Final Project Report

Project Title: Implementation of Deficit Irrigation Regimes: Demonstration and Outreach

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by

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Involved co-sponsors and collaborators: Colorado Northern Water Conservancy District, West Greeley Conservation District, Central Colorado Water Conservancy District, CSU Extension (Water Team), and USDA ARS Water Management Research Unit (Fort Collins, CO)

Introduction

The motivation for the research-outreach project was based on the pressure that irrigated agriculture is under to be more efficient (more crop per drop) in saving water (consumptive use) for other uses (e.g., water transfer to municipal, industrial, recreational, etc.).

The main objective was to evaluate the capability, in monitoring crop water stress (CWS) and crop consumptive use (CU) or evapotranspiration (ET), of some methods (e.g., infra-red thermometry/thermography (IRT) technology (ground-based remote sensing (RS), and/or airborne, satellite RS) for crops managed under limited/deficit irrigation (one alternative Ag water transfer method (ATM) as a mean to conserve CU). The second objective was to demonstrate the implementation of crop water stress monitoring through field days, workshop, and publications.

Methods

Below the different methods implemented, evaluated, demonstrated are listed.

<u>Crop coefficient (K_c)</u>: This approach is suitable to estimate crop water requirement at different stages of growth. Under crop water stress conditions, a crop water stress coefficient (K_s) is used to reduce the potential crop water consumptive use ($ET_c = ET_{ref} \times K_c \times K_s$), computed from weather data, in proportion to the soil moisture deficit, where soil moisture deficit is modeled or measured. This method does not require complex modeling and the analysis can be performed in electronic spreadsheets.

Dr. Allan Andales, a collaborator from the Soils and Crop Sciences Department (CSU), has developed an irrigation scheduling tool called WISE (Water Irrigation Scheduler for Efficient Application). The tool integrates crop coefficients (Kc), reference ET (ET_{ref}), modeling of soil water deficit to estimate the stress coefficient (K_s) to estimate actual crop water use or evapotranspiration (ET_c). And through a simplified soil water balance, with use input of irrigation amounts and precipitation (if measured in the field), then a type of check book/balance is implemented to estimate amounts of water needed and the timing of such.

Details on the tool can be found at: http://wise.colostate.edu/

The tool was implemented for a corn field near Fort Collins (CSU ARDEC) and was evaluated with soil water content readings from neutron probe and decagon 5TE sensors buried at two depths. Appendix A presents details on WISE. Appendix B refers to soil moisture sensors accuracy.

Canopy temperature (Tc): Previous studies have shown that canopy temperature is an effective indicator to determine crop water stress. Crop transpiration rate decreases as water becomes more limited in the root zone. Since transpiration is a major cooling process for plants, a decrease in the rate of this process translates into an increase in canopy temperature. By measuring canopy temperature, it is possible to quantify stress level, generate a crop water stress coefficient, and then calculate the transpiration rate using an estimate of reference evapotranspiration-ET (through weather data), all in a user-friendly spreadsheet format. This spreadsheet integrates the Tc data obtained with the IRT sensor as well as the weather data in an automated environment. Temperature measurements can be made using handheld Infra-red Thermometers (IRTs), which are now available at high accuracies and prices that are lower than most smart phones. In this demonstration project, two different handheld IRT models (varying in cost and sophistication) were used to measure Tc on a biweekly basis. These IRTs include mobile and stationary units. Sensor calibration procedures are presented in Appendix C.

The detailed step by step implementation of canopy temperature measured with an IRT in the crop water stress index (CWSI) model is included in Appendix D.

Crop Water Stress definitions

- "Stress," in the context of plants, is a broad term used to describe some type of adversity that, if prolonged, can result in economic yield loss (Jackson, 1982).
- "Water stress" then describes a condition where the supply of water in plant leaves is insufficient to carry out photosynthesis and respiration using all available energy.
- Under water stress conditions, a greater amount of available energy must be converted to sensible heat compared with what would have occurred for non-water-stressed conditions. The result is that the temperature of the plant canopy increases over the temperature that would have resulted for no shortages in water.

