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Using a Handheld IRT to Determine Crop Water Stress and Use

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INTRODUCTION

In the Western United States as well as in other semiarid regions of the world, intensifying competition for limited water supplies between urban, industrial and agriculture uses continues to exert profound pressures on the agricultural sector. In the Western U.S., agriculture currently accounts for about 70 percent of consumptive water use (or evapotranspiration, ET), and its water rights are increasingly being transferred to municipal and industrial uses. Farmers in Colorado are allowed to transfer the portion of ET not used in the case when limited (deficit) irrigation practice is adopted. Therefore, there is a need to closely monitor actual crop water stress and water use (ET) so farmers and irrigation districts know how much water the crop uses and thus how much water was not used (the portion that may be approved for water rights' leasing or transfer).

Some researchers have investigated methods to capture crop water use and stress. Among numerous methods that have been developed in the past, there is the "Crop Water Stress Index" (CWSI) approach. This method was developed to obtain canopy temperature (T_c) using specialized infra-red thermometers (IRT) that account for sensor body temperature and surface emissivity. These IRTs have to be pointed in an oblique view and looking at the vegetation leaves only. However, these research grade IRT sensors are costly a need proper raw data processing. On the other hand, commercially available handheld IRT guns are easy to use and are not costly. In this study, the use of a commercially available handheld IRT for potential use with the CWSI method was evaluated in eastern Colorado.

MATERIALS AND METHODS

Application of the CWSI Method

The CWSI method was applied during the 2013 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 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 cover or satisfy the corn full water demand, deficit irrigation (TrT2, only two full irrigations), and reduced irrigation (TrT3, about half the amount of the full irrigation). 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) between the vegetation canopy and the air ($T_c - T_a$), and on upper and lower limits of this difference in temperatures, as indicated in Equation 1.

$$CWSI = (dT - dT_{LL})/(dT_{UL} - dT_{LL}) \quad (1)$$

where: subscripts LL and UL are the lower limit and upper limit of dT, respectively. Upper and lower limits of dT can be estimated following Idso et al. (1981). The dT_{LL} and air vapor pressure deficit (VPD) have a linear relationship for a fully irrigated (no water stress) crop under a given environmental condition. The dT_{UL} has a linear relationship with the so called vapor pressure gradient (VPG), when the crop is experiencing maximum water stress:

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

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

where: the “a” and “b” coefficients are the slope and the intercept of the linear relationship between dT_{LL} 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_{UL} has also been found to be relatively constant around 4 to 5 ºC for corn.

The lower limit occurs when the vegetation is experiencing no 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 coefficient for the lower dT limit, for several crops, can be found in Idso et al. (1982) and for corn in Colorado in Taghvaeian et al. (2012). The upper limit for dT, in contrast, occurs when the vegetation is not transpiring because of soil water limitations (most commonly); however, other types of constraints as high soil salinity concentration, toxicity, or even soil root zone waterlogging or high watertable can affect the ability of the plant to use existing water in the soil profile

To compute the vapor pressure deficit one needs readings of air temperature (T_a, ºC) and relative humidity (RH, %). Weather stations as the ones that are part of the COlorado AGricultural Meteorological nETwork (COAGMET) provide such data. One should be careful to use data from a weather station that is close to the field of interest, in a similar micro-climate, and under similar water management. 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 SI-121 infra-red thermometer (research IRT). 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 and the other south west at corn canopies. In addition, a nadir (straight down) looking Apogee SI-111 IRT was installed on the same mast where the Vaisala sensor was located; one sensor per treatment.

The Apogee IRTs manufacturer's specifications follow:

Apogee infrared radiometers are the most accurate non-contact temperature sensors available anywhere. The SI-121 has a 18 degree half angle field of view. The sensor has tinned leads for connecting to a datalogger. Applications include measuring the temperatures of road surfaces, plant canopies, and soil, snow and water surfaces. Measurement of surface temperature is a crucial component of energy transfer. Accurate measurement of the leaf-to-air temperature gradient is essential to the determination of transpiration rate and stomatal conductance in both single leaves and plant canopies.

