Proceedings of the 26th Annual Central Plains Irrigation Conference, Colby, KS, February 17-18, 2015
Available from CPIA, 760 N.Thompson, Colby, Kansas

USING CANOPY TEMPERATURE AS AN INDICATOR OF PLANT STRESS

José L. Chávez
Assistant Professor and Extension Irrigation Specialist
Civil & Environmental Engineering Department
Colorado State University
Fort Collins, Colorado
Voice: 970-491-6095   Fax: 970-491-7727
Email: Jose.Chavez@colostate.edu

INTRODUCTION

In a world of climate change, population growth and drought, managing scarce water resources (tightly) is a must. Therefore, there is a need to closely monitor crop water stress to effectively decide on irrigation timing and amounts for set irrigation strategies (fully to deficit or limited irrigated crops).

In particular, measuring crop canopy temperature, using infra-red sensors, has been found to be useful in determining the degree of crop water stress. Canopy temperature can be used in the so called crop water stress index method (CWSI). This study shows how to apply the CWSI method and also shows comparisons between CWSI values and soil volumetric water content (moisture). In addition, a comparison of CWSI with a newly defined soil water stress index (SWSI) is shown. In this latter comparison, there is evidence that the canopy temperature indeed can be used to quantify the degree of crop water stress.

MATERIALS AND METHODS

Application of the CWSI Method

The CWSI method was applied during the 2014 growing season on a corn field located near Greeley, CO. The corn field area was 400 m (1312 ft) long by 135 m (443 ft) wide. The field was divided into three blocks, each 400 m by 45 m (1312 ft by 148 ft). Each block received a different irrigation water amount (different treatments). The different treatments were: full irrigation (Treatment 1, TrT1) to replenish the full crop water use/demand or evapotranspiration but with a low application efficiency (more water applied than needed), deficit irrigation (TrT2, only two full irrigations during the corn reproductive growth stage), and reduced irrigation (TrT3, about half the amount of the full irrigation but still fulfilling the crop water requirements, higher irrigation application efficiency). In this article, only TrTs 3 and 2 are used for illustration of the CWSI procedure. The field was surface irrigated through gated pipes and furrows. The water supply was a deep well with a capacity of 129 m^3 h^{-1} (568 gpm).

The CWSI method relies on the temperature difference (dT, ºC) between the vegetation canopy and the air ($T_c - T_a$), and on minimum and maximum differences in these “$T_c - T_a$” temperatures, as indicated in Equation 1. Air temperature measured at a height of 2.0 – 3.0 m above the ground and in the crop field.

$$CWSI = (dT - dT_{min})/(dT_{max} - dT_{min}) \quad (1)$$

where: subscripts “min” and “max” are the minimum and maximum dT (or $T_c - T_a$), respectively. These dT boundaries can be estimated following the methodology developed by Idso et al. (1981). The dT_{min} and air water vapor pressure deficit (VPD, kPa) have a linear relationship for a fully irrigated (no water stress) crop under a given environmental condition. The dT_{max} has a linear relationship with the so called water vapor pressure gradient (VPG), when the crop is experiencing maximum water stress (dry soil to a soil water tension of about 15 bars):

$$dT_{min} = a\ (VPD) + b \quad (2)$$

$$dT_{max} = a\ (VPG) + b \quad (3)$$

where: the “a” and “b” coefficients are the slope and the intercept of the linear relationship between dT_{min} and VPD. The VPG is estimated as the difference between saturated air vapor pressure at air temperature and saturated air vapor pressure at air temperature plus the coefficient “b.” The value of dT_{max} has also been found to be relatively constant around 4 to 5 ºC for corn fields.

The minimum dT occurs when the vegetation is not experiencing water stress. Under this condition the crop has sufficient water available in the soil root zone and the transpiration process is only limited by weather conditions. Appropriate coefficients for dT_{min}, for several crops, can be found in Idso et al. (1982). For this study, coefficients “a” and “b” were developed from in-situ field data (i.e., air temperature, vapor pressure, canopy temperature) collected one to two days after irrigation events (no water stress conditions) after corn had reach effective full cover. A linear regression was performed between dT_{min} and VPD (VPD calculation explained below). The resulting coefficients were slope “***a = -1.99***” and intercept “***b = 3.04***”. These coefficients were very close to those found by Idso (1981) for corn in Arizona; which were “a = -1.97” and “b = 3.11”.

