h periods, it is safe to assume that the soil heat flux G is negligible. With Jackson et al.'s (1977) simplifying assumptions, Eqn (27.3) becomes

$$ET = R_n - B(T_c - T_a), \tag{27.4a}$$

in which B is a composite constant that must be determined.

The parameter B in Eqn (27.4a) was evaluated by using daily values for ET from a lysimeter, daily values of R_n over the lysimeter, and one-time-of-day (taken between 13:30 and 14:00 h) measurements of $T_c - T_a$ for every day for which ET, R_n, and $T_c - T_a$ data were available, from day 60 until harvest of the wheat. These data are shown in Figure 27.3. Figure 27.3(A) shows the relation for $ET - R_n$ versus $T_c - T_a$. A statistical value for B was obtained by forcing Eqn (27.4a) through the

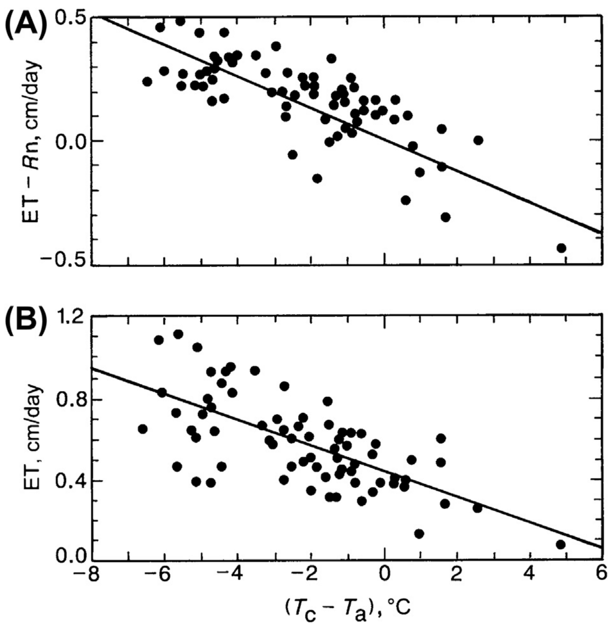

FIGURE 27.3 Evapotranspiration and net radiation as a function of canopy−air temperature difference. *From Jackson et al. (1977). American Geophysical Union. Reproduced by permission of American Geophysical Union. See text for explanation of parts A and B.*

origin, since Eqn (27.4a) indicates that for $T_c - T_a = 0$, $\mathrm{ET} - R_n = 0$. This yielded

$$\mathrm{ET} = R_n - 0.064(T_c - T_a). \tag{27.4b}$$

In Figure 27.3(B), the dependence of ET on $T_c - T_a$ alone was determined. The relation is

$$\mathrm{ET} = 0.438 - 0.064(T_c - T_a). \tag{27.5}$$

The constants in Eqn (27.4b) and Eqn (27.5) were evaluated by using ET data from lysimeters. To test their applicability, ET was calculated by using R_n and $T_c - T_a$ data from the wheat plots. Water depletion was also calculated. The measured and calculated data are compared in Figure 27.4. In Figure 27.4(A), ET was calculated from Eqn (27.4b) by using net radiation measured over the north sides of each plot. In Figure 27.4(B), the net radiation was averaged over the six plots for each day, and the average was used in Eqn (27.4b). In Figure 27.4(C), the seasonal average of R_n was used in Eqn (27.4b), whereas in Figure 27.4(D), R_n was taken as the statistically derived constant from Figure 27.3(B) (i.e., from Eqn (27.5)). The data in Figures 27.4(A) and (B) indicate that if daily estimates of R_n are available, water use can be estimated reasonably well by using Eqn (27.4a).

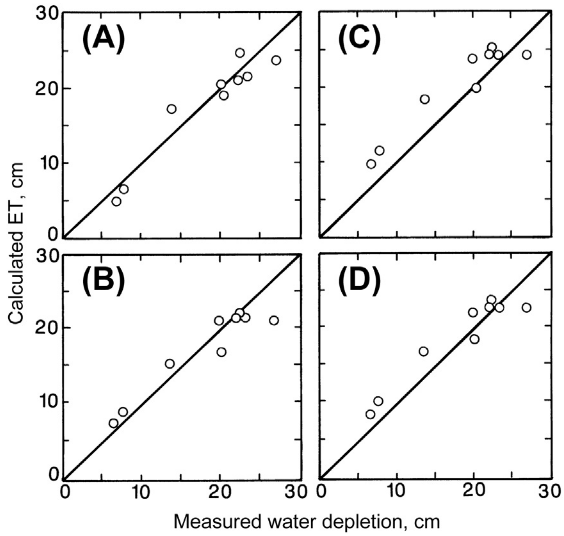

FIGURE 27.4 Calculated evapotranspiration and measured water depletion. The lines indicate a 1:1 relation. See text for explanation of different parts of figure. *From Jackson et al. (1977). American Geophysical Union. Reproduced by permission of American Geophysical Union.*