Approximate Sensitivity: 40 µV per ºC

Output from Thermistor: 0 to 2500 mV (typical, depends on input voltage)

Input Voltage Requirement: 2500 mV excitation

Calibration Uncertainty (-20 to 65 C): 0.2 ºC, when target and detector temperature are within 20 ºC

Calibration Uncertainty (-40 to 80 C): 0.5 ºC, when target and detector temperature are different by more than 20 ºC

Measurement Repeatability: < 0.05 ºC

Stability (Long-term Drift): less than 2 % change in slope per year when germanium filter is maintained in a clean condition

Response Time: 0.2 s

Field of View: 18° half angle

Spectral Range: 8 to 14 µm; atmospheric window

Operating Environment: -55 to 80 ºC, 0 to 100 % relative humidity (non-condensing)

Dimensions: 2.3 cm diameter and 6.0 cm length

Mass: 190 g (with 5 m of lead wire)

Cable: 5 m of four conductor, shielded, twisted-pair wire. Additional cable available in multiples of 5 m. Santoprene rubber jacket (high water resistance, high UV stability, flexibility in cold conditions). Pigtail lead wires.

Data were sampled every three seconds and five minute averages were recorded by an on-site datalogger (CR1000, Campbell Scientific, Inc., Logan, Utah).

Once the corn water stress index was computed, the next computation was the actual corn water use or ET. This computation employs the stress index and the so called potential (no stress) crop (corn in our case) ET rate. Potential corn ET values were calculated by multiplying alfalfa reference ET (ET_r) by the sum of tabulated basal corn crop coefficients (K_{cb}) and surface evaporation coefficients (K_e), Hoffman et al. (2007). Daily ET_r values were computed using weather data from COAGMET, using the standardized ASCE alfalfa reference Penman-Monteith equation (ASCE-EWRI, 2005). The weather station was located approximately 1 km (0.63 miles) from the field site.

Evaluation of CWSI based on oblique Apogee IRTs

Estimated corn actual water use (ET_a), from the Apogee IRTs CWSI method, was evaluated using ETa values derived from a calibrated surface energy balance (EB) algorithm (Chávez et al., 2005).

Estimated corn actual water use (ET_a), from the Apogee oblique IRT-based CWSI method, was evaluated using actual ET values derived from a surface energy balance algorithm (Chávez et al., 2005). For this surface energy balance algorithm a surface bulk aerodynamic resistance model was used to obtain sensible heat flux (H, Equation 4).

$$H= \rho_a Cp_a (T_{aero}-T_a)/r_{ah} \tag{4}$$

where ρ_a is humid air density (kg m^{-3}), Cp_a is specific heat of dry air (1005 J kg^{-1} K^{-1}), T_a is average air temperature (K), T_{aero} is average surface aerodynamic temperature (K). T_{aero} (in ºC) can be expressed as (Chávez, 2005):

$$T_{aero}=0.49T_s+0.23T_a-0.13LAI-0.28U+2.02h_c-1.87Z_m+0.04RH+10.49 \tag{5}$$

where T_s is the surface radiometric temperature (°C) obtained using a nadir looking fixed Apogee IRT sensor, T_a is air temperature (°C), LAI is the leaf area index (m^2 m^{-2}), U is the horizontal wind speed (m s^{-1}), h_c is the crop height (m), and Z_m is the wind speed measurement height (m). Air temperature, and wind speed was collected in the field at two meters above crop height. Crop height was measured periodically through the growing season. LAI was estimated using surface reflectance data acquired with a MSR5 multispectral scanner (CropScan):

$$LAI=(4\ OSAVI-0.8)\times(1+4.73E\text{-}6\ EXP[15.64\ OSAVI]) \tag{6}$$

where OSAVI is the optimized soil adjusted vegetation index. Sensible heat flux was corrected for atmospheric stability conditions using an iterating method as described in Chávez et al. (2005).