In the case of dT_{max}, it occurs when the vegetation is not transpiring because the soil is very dry (soil water tension of about 15 bars) and the plant can’t exert so much tension (negative pressure) to remove any more water from the soil.

To compute the vapor pressure deficit one needs readings of air temperature (T_a, ºC) and relative humidity (RH, %) obtained just above the canopy (i.e., in field or in-situ measurements); preferentially from the middle of the field. In the case of our application of the CWSI method, each irrigation level (plot) was equipped with a Vaisala HMP45C sensor, installed at a height of approximately 2.7 m (8.9 ft) above the ground, to measure air temperature and relative humidity. Canopy temperature was measured with a research grade Apogee (Logan, UT) SI-121 infra-red thermometer. These IRTs were installed two per treatment, at a height of 2.8 (9.2 ft), oblique at 45 º below hypothetical horizontal line and one looking south east (SE) and the other south west (SW) at corn canopies. Average canopy temperature values of these SE and SW IRT sensors were used as representative of the ensemble or overall canopy temperature.

Canopy temperature, air temperature and relative humidity data were sampled every three seconds and five minute averages were recorded by an on-site datalogger (CR1000, Campbell

Scientific, Inc., Logan, Utah). In this study the five minute averages were further averaged over a one-hour period to report hourly values of these variables.

Vapor Pressure Deficit (VPD) Calculation

Vapor pressure deficit (VPD, in units of kilo-Pascals, kPa) was computed as follows:

$$\mathrm{VPD} = e_s - e_a \tag{4}$$

where, "e_s" is saturation vapor pressure (kPa) and "e_a" is actual vapor pressure (kPa), both computed as show below (where T_a is air temperature in ºC).

$$e_s = 0.6108 \times \exp\left(\frac{17.27 \times T_a}{237.3 + T_a}\right) \tag{5}$$

$$e_a = (\mathrm{RH}/100) \times e_s \tag{6}$$

where, RH is relative humidity in percent (%).

Vapor Pressure Gradient (VPG) Calculation

The VPG is the difference between saturated air vapor pressure at air temperature and saturated air vapor pressure at air temperature plus the coefficient "b." Thus:

$$VPG = \left[0.6108 \times \exp\left(\frac{17.27 \times T_a}{237.3 + T_a}\right)\right] - \left[0.6108 \times \exp\left(\frac{17.27 \times (T_a + b)}{237.3 + (T_a + b)}\right)\right] \tag{7}$$

Once the corn CWSI was computed, in our case using data collected from 11 a.m. to 12 p.m. (reported at 12 p.m.), the next step was to compare it to measured soil moisture or soil volumetric water content (VWC, %) to infer whether the canopy temperature in the CWSI was a viable form to monitor crop water stress.

Comparison of the canopy temperature approach with soil volumetric water content

The CWSI method based on canopy temperature was evaluated using measured soil volumetric water content (VWC). The instrument used to measure VWC (%) was a Campbell Scientific, Inc. (Logan, UT) CS-616 water content reflectometer. Three sensors per site were installed at depths of 0.15, 0.30 and 0.45 m (approximately 0.5, 1.0 and 1.5 ft, respectively) from the soil surface. The sensor sampled/measured soil moisture every 15 min and averaged four readings in an hour period to report hourly average VWC values. The CS-616 raw VWC values were calibrated using a soil specific calibration function as published in Varble and Chávez (2011).

RESULTS AND DISCUSSION

Canopy Temperature

In Figure 1 (below), corn canopy temperature for the deficit irrigation treatment (Trt 2) was larger than the fully irrigated treatment (Trt 3) most of the period considered (August). For Trt 2, temperature of corn canopy was up to 3.5 ºC larger than that of Trt 3 for the same period. This result shows that indeed deficit irrigation causes the canopy temperature to be hotter (higher) than the temperature the plant would have if well irrigated. Therefore, this result is evidence that canopy temperature could be a valuable tool in monitoring crop water stress. In Figure 1, DOY is day of year or Julian day.