The data of Jackson et al. (1977) indicate that air temperature could be determined on the ground and airborne scanners could measure T_c, enabling water use by crops to be evaluated over large areas. In sum, the work by Jackson et al. (1977) showed that (1) the SDD concept can be used as an indicator for determining the times and amounts of irrigation; and (2) because predicted ET, from an expression relating ET to net radiation and $T_c - T_a$, and measured water used agreed reasonably well, the expression may be useful in determining amounts of irrigation water to apply.

27.3 CROP WATER STRESS INDEX

Now let us consider the CWSI, which was developed by the Phoenix scientists 4 years after the SDD concept was developed (Idso et al., 1982). The CWSI is also called the plant water stress index (PWSI). Only the difference between canopy temperature and air temperature is considered in the SDD concept. However, SDD may be influenced by factors such as air vapor pressure, net radiation, and wind speed (Idso et al., 1981). It is important to determine the significance of these other factors and to devise a means for adjusting for them. Consequently, the Phoenix

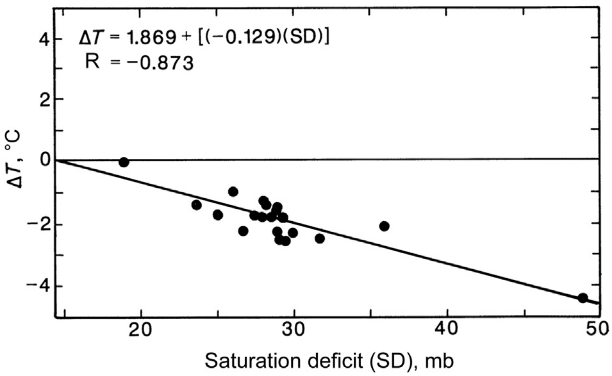

FIGURE 27.5 The regression of cotton leaf–air temperature difference (ΔT, °C) on the saturation deficit of the air (mb). Air temperature and vapor pressure were measured 1 m above the cotton crop. The data are restricted to the period 08:00–18:00 h (Mountain Standard Time) on predominantly sunny days when the crop was fully hydrated, i.e., from 2 to 6 days after a heavy irrigation. *From Ehrler, (1973). American Society of Agronomy, Madison, Wisconsin. Reprinted by permission of the American Society of Agronomy.*

workers developed a plant-(crop-) water-stress index that essentially normalizes the SDD value.

The basis for the PWSI was established by the work of Ehrler (1973). He used thermocouples to measure the leaf temperature of four varieties of cotton (*Gossypium hirsutum* L. 'Deltapine SL', 'Deltapine-16', and 'Hopicala', and *Gossypium barbadense* L. 'Pima-S4'). He found that for clear, sunny days, the difference between leaf and air temperatures from 08:00 to 18:00 h was a linear function of air vapor pressure deficit (VPD), as long as the plants were well supplied with water (Figure 27.5).

Working with IR thermometers, Idso et al. (1981) extended Ehrler's (1973) data to include alfalfa (*Medicago sativa* L.), soybeans (*Glycine max* L. Merr.), and squash (*Cucurbita pepo* L.). They plotted values of $T_c - T_a$ versus VPD (Figures 27.6–27.8) and found that crop-specific linear relationships prevailed throughout the greater portion of the daylight period (i.e., from about 2–3 h after sunrise to about 2–3 h before sunset). They also found these relationships to be essentially undisturbed by variations in other environmental parameters, such as wind speed or the normal course of insolation through the day. Only shading by clouds seemed to have a significant influence, reducing foliage (canopy) temperature relative to that of the air by several degrees (Idso, 1982a).

Figure 27.9 provides a generalized representation of these results and a framework for describing the development of the PWSI (Idso, 1982a). The lower limit of this graph, which represents a state of potential evaporation, is referred to as the *non-water-stressed* baseline. It is crop specific and must be obtained by experimentation as described in the preceding paragraphs. Once established, it is used to define the other limiting condition that prevails when water stress is a maximum and transpiration completely suppressed, which is accomplished as follows (Idso, 1982a).