Net radiation was calculated as:

$$R_n=(1-\alpha)R_s+\varepsilon_a\sigma T_a^4-\varepsilon_s\sigma T_s^4 \tag{7}$$

where R_n is net radiation (W m^{-2}), α is surface albedo, R_s is incoming shortwave radiation (W m^{-2}), σ is the Stefan-Boltzmann constant (5.67E-08 W m^{-2} K^{-4}), ε is emissivity, and T is temperature (K), with subscripts “a” and “s” for both air and surface, respectively.

Soil heat flux was calculated as Chávez et al. (2005):

$$G=[([0.3324+(-0.024\ LAI)]\times\{0.8155+[-0.3032\ln(LAI)]\})Rn] \tag{8}$$

where G soil heat flux in units of W m^{-2}. Latent heat flux could then be calculated from the energy balance equation:

$$LE=R_n-G-H \tag{9}$$

where, LE is latent heat flux (W m^{-2}). Hourly ET can be calculated using LE as:

$$ET_i=3600\ LE_i/(\lambda_v\ \rho_w) \tag{10}$$

where, ET_i is the hourly corn actual ET (mm hr^{-1}), ρ_w is the density of water (taken as 1000 kg m^{-3}), and λ_v is the latent heat of vaporization (J kg^{-1}) equal to ((2.501 – 0.00236 Ta) x 10^6), where Ta is in ºC. Daily ET can then be calculated, (Chávez et al., 2008), from hourly ET as:

$$ET_d = \left[\frac{ET_i}{(ET_r)_i}\right] \times (ET_r)_d \qquad (11)$$

where, ET_d is corn ET daily (mm d^{-1}), $(ET_r)_i$ is the alfalfa reference hourly ET (mm hr^{-1}), and $(ET_r)_d$ is the daily alfalfa reference ET rate (mm day^{-1}). This final corn ET_d value was used in the evaluation (comparison) of the oblique Apogee IRT CWSI-based corn ET_a values.

Handheld IRT Calibration

The use of a handheld IRT gun to measure canopy temperature was evaluated with the research grade oblique Apogee IRT. The purpose was to assess whether a relatively cheap IRT gun could be calibrated to be efficiently used by farmers with the CWSI to monitor crop water stress and use.

The commercially available handheld IRT used was the Ryobi[1] TEK 4 Model RP4030. Its retail cost is approximately $70 per unit.
Manufacturer's sensor specifications:

- Continuously, real-time, reads temperature of surfaces remotely
- Pro-Grade 10:1 Spot / Distance ratio – Accurately measures temperatures ranging from -4 to 590 degrees Fahrenheit (-20 to 310 º Celsius)
- Measurement Memory Function – Internal Memory stores up to 10 readings for easy comparison and convenient data logging
- Impact Resistant – Able to withstand the daily abuse of any tough job site environment
- Powered by Tek4 4-volt lithium-ion battery
- Backlit LCD display for easy reading
- Impact- and water resistant for use in tough environments
- Laser line to help indicate measurement spot
- Up to 4,000 measurements per charge
- Automatic shut-off

The handheld IRT gun data collection procedure was as follows. Readings were taken by standing by the stationary oblique Apogee IRTs, by the middle access row, pointing the IRT gun down the row at a vertical angle of roughly 45 degrees from the horizontal line mimicking the angle of the stationary oblique IRTs. The horizontal angle of the gun is roughly 45 degrees to measure only leaf temperature down the row of corn.
Once the gun was properly angled, the trigger was held down for approximately 10 seconds while the operator slowly moved it around to try to find the average canopy temperature of a small area of leaves. After the 10 seconds the reported average, minimum, and maximum temperature, from the scan displayed by the device, was written down before the procedure was repeated. On average, based on the angles of the gun and the distance to spot ratio of 10:1, it measured a spot about 3 m (10 feet) away, which would result in a footprint roughly 0.3

[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.

m (1 foot) in diameter. This was done standing on the ground (operator was 5', so height of gun was approximately 4'), for all four directions (NE, SE, SW, and NW), readings were taken, and then the average of the four measurements was used for analysis.