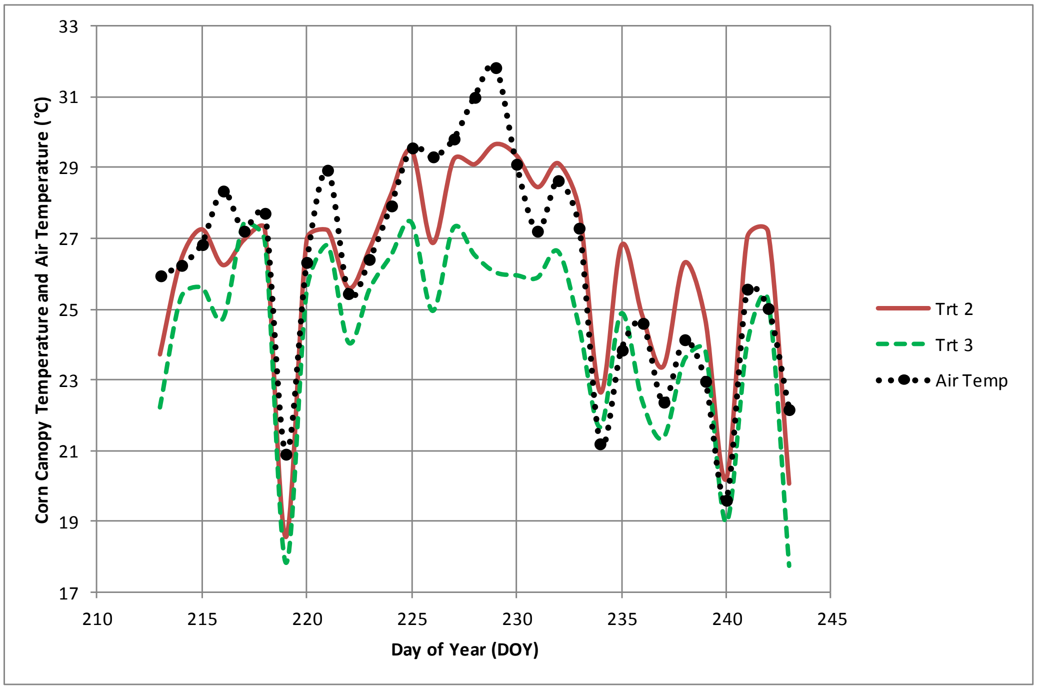

Figure 1. Plot of canopy temperature for non-water stressed treatment (Trt 3), for water stressed treatment (Trt 2), and of air temperature (Air Temp) in degrees Celsius (°C).

Evaluating CWSI with Soil Water Content (SWC)

Figure 2 depicts estimated corn water stress index values for treatment 3 (CWSI3) with diamond (blue) symbols. The volumetric soil water content, for the same treatment (VWC3, %) is shown in large square (red) symbols connected by a solid (red) line. The upper most long-dashed (black) line represents the sandy clay loam soil volumetric water content (VWC) when saturated (Sat line). The corresponding saturation VWC was 46 %. The solid (green) line (FC) represents the soil VWC at field capacity, VWC_{FC}, (i.e., amount of water retained in the soil after a wetting event when natural drainage has ceased). In our research field, the VWC at field capacity was 32 %. The small square (orange) symbols represent the threshold VWC (VWC_t). This is, the VWC limit that if crossed (i.e., for lower values) the plant starts experiencing water stress. VWC_t was computed as follows:

$$VWC_t = VWC_{FC} - (MAD \times AV) \tag{8}$$

$$AV = VWC_{FC} - VWC_{WP} \tag{9}$$

where, AV is available water in the soil, VWC_{WP} is the volumetric water content at wilting point (%), represented by a short-dashed line (purple) in Fig. 2. For the sandy clay loam soil of our study VWC_{WP} was determined to be 16 %. And, MAD is the soil water "Management Allowed Depletion." This is, the fraction that one is allowed to deplete available water in the soil before causing water stress in the plant. Available water (AV) is defined as the difference between $VWC_{FC} - VWC_{WP}$. MAD for the corn in the study was assumed to be 0.45 (or 45%).