How to monitor crop water stress?

- By measuring or estimating crop water use and comparing resulting values to non-stress crop water use
- Crop water use = crop evapotranspiration = E + T = ET

where: E = evaporation and T = transpiration

- ET = (Kcb Ks + Ke) ETref
- ET from a soil water balance (soil water sensors)
- ET from remote sensing sensors
- ET from micro-meteorological heat flux towers (e.g., EC)
- ET from lysimeters
- ET from plant heat balance or heat pulse techniques

IRTs

There is a variety of IRT technologies commercially available. From cheap ($75-100) handheld IRT guns/sensors to research grade ($750) stationary IRTs that provide point measurements to handheld thermal cameras (~$5,000-40,000) and specialized cameras for airborne platforms (~$50,000-90,000). Figure XX below depicts some of these thermal technologies.

Figure 1. Infra-red thermometry/thermography technologies.

In this study, several research grade IRTs (Apogee) were installed in a corn field near Greeley, CO. The data from these IRTs were used to calculate crop water stress/use and to evaluate and calibrate a cheap commercially available IRT gun (Ryobi).

The Crop Water Stress Index (CWSI; Jackson et al., 1981; Idso et al., 1981) has received the most attention of any water stress index. It is derived from the energy balance where, for a given set of meteorological conditions, a range of canopy minus air temperature differences exist that are bound by a lower limit (no water stress) and an upper limit (complete water stress where no ET is occurring). The measured canopy - air temperature difference should fall within these lower and upper limits, and is normalized as an index where zero indicates no water stress and one indicates complete water stress. It is to be used with an infrared "gun" sensor to monitor crop canopy temperature (Tc). Simultaneously measure air temperature (Ta) and vapor pressure deficit (VPD = $e_s – e_a$), with thermometer and humidity sensor. When Tc – Ta deviates from a "baseline" of Tc – Ta vs. VPD the crop is stressed and it is time to irrigate. Tc increases due to stress, and Tc – Ta becomes more positive and the point rises above the baseline. This method should always be used between 12:00 noon and 2:00 pm, and on sunny days, for consistency in measurements.

Landsat NDVI: Remote sensing images (multispectral) from satellites such as Landsat are processed by the USGS and made available to the public at no cost. Products such as the Normalized Difference Vegetation Index (NDVI) can be generated from these images by following a few simple steps. According to previous studies, NDVI can be directly related to crop coefficient. For example, Neale et al. (1989) conducted a comprehensive study between 1981 and 1986 at two sites near Greeley and Fruita, Colorado, and found that NDVI-based estimates can be used accurately to estimate corn Kc. The pixel size of NDVI images is less than 100 ft × 100 ft and temporal frequency of overpass is every 16 days, so they can be used to map water use over larger areas. The required analysis to generate NDVI maps and to convert them to distributed Kc is relatively simple and can be performed using open-source software packages that are available free of charge. A selected package will be made available to users (e.g., irrigation districts, water managers, etc.) along with a manual that describes the procedure and implementation steps.

Landsat NDVI-surface temperature: NDVI images can be combined with Landsat surface radiometric temperature images to increase the accuracy of estimated water use. Compared to the NDVI method, the NDVI-surface temperature method requires a few more implementation steps. However, this method is still much simpler than other remote sensing methods and can be applied by a technician without the knowledge of solar radiation interaction with land surfaces. Landsat has a wide swath (115 miles). Therefore, a single image provides maps of Kc and consumptive use over large irrigated areas. This extensive spatial coverage makes the last two techniques appropriate for ditch level analysis. CSU engineering in cooperation with Northern Water has developed the ReSET (Remote Sensed ET) method.

A ground-based version of the NDVI product will be derived from data collected using a hand-held multispectral radiometer which has similar spectral bands as Landsat sensors. This product will serve as a verification of the quality of the Landsat product. Readings with the radiometer will be taken weekly to bi-weekly concurrently with IRT readings and neutron probe soil moisture readings on all fields and treatments/plots involved in the project.