Consider a well-watered plant transpiring at the potential rate. A plot of $T_c - T_a$ versus VPD (T_c, canopy temperature, is also called T_f, foliage temperature) for this plant will fall somewhere on the non-water-stressed baseline; and as the air VPD decreases to zero, it will move along this baseline to achieve the $T_f - T_a$ value representative of the linear relationship's intercept. If this term is positive, as it has proven to be (Idso, 1982a) (value a in Figure 27.9), there will still be a small evaporative flux from the plant to the air, even though the air at that point is saturated, due to the positive vapor pressure gradient (VPG) that exists between the plant and the air as a result of the plant's higher temperature.

This driving force for evaporation is easily evaluated as VPG $= \rho_s(T_f) - \rho_s(T_a)$, where $\rho_s(T_f)$ is the saturated vapor pressure at the temperature of the foliage and $\rho_s(\mathrm{T_a})$ is the saturated vapor pressure at the temperature of the air; for transpiration to be reduced to zero, VPG must be reduced to zero. One way by which this may be accomplished is to supersaturate the

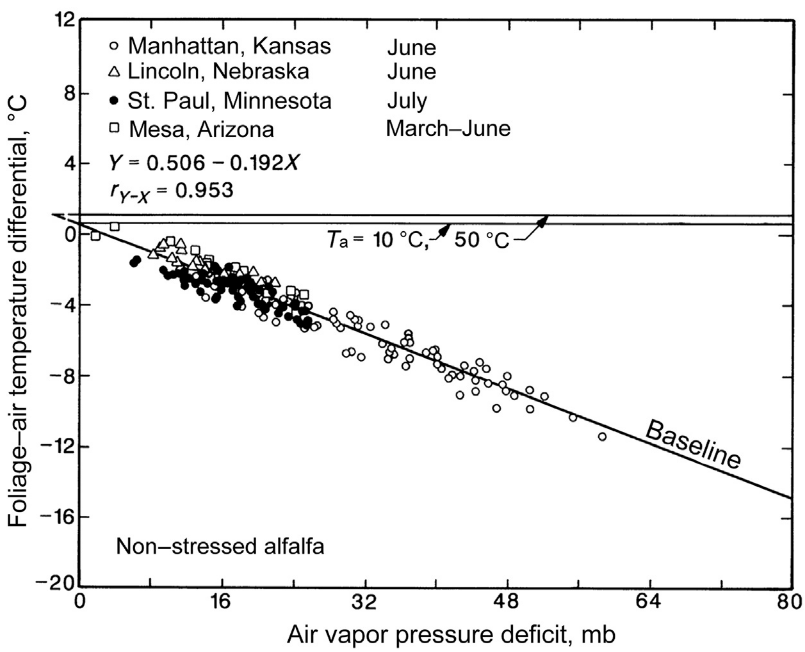

FIGURE 27.6 Foliage—air temperature differential versus air vapor pressure deficit for well-watered alfalfa grown at the specified sites and dates during 1980. *From Idso et al. (1981). Elsevier Scientific Publishing Company, Amsterdam. Reprinted by permission of Elsevier, Amsterdam.*