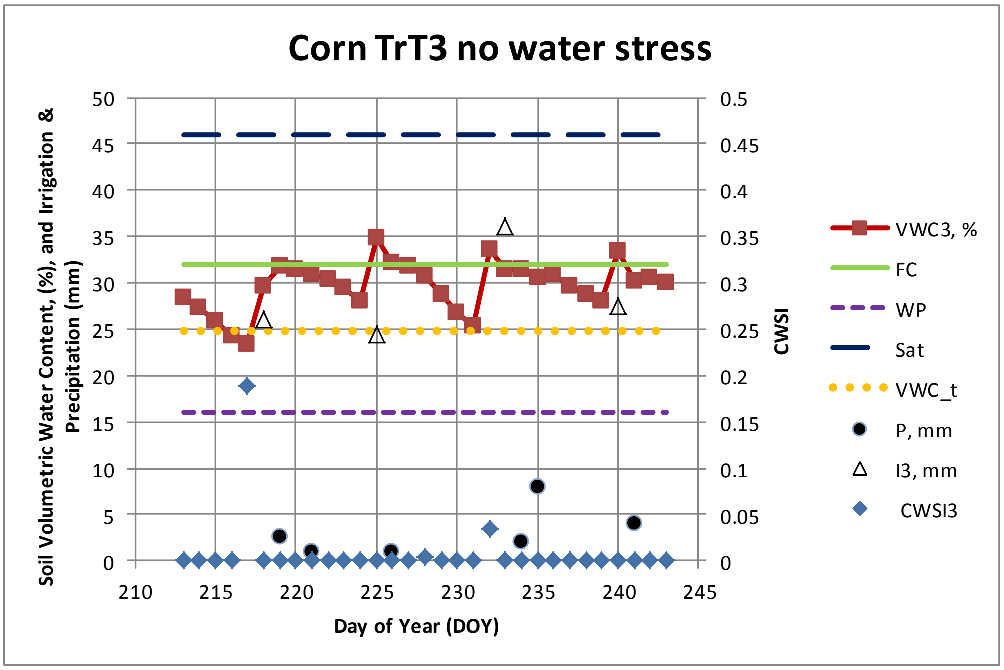

Figure 2. Plots of corn water stress (CWSI3) and soil volumetric water content (VWC3) for non-water stressed treatment (Trt 3).

Tables reporting suggested MAD values for different crops can be found in Allen et al. (1998), as "depletion fractions", and in Hoffman et al. (2007). In addition, Merriam (1966) published MAD values for different crop types, soils, evapotranspiration rates, root depths, salinity levels, and type of irrigation among other variables. In this study, VWC_t was calculated to be 24.8 %.

Still in Figure 2, for treatment 3 (no water stress), the triangle (empty) symbol represents the net irrigation water depth (I3, mm) received by the field in August. Lastly, in Fig. 2, the round (black) symbol represents effective rainfall or precipitation amounts (P, mm) for the month of August.

In Fig. 2, for the fully irrigated treatment (Trt3), estimations of CWSI using canopy temperature indicated that only in two instances corn experience some level of water stress. The first and larger stress occurred on DOY 217 (Aug 15th) where the CWSI was 0.18 (or 18%). For the same day, the soil VWC was 23.4% and thus had crossed (was less than) the threshold VWC (VWC_t of 24.8 %) for the plant to experience no water stress. Therefore, this result may be evidence that the CWSI indeed was able to detect the plant water stress due to shortage of water (beyond the MAD selected) in the soil root system. The second instance that there was some water stress for this treatment 3 was on DOY 232 (Aug 20th). However, the value was very small (CWSI = 0.03 or 3 %). In this case, measured soil water content indicated that the VWC on DOY 232 was 25.4 %. This value was practically the same as the VWC_t an indicated that, most likely, some crop water stress may have started to developed just before the soil VWC was at the set threshold; perhaps because the assumed MAD value (0.45) was somewhat larger than the value that should have been used (maybe 0.40-0.43), for the crop variety and environment, in order to completely avoid any crop water stress for this treatment.