Results

Crop Coefficients (Kc) approach

The WISE tool (on line) seems to be a feasible option to estimate crop water requirements (amounts needed) and schedule irrigations. The tool seems to work well for well managed/irrigated fields. The overall discrepancy, when compared to soil water content measurements, seems to be in the order of 13-15% on a seasonal basis (amount-wise). However, for deficit/limited irrigation strategies the error may me larger due to some bias in the estimation of the crop stress coefficient (FAO method). Figure 2 below shows a soil water deficit graph where WISE estimated less soil water deficit than the actual for the deficit irrigation plot (at CSU ARDEC). The Ks estimated with the FAO method in WISE is over-estimated (larger values) which causes the resulting ETc to not be reduced enough to reflect actual field conditions and therefore the deficit is less than the actual. One possible source of error, in the soil water balance, that may have contributed to this result is the accuracy of irrigation and rainfall amounts that the user enters in WISE. For instance, for the deficit irrigation plot since in Figure 2, the field log book indicated two irrigations applied for that plot (303) when in reality no irrigation occurred (as shown by the buried soil water content sensors). However, the trend of deficit with WISE follows very well the trend when measured soil water content (neutron probe) was used.

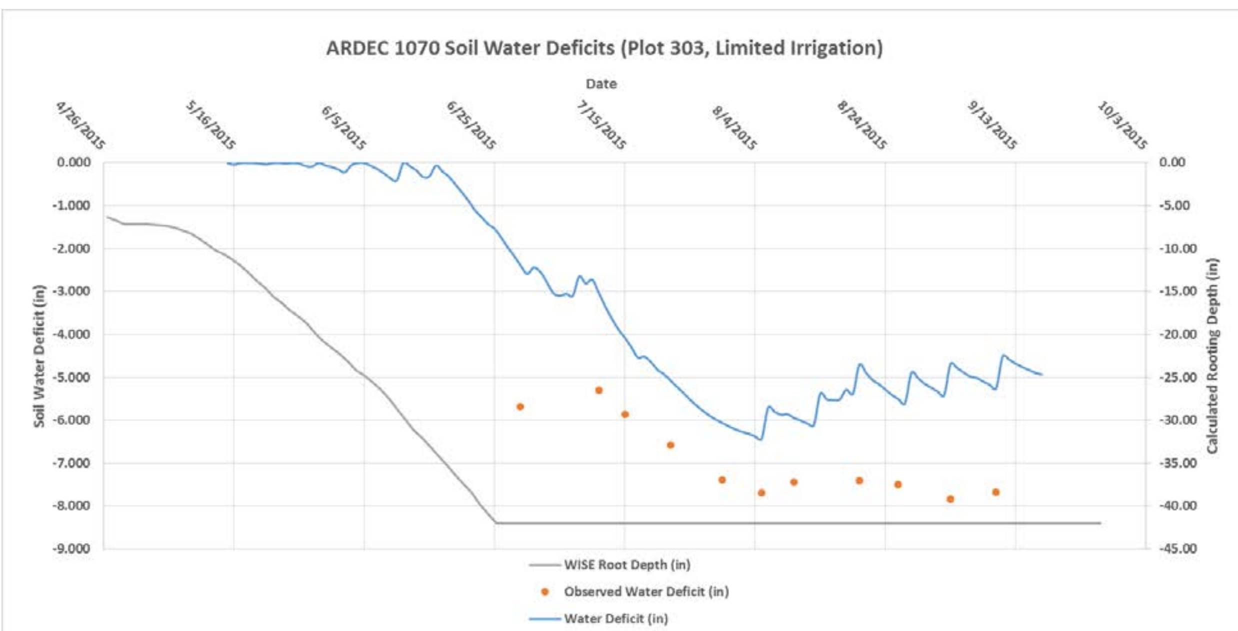


Figure 2. WISE tool soil water deficit graph for a deficit irrigated corn field near Fort Collins, CO in 2015.

Thus, there seems to be a need of some calibration for the deficit/drought irrigation conditions. Specifically, adjustments need to be made on how the stress coefficient (Ks) is calculated. Future work will be directed to incorporating estimates of Ks using remote sensing techniques.