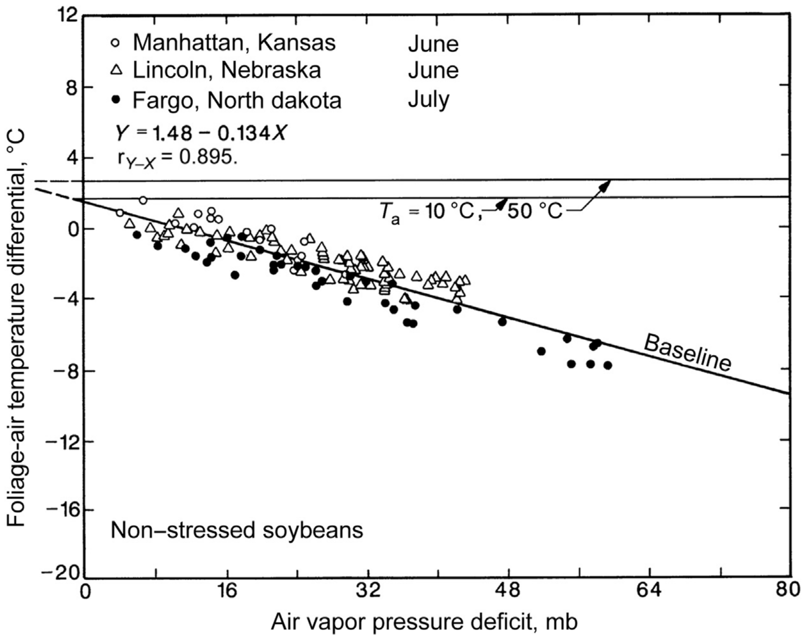

FIGURE 27.7 Foliage–air temperature differential versus air vapor pressure deficit for well-watered soybeans grown at the specified sites and dates. *From Idso et al. (1981). Elsevier Scientific Publishing Company: Amsterdam. Reprinted by permission of Elsevier, Amsterdam.*

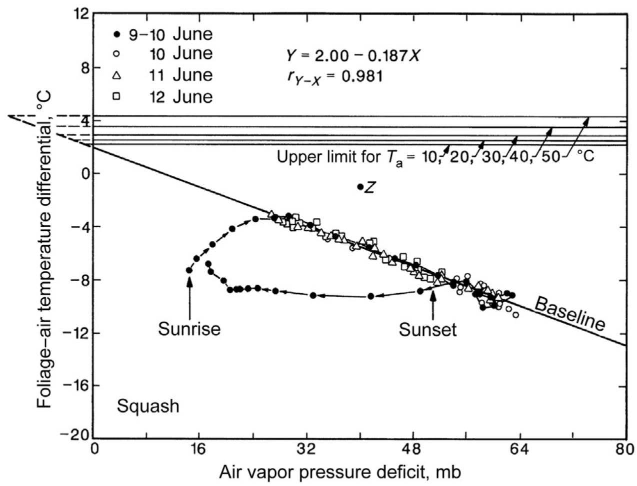

FIGURE 27.8 Foliage–air temperature differential versus air vapor pressure deficit for well-watered squash grown at Tempe, Arizona, in June, 1980. *From Idso et al. (1981). Elsevier Scientific Publishing Company: Amsterdam. Reprinted by permission of Elsevier, Amsterdam.*

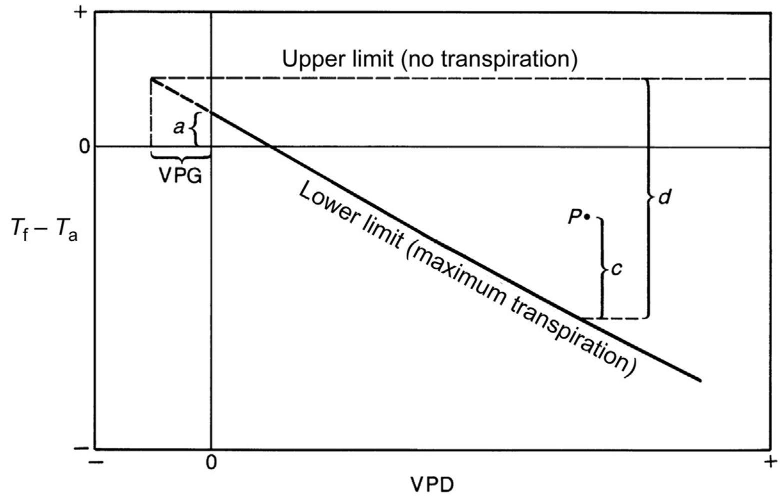

FIGURE 27.9 The general form of the relationship between foliage—air temperature differential ($T_f - T_a$) and air vapor pressure deficit (VPD) for a stand of vegetation sufficiently supplied with water to transpire at the potential rate, i.e., the lower limit (maximum transpiration line), plus an illustration of how the upper limit (no transpiration line) is derived using the vapor pressure gradient (VPG). The values *c* and *d* are used to define the plant water stress index. See text for explanation. *From Idso et al. (1982). American Geophysical Union. Reproduced by permission of American Geophysical Union.*

air, that is, to create a negative VPD equivalent in absolute magnitude to the VPG. Then, following the non-water-stressed baseline back into the negative VPD region by this amount will specify the upper limit to which $T_f - T_a$ may rise at the particular air temperature in question. This latter point of emphasis is made to underscore the fact that there is not a unique upper limit for a given species, as is the case with the non-water-stressed baseline, but rather a variety of limits corresponding to the variety of air temperatures that may prevail. For plants with a small baseline intercept (i.e., less than 0.5 °C), this upper limit dependency on air temperature is weak and can sometimes be ignored (Idso, 1982a).