In the case of the deficit irrigation treatment (Trt 2), there was no irrigation during the month of August. Soil VWC levels reached the VWC_t (threshold) on DOY 218 (Aug 6th) at which the CWSI was 0.1 (or 10 %). As in the case for Trt 3 above, this is evidence that the canopy temperature in the CWSI can be capable of monitoring water stress as indicated by the soil VWC depletion beyond the established threshold level (through the MAD value); and that perhaps the MAD value used was a bit larger than the optimal value for the corn in this study. There were a couple of cloudy and rainy days (DOY 219 and 221) after VWC_t had been crossed (VWC less than) when CWSI values decreased to very small values but the VWC (soil moisture) in the soil root zone continued to declined. This is because the rain was small and did not effectively wet (penetrated) the soil crop root zone and therefore was not detected by the soil moisture sensors. Furthermore, readings of crop canopy temperature should be performed under clear skies (sunny days) during the time window between around noon and 3 pm local time. Thus, being a rainy and cloudy day (DOY 219 and 221) the canopy temperature was temporarily lower which resulted in a low CWSI for Trt2. Nevertheless, the next day when the surface was dry, and under clear skies, the canopy temperature was larger again resulting in large CWSI values. As depicted in Fig. 3, the CWSI increased as the season progressed (in August) reaching a maximum value of 0.39 (39 %) on DOY 235. After that day, a couple of rainfall events temporarily lowered the CWSI; which returned to larger values once the surface dried up and the corn was subjected to the dry environment and clear sky radiation. When the CWSI reached the 39 % mark on DOY 235 the soil VWC was just 18 % and thus very close to the wilting point (very dry soil). Again, this result seems to corroborate that crop canopy temperature (in the CWSI method) may be a viable procedure (tool) to effectively monitor crop water stress to improve crop irrigation management.

The validation of the CWSI approach using VWC data is supported by other studies. For instance, Taghvaeian et al. (2012) found a strong correlation between CWSI and soil volumetric water content (Figure 4). In that study, it was found that VWC should be equal to or greater than 28.3 % for no crop water stress for a clay loam soil texture in Iliff, CO.

To better illustrate the relationship between CWSI and the level of soil water content (depletion) beyond (below) the set threshold (VWC_t) a “Soil Water Stress Index (SWSI) was developed. The SWSI is defined below.

The SWSI is applied for actual VWC (VWC_a) values that are less than VWC_t.