The following variables were considered in the calibration of the handheld IRT: air temperature, canopy temperature, wind speed, atmospheric (barometric) pressue, relative humidity, vapor pressure deficit, and leas area index (LAI). In the case of the handheld IRT gun calibration procedure, LAI was calculated using interpolated MSR5 (CropScan) multispectral surface reflectance data by first using Equation 12 to find the Normalized Difference Vegetation Index (NDVI):

$$\mathrm{NDVI} = (\rho_R - \rho_{NIR})/(\rho_R + \rho_{NIR}) \qquad (12)$$

where, ρ_R is the reflectance value in the red band and ρ_{NIR} is the reflectance value in the near infra-red band. NDVI was then entered into Equation 13 which correlates NDVI with LAI ($m^2\ m^{-2}$) for corn crops.

$$\mathrm{LAI} = \mathrm{EXP}(((\mathrm{NDVI}-0.6528)/0.1706)) \qquad (13)$$

where all variables have been previously defined (Wittamperuma, 2012) . LAI was included in the correlation analysis to see whether a plant biophysical parameter was correlated to the canopy temperature measurements (made with the Apogee IRT) of the crop and to assess whether it could be used in a multiple linear regression analysis to provide a calibration equation for crop canopy temperature measurements with the Ryobi handheld IRT gun.

Statistical Analysis

Statistical measures were computed to compare and evaluate each model-predicted (*P*) with the observed (*O*) values (%) taken from the field. These include the mean bias error (MBE; Equation 14), and the root mean square error (RMSE; Equation 15), as defined by Willmott (1982).

$$\mathrm{MBE} = n^{-1} \sum_{i=1}^{n} (P_i - O_i) \qquad (14)$$

$$\mathrm{RSME} = \left[n^{-1} \sum_{i=1}^{n} (P_i - O_i)^2\right]^{0.5} \qquad (15)$$

where *n* is the sample size.

First, all the weather station data from the Greeley 4 weather station nearby was compiled with 30 minute accuracy to provide the corresponding weather parameters which corresponded to each measurement of canopy temperature. Handheld IRT gun data were compared to the stationary oblique Apogee IRTs' canopy temperature data and the MBE and RMSE were determined. In addition, the least squares linear regression method was used in the evaluation.

RESULTS AND DISCUSSION

Evaluation of Apogee Oblique IRT derived CWSI-ETa

Data collected between July 22nd and August 31st of 2013 were used in the evaluation of the fixed oblique Apogee IRT S-121.

Two different times of the day of data acquisition were considered, i.e. 9-10 a.m. and 1-2 p.m. (MST). According to Idso, canopy temperature should be collected around 1 to 2 p.m. During the study period and the 9-10 a.m. time of the day, data corresponding to July 28th, 29th, and August 6th were not used since there was considerable cloud cover conditions (approximately 21, 55, and 45%, respectively). Therefore, those days were not included in the analysis. The CWSI is supposed to be applied with data collected under mostly clear sky conditions.

Figure 1 below shows the comparison of ETa obtained with both methods (CWSI and EB). The error MBE±RMSE in the estimation of ETa for the different treatments were: -1 mm d^{-1} (-0.04 in d^{-1}) ± 0.7 mm d^{-1} (0.03 in d^{-1}) for treatment 1 (TrT1), -1.7 mm d^{-1} (-0.07 in d^{-1}) ± 0.8 mm d^{-1} (0.03 in d^{-1}) for treatment 2 (TrT2), and -1.4 mm d^{-1} (-0.06 in d^{-1}) ± 0.8 mm d^{-1} (0.03 in d^{-1}) for treatment 3 (TrT3), respectively.