Consider now a data point representative of a stressed plant that locates it at position *P* in Figure 27.9. In this format, Idso et al. (1981) defined the PWSI (or CWSI) as the ratio of the vertical distance between the data point and the non-water-stressed baseline and the total vertical distance between the baseline and the upper limit (i.e., PWSI $= c/d$). Thus defined, it can be seen that as a plant goes from a condition of maximum transpiration to one of no transpiration, the index goes from a value of zero to unity; Jackson et al. (1981) have demonstrated that actual transpiration (E) at any point *P* in this range is specified as $E = E_p(1-\text{PWSI})$, where E_p is the potential evaporation rate that could be sustained in the given circumstances, but with a nonlimiting supply of soil moisture (Idso, 1982a). (The PWSI or CWSI has sometimes been referred to as the IJ index after Idso and Jackson, the two scientists who developed the concept. For a biography of Idso, see the Appendix, Section 27.8. A biography of Jackson appears in Chapter 26, Section 26.7.)

27.4 HOW TO CALCULATE THE CROP WATER STRESS INDEX

Let us now take a specific example that shows how to obtain the PWSI (or the CWSI). Let us refer to Figure 27.8 (Idso et al., 1981). Suppose at a time when the air VPD is 40 mb, the value of $T_f - T_a$ is $-1\ ^\circ C$, so that the point Z on Figure 27.8 represents the status of the crop, which in this case is squash. Now, if the crop had been sufficiently supplied with water to evaporate at the potential rate, $T_f - T_a$ would have been $-5.5\ ^\circ C$, as obtained from intersecting the non-water-stressed baseline at VPD = 40 mb. Conversely, if the crop had not been transpiring at all, and T_a was 30 °C (for example), then $T_f - T_a$ would be expected to have been about 3 °C. With this information, we can define the PWSI (or CWSI) to be the ratio of the vertical distance above the non-water-stressed baseline that the point Z has conceptually traveled in falling below the potential evaporation rate to the total possible distance that it could conceptually travel, which in this example is $-1\ ^\circ C - (-5.5\ ^\circ C)$ divided by $3\ ^\circ C - (-5.5\ ^\circ C)$ or $4.5\ ^\circ C/8.5\ ^\circ C = 0.53$. Thus, we see that as the ratio of actual to potential evaporation goes from 1 to 0, the CWSI goes from 0 to 1.

27.5 CROP WATER STRESS INDEX FOR ALFALFA, SOYBEANS, AND COTTON

Idso et al. (1981) did not determine $T_c - T_a$ versus VPD for water-stressed squash, so no measured points in Figure 27.8 lie around point Z in the figure. They did, however, determine $T_c - T_a$ versus VPD for water-stressed alfalfa and soybeans (Figures 27.10 and 27.11). Note that for water-stressed alfalfa and soybeans points lie between the baseline or lower limit (maximum transpiration) and the upper limit (no transpiration). In Figure 27.12, Idso et al. (1981) have converted the data from Figures 27.10 and 27.11 into the format of the CWSI. The soybeans, in this instance, were still fairly young, and covered only about 10% of the ground. Thus, with their rather limited rooting volume, they experienced a dramatic rate of stress development as the hot and dry day, on which the data were obtained, progressed (maximum air temperature was 39 °C and minimum relative humidity was 17%). But the alfalfa, with its

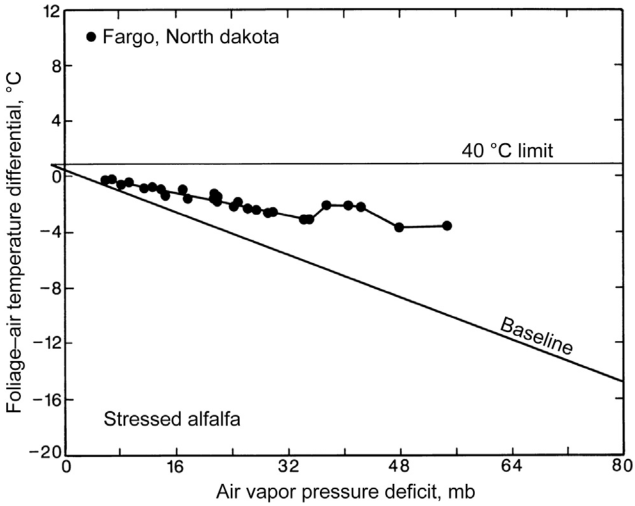

FIGURE 27.10 Foliage–air temperature differential versus air vapor pressure deficit for stressed alfalfa growing at Fargo, North Dakota. *From Idso et al. (1981). Elsevier Scientific Publishing Company: Amsterdam. Reprinted by permission of Elsevier, Amsterdam.*