$$SWSI = \frac{VWC_t - VWC_a}{VWC_t - VWC_{WP}} \quad (10)$$

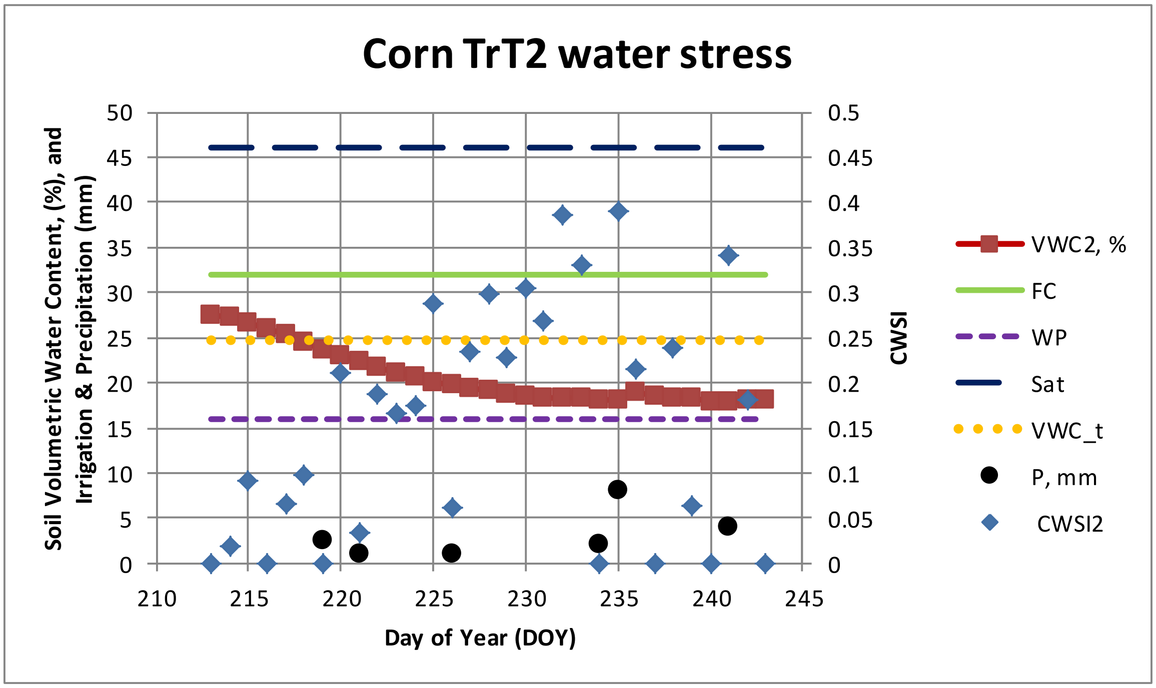

Figure 3. Plots of corn water stress (CWSI2) and soil volumetric water content (VWC2) for the deficit irrigated or water stressed treatment (Trt 2).

where, VWC_a is the actual VWC or current measured soil moisture level. If VWC_a is used as a fraction or decimal (or as a percent), then all other variables in Equation 10 should be used with the same unit(s), consistently.

The SWSI scales VWC_a between the threshold VWC (VWC_t) and the wilting point VWC (VWC_{WP}). Thus, the range is [0, 1]. This is, a SWSI of zero (0) would mean that the soil moisture level was at the threshold level or above and was defined as no soil water stress (note: in relation to the selected MAD). On the other hand, a SWSI value of one (1 or 100 %) would mean that all moisture in the soil was used up by the plant and the plant is reaching the wilting point.

Figure 5 below illustrates the type of relationship found between CWSI and the newly defined SWSI. The polynomial relationship found was very good with a coefficient of determination of practically 0.9. Therefore, this result is evidence of the strong relationship between the level of soil water depletion beyond the established soil water threshold for no stress (through SWSI) and the above ground crop water stress detected through the canopy temperature (CWSI method). This result provides confidence in regards to using canopy temperature to improve crop water management under limited irrigation conditions.