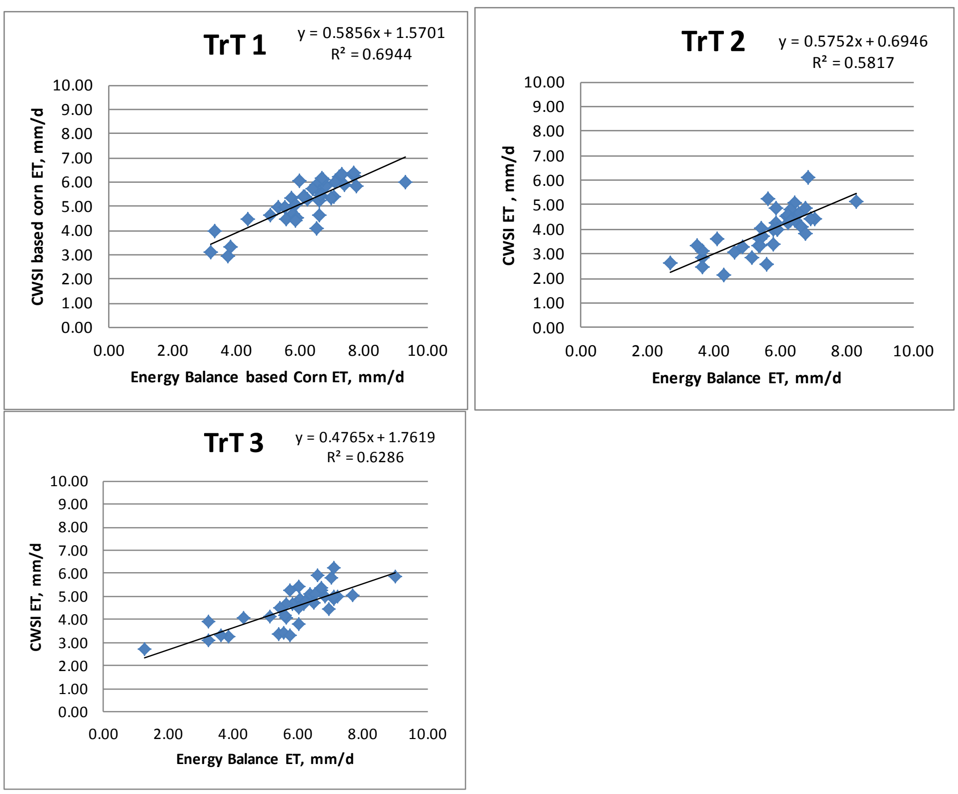

Figure 1. Actual corn ET (ETa) derived using the CWSI (Y-axis) vs. ETa from the surface energy balance algorithm (X-axis) for the three irrigation treatments (TrT) and with canopy temperature data collected between 9 and 10 a.m. (MST).

From these statistical results, it is evident that TrT1 (fully irrigated) resulted with the most accurate corn ETa estimation using the CWSI and oblique Apogee IRT data collected between 9 and 10 a.m. Although a general underestimation of ET (or overestimation of the CWSI) occurred.

The error for this treatment is within the range of errors in ET estimation found in the literature for a number of energy balance and combination methods. TrT3 showed a larger error than TrT1 with similar variability (standard deviation). TrT2 resulted with the largest under estimation of ETa, with larger errors shown for larger ET rates (i.e., smaller CWSI values). Some wetting events (e.g., irrigation and/or rainfall) may mask the true canopy temperature since for stress crops depicting less biomass (LAI) some wet soil background may be seen in the field of view of the oblique IRT and therefore resulting in a lower CWSI (larger ET). Thus, the importance to only target at plant canopy (narrower field of view of the IRT sensor) to avoid other surfaces.

In the case of data collected between 1 and 2 p.m., Figure 2 below shows the comparison of ETa obtained with both methods (CWSI and EB). The following days were excluded due to cloudy conditions during the 1-2 pm period: July 24, 28, and 29, and August 7.