This is a promising tool to aid in the appropriate management of deficit/limited irrigation. Appendix A details step by step how to use WISE.

Soil moisture sensors data to estimate CU

Figure 3 below shows the typical behavior or response of a manufacturer's laboratory calibrated sensor. There is an obvious over estimation of the true soil water content in addition to a diurnal variability of readings influenced by the diurnal pattern of soil temperature.

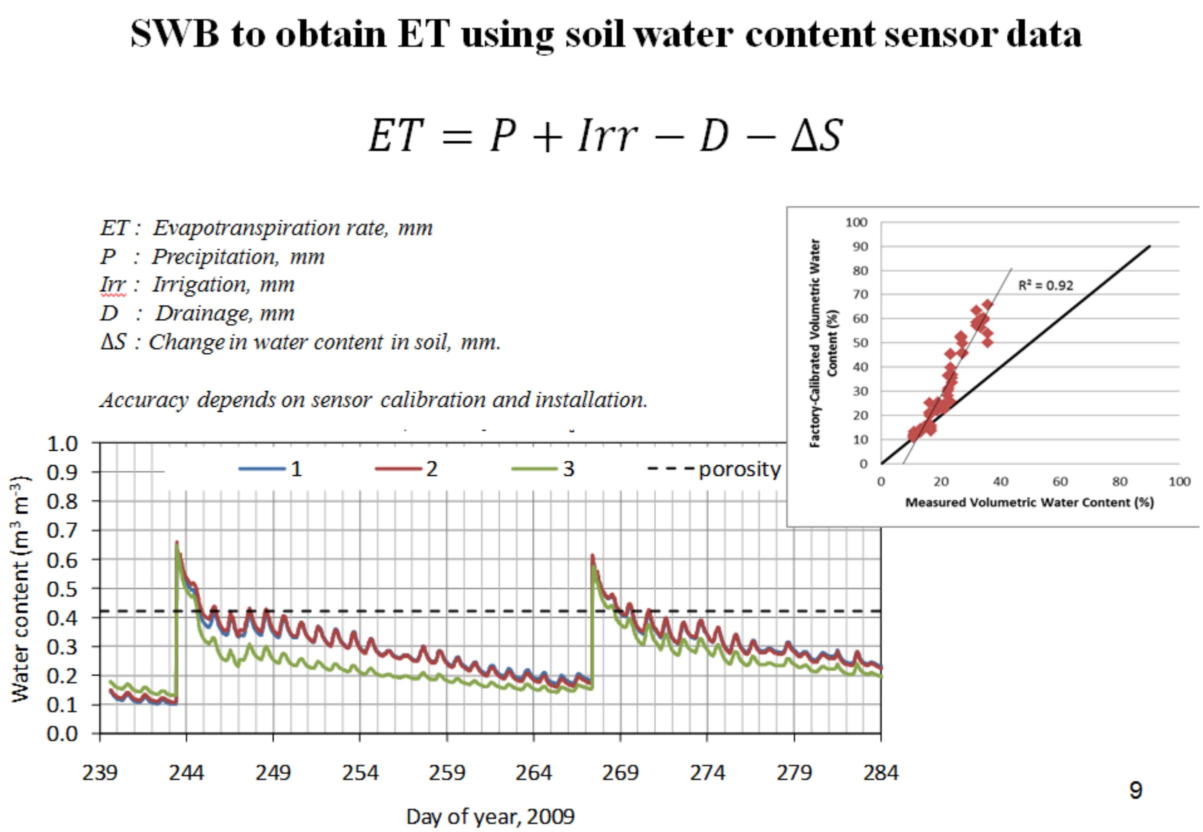


Figure 3. Typical soil water content data pattern of sensors used in field operations without a field or in-situ calibration.