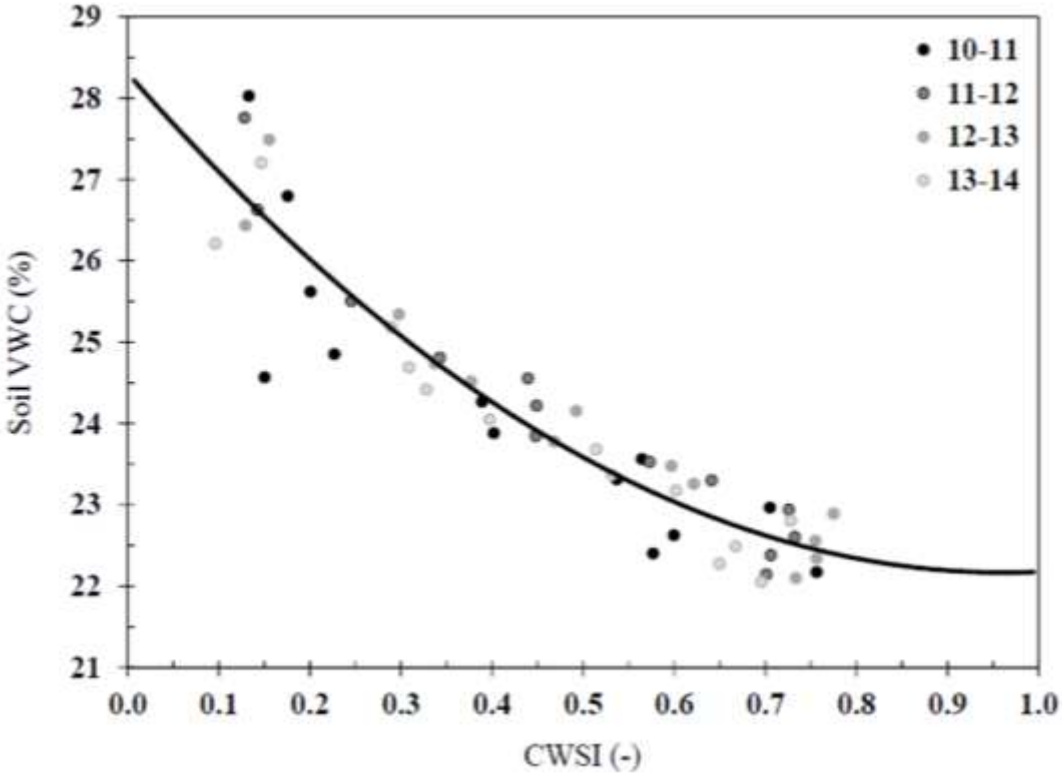

Figure 4. Relationship between CWSI and VWC for a shallow depth clay loam soil texture soil near Iliff, CO. [Taghvaeian et al. (2012)]

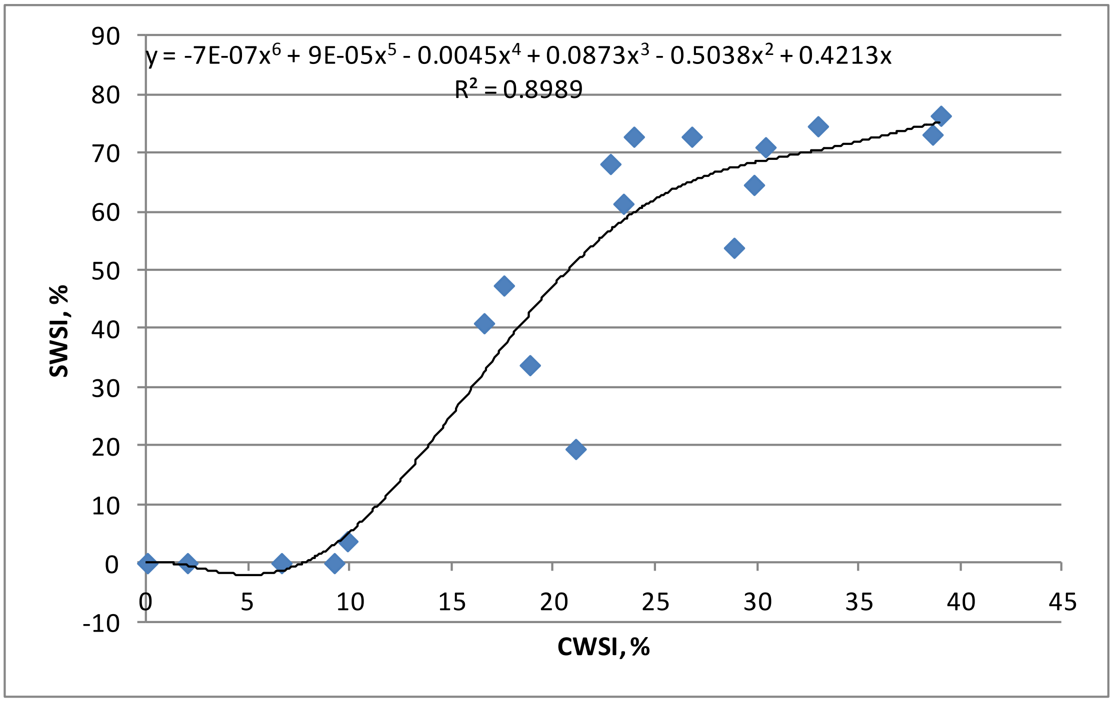

Figure 5. Relationship between CWSI and SWSI for the sandy clay loam soil near Greeley, CO.

Furthermore, to avoid severe crop water stress and therefore considerable crop yield loss, a CWSI of no more than 0.20-0.22 (20-22 %) is recommended as per Fig. 5 above. This is, CWSI > 22 % would increase rapidly for smaller depletions of soil moisture thereafter. This behavior or pattern has to do with the non-linear relationship between volumetric soil water content and soil water potential.