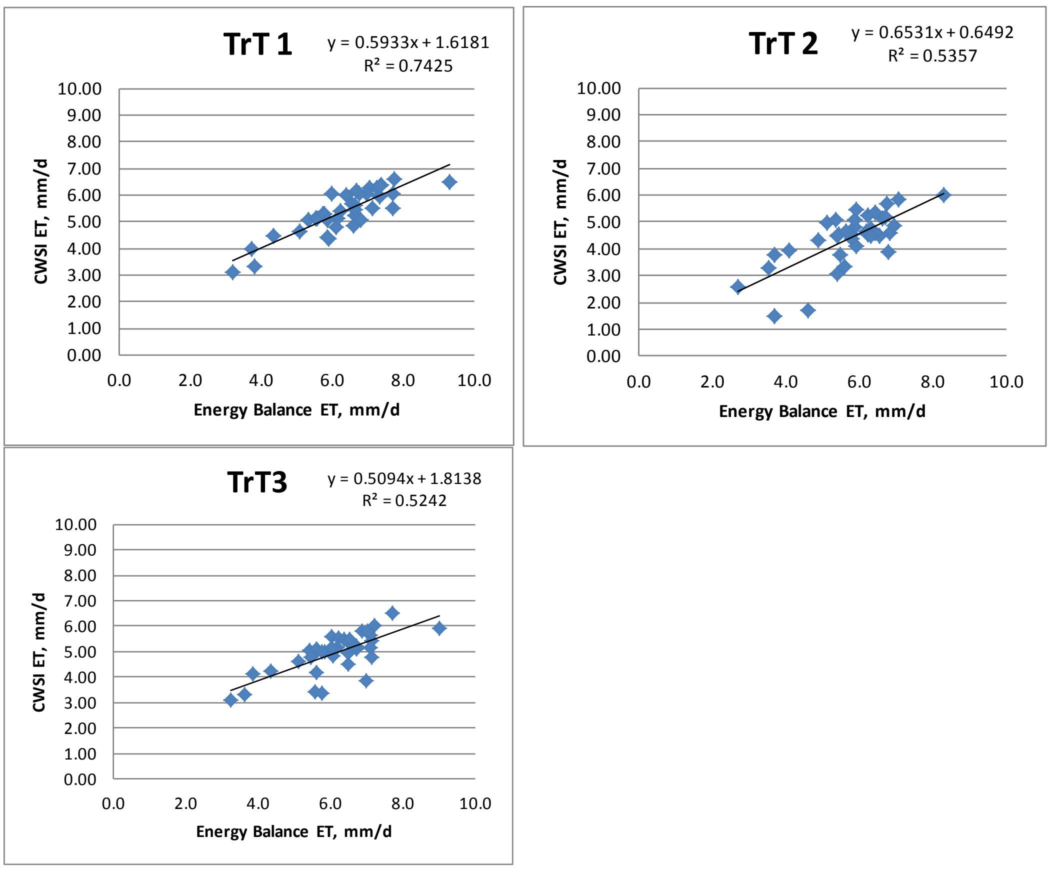

Figure 2. Actual corn ET (ETa) derived using the CWSI (Y-axis) vs. ETa from the surface energy balance algorithm (X-axis) for the three irrigation treatments (TrT) and with canopy temperature data collected between 1 and 2 p.m. (MST).

The error MBE±RMSE in the estimation of ETa, for the afternoon data collection, for the different treatments were: -0.9 mm d^{-1} (-0.04 in d^{-1}) ± 0.7 mm d^{-1} (0.03 in d^{-1}) for treatment 1 (TrT1), -1.3 mm d^{-1} (-0.05 in d^{-1}) ± 0.8 mm d^{-1} (0.03 in d^{-1}) for treatment 2 (TrT2), and -1.2 mm d^{-1} (-0.05 in d^{-1}) ± 0.8 mm d^{-1} (0.03 in d^{-1}) for treatment 3 (TrT3), respectively.
From these results in can be inferred that canopy temperature reading taken in the afternoon, between 1 and 2 p.m., were more effective in estimating corn ETa than readings taken earlier in

the morning when the corn has not shown or developed the water stress. For TrT2, errors in ETa estimation were much lower when the CWSI was computed using canopy temperature readings from 1-2 pm.