Therefore, using soil water content sensor data, in the soil water balance, to estimate crop actual ET (ETa) demands well calibrated and well installed sensors throughout the soil root zone. Estimates of ET and soil water deficit only represent a very small area of the field. The cost of one sensor varies from $120 to $300 depending on technology. Moreover, the cost increases when a datalogger cost is considered and the fact that more than one sensor per location (root zone), and more than one location per field, may be needed. Thus, this technology is very limited in its capability to assist in the efficient monitoring of deficit/limited irrigated field crops. It requires training of the user and a close data quality control and quality assurance.

Use of Infra-Red Thermometers (IRT) to monitor crop water stress

Canopy temperature recorded with an IRT is related to water status of plant and soil. This is true because the ET process cools the plant. Therefore, a well-watered plant will present lower tissue temperature than a non-well watered plant. If the actual crop evapotranspiration (ETa) is less than the potential ET (ETp), of well watered conditions, then the plant heats up. This vegetation temperature can be measured by non-contact infrared thermometers.

Below, Figure 4 shows the canopy temperature contrast between a well irrigated corn plot versus a deficit irrigated plot, near Greeley, CO, using FLIR infra-red thermography.

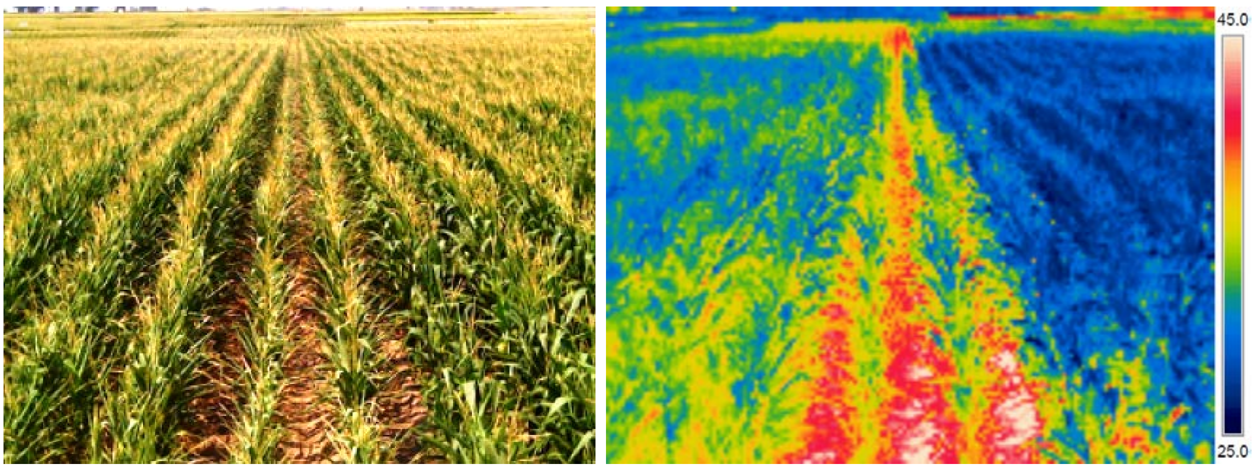


Figure 4. Contrast of temperatures between well irrigated (right) and deficit irrigated (left) corn plots.

The above figure shows that infra-red thermography (also thermometry) is capable of capturing canopy and soil temperature from different irrigation strategies (e.g., full to limited irrigation). The fully irrigated plot (right figure) had a corn temperature range of 28 to 31 °C (82.4 – 87.8 °F), while the stressed limited irrigated plot (left figure) had a corn temperature range of 32 to 34 °C (90 – 93.2 °F).

IRTs need sensor body temperature and thermal emissivity corrections. Users of IRTs cannot use the temperature read by the sensor if the temperature value has not been corrected for sensor body temperature. This is, as the sensor heats up for exposure to solar radiation and ambient temperature then the recorded thermal readings are affected and therefore the error needs to be removed through a calibration developed by the manufacturer. Most professional IRTs do have a thermocouple measuring sensor body temperature. In addition, IRTs not only register the thermal signal from the target (e.g., crop canopies) but also from background (e.g., sky temperature) and need to be corrected for its effect as well as for surface thermal emissivity effects. In the Appendix C, a procedure to calibrate Apogee IRTs has been inserted.