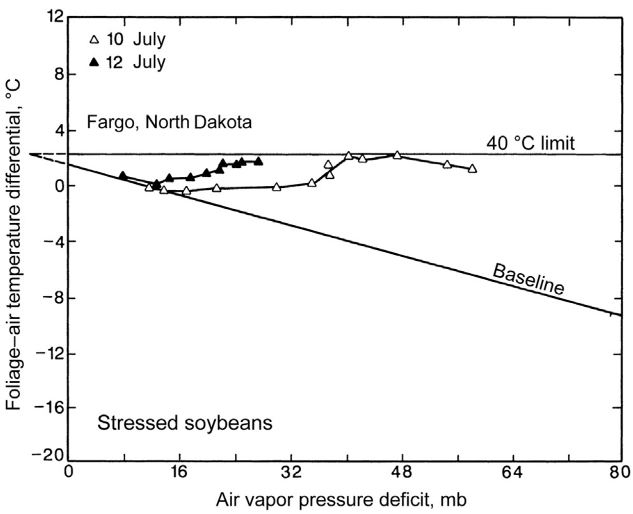

FIGURE 27.11 Foliage–air temperature differential versus air vapor pressure deficit for stressed soybeans growing at Fargo, North Dakota. *From Idso et al. (1981). Elsevier Scientific Publishing Company: Amsterdam. Reprinted by permission of Elsevier, Amsterdam.*

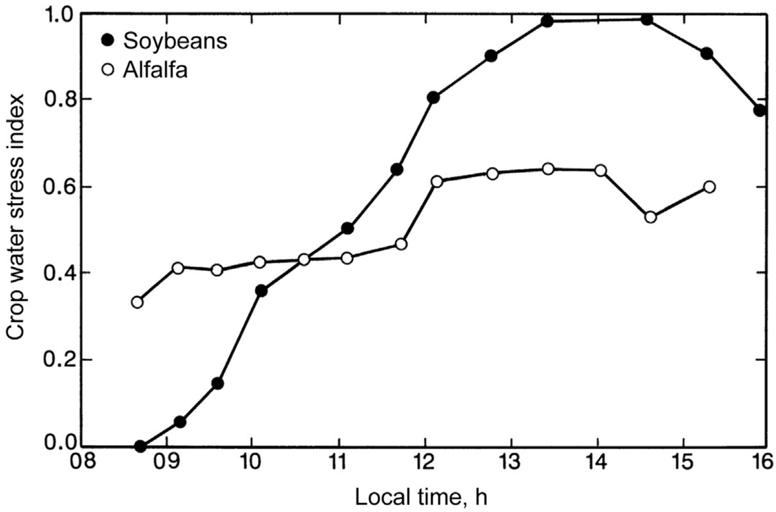

FIGURE 27.12 The crop water stress index as a function of time for severely stressed soybeans and less severely stressed alfalfa at Fargo, North Dakota. *From Idso et al. (1981). Elsevier Scientific Publishing Company: Amsterdam. Reprinted by permission of Elsevier, Amsterdam.*

well-developed root system, showed a much greater buffering capacity to stress development, although it too showed a significant increase in stress in the afternoon. Maximum stress for both crops occurred about 1−2 h after solar noon, indicating that this was a good time for a once-a-day measurement, as was used by Jackson et al. (1981), to quantify the stress history of several differently irrigated wheat plots. Figure 27.13

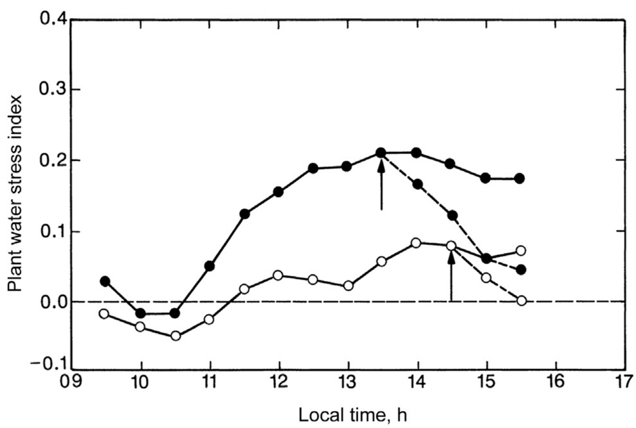

FIGURE 27.13 The plant water stress index for mildly and moderately stressed cotton preceding and following irrigations shown by arrows. *From Idso et al. (1982). American Geophysical Union. Reproduced by permission of American Geophysical Union.*

shows the crop-(plant-) water-stress index plotted for mildly stressed cotton (lower line) and moderately stressed cotton (upper line) before and after irrigation (Idso et al., 1982).