The evaluation of the Apogee oblique IRT CWSI-based ETa resulted in a somewhat under estimated ET value. However, the overall results indicate that the errors in ETa are within the uncertainty of complex energy balance algorithms (Gowda et al., 2008).

Handheld IRT Calibration

For all treatments, when comparing corn canopy temperature obtained with the Ryobi handheld IRT gun to similar values obtained with the Apogee oblique IRT fixed sensor, the MBE±RMSE was -1.7±3.3 ºC (or -6.4±12.2 %). This result indicates a somewhat large range (variability), general under estimation, of canopy temperature. It is hypothesize that the wide range in the errors of predicted canopy temperature is due to the sensor (handheld IRT) lack of compensation for the body temperature. Commercially available (low cost) IRTs do not have a thermocouple sensing the sensor body temperature which introduces noise in the sensor readings of target temperatures; and are limited on including (accounting for) surface long wave emissivity values. Therefore a calibration is needed. Research grade IRT sensors are calibrated using black bodies (Kalma and Alksnis, 1988). However, black bodies are expensive. Instead, an easy methodology to calibrate handheld IRT with accessible data is desirable.

When calibrating the Ryobi handheld IRT gun to the Apogee oblique IRT fixed sensor, the correlation analysis revealed that the most highly correlated independent variables were the handheld IRT (Ryobi) surface/canopy temperature (ºC) and the following weather variables obtained from the COAGMET weather station (Greeley 4): horizontal wind speed (m s^{-1}), shortwave solar radiation (W m^{-2}), air temperature (ºC), and vapor pressure deficit (kPa). It may be possible to obtain a higher correlation if the infield weather variables measurements are used for each treatment. However, since farmers would not be able to replicate (have in-field weather data) that, it was chosen to use the weather station data to simulate the data a farmer would have access to.

The highest coefficient of determination (R^2) obtained was 0.912, for Equation 16, using solver to minimize the RMSE for a multiple linear regression analysis, in the process to find coefficients for the variables mentioned above. The optimizing procedure was set to minimize the RMSE between the predicted canopy temperature (Ryobi handheld IRT gun) and the average canopy temperature measured by the SE and SW stationary Apogee oblique infra-red thermometers.

The resulting calibration equation was:

$$T_{pred}=0.17T_{Ryobi}+0.47u+0.69T_a-0.85VPD+0.06R_s+1.73 \qquad (16)$$

where, T_{pred} is the calibrated radiometric temperature (Apogee oblique IRT data) 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}), Ta or air temperature (ºC), VPD or vapor pressure deficit (kPa), and R_s the hourly shortwave incoming solar radiation (kJ m^{-2} min^{-1}).

CONCLUSIONS

The purpose of this study was to assess whether a commercially available low cost handheld infra-red thermometer (IRT) could be used to estimate corn water stress and water use or evapotranspiration.

Results indicate that a research grade (costly) IRT can be used to monitor corn water stress and use with certain associated uncertainty (determined).

A low cost handheld IRT is desirable to promote a wide adoption of the Crop Water Stress Index (CWSI) method to improve irrigation water management under full and deficit irrigation regimes.

The evaluation of the handheld IRT indicated that the sensor surface readings, in general, underestimate the true canopy temperature and present a relatively large standard deviation (or RMSE) most probably attributed to lack of correction for sensor body temperature. Therefore, a calibration of the handheld IRT is warranted to more accurately apply the CWSI.

In this study, the handheld IRT was successfully calibrated using weather data, from a COAGMET weather station, resulting with a high coefficient of determination. Thus, it is expected that the calibration developed will facilitate the use of the handheld IRT in the application of the CWSI to monitor the crop water stress and use.

The next step is to test and further developed the calibration equation and to test different brands of commercially available handheld IRTs.

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