Evaluation and calibration of a commercially available handheld IRT (gun)

An inexpensive handheld IRT gun Ryobi TEK 4 Model RP4030 was evaluated using a research grade IRT model SI-111 from Apogee. Figure 5 shows the overall under-estimation of crop canopy temperature by the Ryobi IRT. Therefore, the sensor is not reliable and accurate for routine true canopy temperature readings. Thus, a good calibration for this type of tool is needed and strongly recommended. Potential reasons for the lack of accuracy of the Ryobi sensors (and variability in the readings) may include: a) sensor not correcting readings for sensor body temperature, b) surface thermal emissivity corrections not incorporated in sensor, c) readings affected by relative humidity and wind effects, etc.

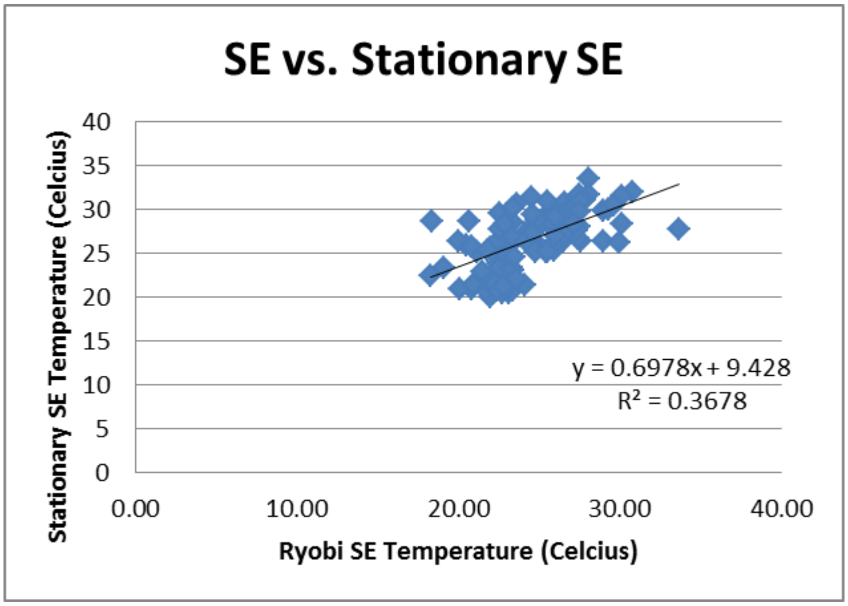


Figure 5. Ryobi IRT vs Apogee IRT corn canopy temperatures obtained near Greeley, CO.

A calibration was attempted on the Ryobi IRT. Below the equation obtained is depicted.

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

Where,

T_{pred} = predicted target temperature, ºC

$\boldsymbol{T_{Ryobi}}$= Ryobi IRT temperature measurement, ºC

u = wind speed, m/s

T_a = air temperature, ºC

VPD = vapor pressure deficit, kPa (i.e., e_s-e_a)

Rs = solar shortwave radiation, kJ m^{-2} min^{-1}

Thus, including the weather variables wind speed, air temperature, vapor pressure deficit and solar radiation helped improve the quality/accuracy of the Ryobi sensor target temperature readings.

Independent data were used to evaluate (with Apogee IRT sensor data) the calibration equation shown above. Below Figure 6 shows the performance of the calibrated Ryobi corn canopy temperature data. The figure shows that the calibrated Ryobi temperatures much better matched true temperatures measured with the research grade Apogee IRT (SI-111).