27.6 IMPORTANCE OF A WIDE RANGE OF VAPOR PRESSURE DEFICIT VALUES

Plots of $T_c - T_a$ versus VPD for well-watered plants appear to yield a unique linear relationship under a specific climatic condition. The Phoenix scientists postulate that the existence of such linear relationships provides a simple criterion for identification of a potential evaporation (Idso et al., 1981). Their findings also provide a means for normalizing the SDD value for environmental variability, by converting it into the CWSI. It is evident, however, that defining stress in this fashion limits the ability to quantify, with confidence, the CWSI under conditions of low VPD, where the variability of $T_c - T_a$ approaches the degree of scatter inherent in the data (see Figures 27.6 and 27.7). Therefore, it is important to have a wide range of VPD values to obtain meaningful CWSIs.

27.7 NORMALIZED DIFFERENCE VEGETATION INDEX

What the CWSI measures should not be confused with what the normalized difference vegetation index (NDVI) measures. Light from the sun, reflected from plants, can show approximately how much plant material is present in a field (Jackson et al., 1980). Jackson et al. (1980) present a vegetation index, now called the NDVI, as follows:

$$\mathrm{NDVI} = [(\mathrm{IR} - \mathrm{red})]/[(\mathrm{IR} + \mathrm{red})]. \tag{27.6}$$

The NDVI is obtained from the ratio between the red and near-red IR reflectance bands, which are measured with radiometers (Hillel and Rosenzweig, 2005). Tucker et al. (1981) found that the band 0.63–0.69 μm in the red region and the band 0.76–0.90 μm in the IR region give reliable results to analyze natural materials in situ. These two bands are sensitive to the chlorophyll density and the green leaf density, respectively, of a plant canopy. Their results were confirmed by Stone and Kirkham (1983). Chlorophyll absorbs in the red and blue bands (see Chapter 3, Section 3.2, Part 6 for the exact wavelengths), but the NDVI is based on the red band, not the blue band. The reflectance data can be obtained on land by handheld radiometers (Stone and Kirkham, 1983) or remotely by aircraft or satellites (Hillel and Rosenzweig, 2005). The CWSI measures the difference between canopy and air temperatures and cannot be monitored by aircraft or satellites. How far into the sky a temperature differential occurs due to evaporational cooling needs to be determined (Kirkham, 2013). Turbulence of the atmosphere mixes canopy temperature with ambient air temperature, so the difference between canopy and air temperatures should occur only over a short distance. As noted in Chapter 26, Kirkham et al. (1984) measured canopy temperature at a distance 1.2 m away from the crop.

However, scientists who obtain reflectance data remotely are trying to take measurements of canopy temperature from aircraft. Drones are now being used to obtain reflectance data for monitoring of crop health. A drone is a pilotless airplane whose flight is controlled by an operator in an accompanying craft or on the ground (Webster's New World Dictionary of the American Language, 1959). Drones measure the NDVI, which tells that a crop is stressed, but not the reason for the stress. It can be stressed due to drought, flooding, cold, heat, or insects. We need ground truth to tell the reason for the stress. The CWSI can tell us that a crop is water stressed and can be used for irrigation scheduling. Drones are either fixed-wing aircraft or helicopters. When helicopters are used, the blades stir up the air and affect the plant temperature. However, drones are being equipped with temperature sensors that can measure within 1/100th of a degree centigrade (Kevin P. Price, Department of Agronomy, Kansas State University, personal communication, August 15, 2013). It is hoped that the air mixing problem from the aircraft can be overcome, so that drones eventually could measure a CWSI. Temperature data from drones may soon be able to detect how far above a crop the temperature differential exists.