Handheld IRT Use

A handheld IRT gun to measure canopy temperature can be used by farmers in case it is difficult to acquire an Apogee type sensor. The commercially available handheld IRT Ryobi[1] TEK 4 Model RP4030 is approximately $70 per unit. Chávez et al. (2014) provide explanations on the use and calibration of this TEK 4 sensor. The calibration equation is provided below for the convenience of the reader.

$$T_{pred}=0.17T_{Ryobi}+0.47u+0.69T_a-0.85VPD+0.06R_s+1.73 \qquad (11)$$

where, T_{pred} is the calibrated canopy temperature and T_{Ryobi} is the average surface (canopy) radiometric temperature measured by the handheld IRT gun in the NW, NE, SE, and SW directions. Weather station measured variables included were u or wind speed (m s^{-1}), T_a or air temperature (ºC), VPD or vapor pressure deficit (kPa), and R_s the hourly shortwave incoming solar radiation (kJ m^{-2} min^{-1}).

If a weather station can't be found nearby the field of interest then an inexpensive handheld sensor could be used in the field. For instance, the Kestrel 4000 Pocket Weather Tracker measures air temperature, relative humidity, wind speed, barometric pressure, altitude, and dew point temperature among other variables.

CONCLUSIONS

In this study, it was possible to show that through the corn canopy temperature it was possible to determine and monitor the crop water stress level. Soil volumetric water content sensors were used to measure soil moisture levels and produce a new soil water stress index (SWSI) and through this index show that the crop water stress index (CWSI) indeed captures the plant stress. Furthermore, it seems that a corn CWSI of about 0.20-0.23, for the sandy clay loam soil of the study, should not be crossed if one wants to avoid severe crop stress. This CWSI corresponded to a SWSI of about 0.43 (43 %).

ACKNOWLEDGEMENTS

The author is grateful to the following institutions and individuals for the support received and for their involvement, in one way or another, in the studies related to the application of the CWSI method: Colorado Water Conservation Board (CWCB), Colorado Northern Water Conservancy District (Northern Water), West Greeley Conservation District (WGCD), Central Colorado Water Conservancy District (CCWCD), USDA NRCS (CIG program), USDA ARS Water Management Research Unit (Dr. Tom Trout and Dr. Kendall DeJonge) in Fort Collins, CO. Graduate students: Emily Kullberg, Brenna Mefford, Pratigyna Rajkrishna, and Abhinaya Subedi. As well as hourly student Riley Russell.

---

[1] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by Colorado State University.

REFERENCES

Allen, R.G., L.S. Pereira, D. Raes, D., and M. Smith. 1998. Crop evapotranspiration, guidelines for computing crop water requirements. FAO Irrig. and Drain. Paper 56, Food and Agric. Orgn. of the United Nations, Rome, Italy. 300 pp.

Chávez, J.L.; E. Kullberg, and B. Mefford. 2014. Using a handheld IRT to determine crop water stress and use. In Proceedings of the 25th Annual Central Plains Irrigation Conference, Burlington, CO, February 25-26, 2014, pp. 115-125. Available on line at: https://www.ksre.ksu.edu/irrigate/OOW/P14/Chavez14.pdf.

Hoffman, G.J., R.G. Evans, M.E. Jensen, D.L. Martin, and R.L. Elliott. 2007. Design and Operation of Farm Irrigation Systems. 2nd Ed., ASABE, St. Joseph, MI, 1040 pp. ISBN: 1-892769-64-6.

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. Agricultural Meteorology 1981, 24(1), 45-55.

Idso, S.B. 1982. Non-water-stressed baselines: A key to measuring and interpreting plant water stress. Agricultural Meteorology 1982, 27(1-2), 59-70.

Saleh Taghvaeian, José L Chávez, and Neil C Hansen. 2012. Infrared Thermometry to Estimate Crop Water Use and Stress Index of Irrigated Maize in Northeastern Colorado. Special issue: Advances in Remote Sensing of Crop Water Use Estimation. Remote Sensing, 2012, 4(11), 3619-3637; doi:10.3390/rs4113619

Varble, J.L, and J.L. Chávez. 2011. Performance evaluation and calibration of soil water content and potential sensors for agricultural soils in eastern Colorado. Agricultural Water Management Journal, 101: 93-106.