27.8 APPENDIX: BIOGRAPHY OF SHERWOOD IDSO

Sherwood B. Idso was born on June 12, 1942, in Thief River Falls, Minnesota, where he lived until graduating from high school in 1960. He then enrolled in the Institute of Technology at the University of Minnesota, where he received a bachelor's degree in physics with distinction in 1964, an M.S. degree in 1966, and a Ph.D. in 1967. He moved to the US Water Conservation Laboratory of the USDA in Phoenix, Arizona, in 1967, where he worked as a research physicist. He also was an adjunct professor in the Departments of Geology and Geography at Arizona State University in Tempe. Much of his work at the US Water Conservation Laboratory related to the study of the effects of elevated carbon dioxide on plant growth, often done in collaboration with Bruce A. Kimball. See Kirkham (2011) for citations of their work. Since stopping doing research with the USDA, Idso has been actively involved in disseminating information, through a Web site, about the climatic and biological effects of elevated carbon dioxide in the atmosphere. Idso and his wife have seven children (Idso, 1982b). Two of his children, Craig D. Idso and Keith E. Idso, also work to disseminate information about carbon dioxide in the atmosphere.

Sherwood Idso has published numerous scientific papers. In addition to his publications on carbon dioxide, he has studied heat and moisture transfer in the soil-plant-atmosphere continuum (SPAC). He developed methods for evaluating evaporative water losses from soil, plants, and open water, along with a number of techniques for the remote sensing of soil- and plant-water status. He has an abiding interest in severe weather phenomena and is a dedicated investigator of dust storms and dust devils (Idso, 1982b). He is well known for his writings related to climate change.

In 1977, Idso received the Arthur S. Flemming Award “for his innovative research into fundamental aspects of agricultural-climatological interrelationships affecting food production and the identification of achievable research goals whose attainment could significantly aid in assessment and improvement of world food supplies”. The Flemming Award is presented annually to people under the age of 40 years who work in civilian or military capacities in the federal government. The Downtown Jaycees of Washington, D.C., sponsor the award (American Meteorological Society, 1978).

References

American Meteorological Society, 1978. About our members. Bull. Am. Meteor. Soc. 59, 747.

Agam, N., Cohen, Y., Berni, J.A.J., Alchanatis, V., Kool, D., Dag, A., Yermiyahu, U., Ben-Gal, A., 2013. An insight to the performance of crop water stress index for olive trees. Agr. Water Manage. 118, 79−86.

Anda, A., 2009. Irrigation timing in maize by using the crop water stress index (CWSI). Cereal Res. Commun. 37, 603−610.

Dean, J.P., 1976. Sensing soil moisture—remotely. Agr. Res. 25 (4), 7−9.

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

Hillel, D., Rosenzweig, C., 2005. Desertification. In: Hillel, D. (Ed.), Encyclopedia of Soils in the Environment, vol. 1. Elsevier, Amsterdam, pp. 382−389.

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

Idso, S.B., 1982b. Carbon Dioxide: Friend or Foe? IBR Press, Tempe, Arizona (Available from the Institute for Biospheric Research, Inc., 631 E. Laguna Drive, Tempe, Arizona 85282).

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

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

Jackson, R.D., 1982. Canopy temperature and crop water stress. In: Hillel, D. (Ed.), Advances in Irrigation, vol. 1. Academic Press, New York, pp. 43−85.

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

Jackson, R.D., Pinter Jr, P.J., Reginato, R.J., Idso, S.R., 1980. Hand-held Radiometry. Agr Rev Manuals ARM-W-19. United States Department of Agriculture, Science and Education Administration, Western Region, Oakland, California.

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

Kirkham, M.B., 2011. Elevated Carbon Dioxide: Impacts on Soil and Plant Water Relations. CRC Press, Boca Raton, Florida.

Kirkham, M.B., 2013. Research needs for agriculture under elevated carbon dioxide. In: Hillel, D., Rosenzweig, C. (Eds.), Handbook of Climate Change and Agroecosystems. Global and Regional Aspects and Implications. Imperial College Press, London, pp. 225–234.

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

Lowry, W.P., 1969. Weather and Life: An Introduction to Biometeorology. Academic Press, New York.

Stone, J.M., Kirkham, M.B., 1983. Water content of sludge-injected soil growing wheat. Environ. Conserv. 10, 337–342.

Stone, L.R., Horton, M.L., 1974. Estimating evapotranspiration using canopy temperatures: field evaluation. Agron. J. 66, 450–454.

Tucker, C.J., Jones, W.H., Kley, W.A., Sundstrom, G.J., 1981. A three-band hand-held radiometer for field use. Science 211, 281–283.

Webster's New World Dictionary of the American Language, College ed., 1959. World Publishing, Cleveland.