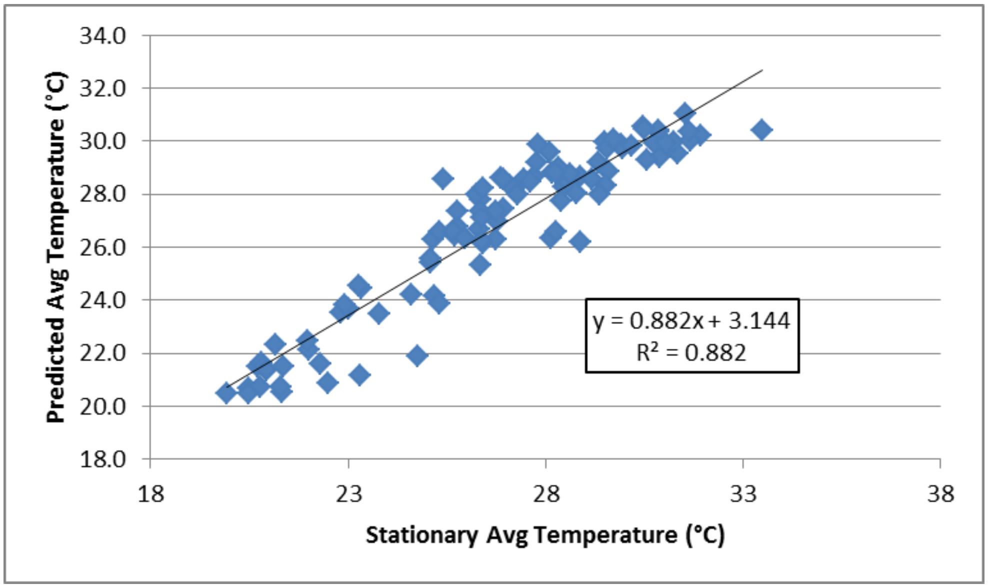


Figure 6. Calibrated Ryobi vs Apogee IRT corn temperatures.

Crop Water Stress Index (CWSI)

<u>Evaluation</u>:

A land surface energy balance (SAT) algorithm (Chávez et al., 2005) was used to evaluate the CWSI performance for data collected on corn fields near Greeley, CO, managed under full and deficit irrigation. Results are shown in Figure 7 below. The CWSI method tends to under-estimate ETa by as much as 40% for stressed corn (limited/deficit irrigation). The mean bias error was -0.04 inches per day and the associated root mean square error was 0.03 inches per day. The possible reasons for the under performance of the CWSI could be: a) the calculation of the upper limit (stress boundary) for the dT (dTmax) that seems to be under-estimated resulting in a larger CWSI than the actual value; and b) the field of view (FOV) of the IRT (oblique looking) sensor reading/recording not only canopy temperature but also some soil background temperature which results in a larger target temperature than the true canopy temperature.

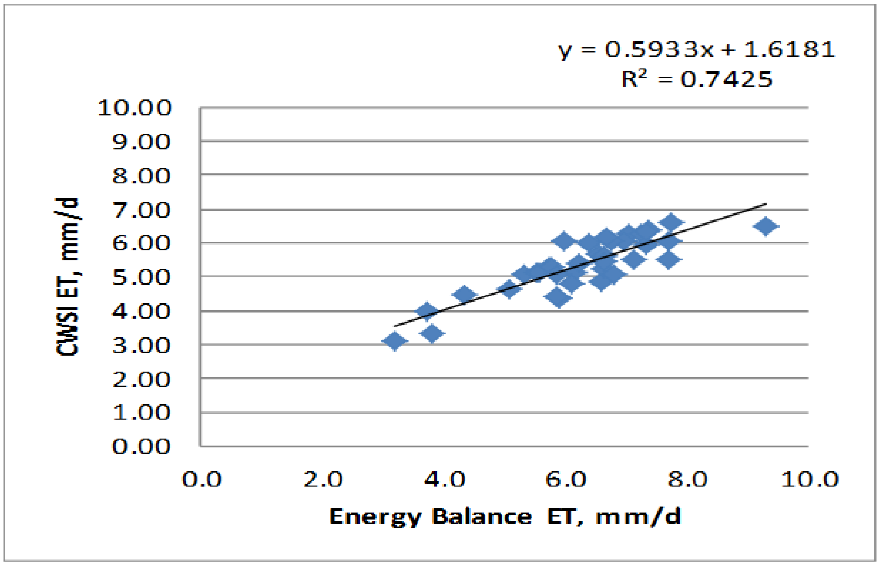


Figure 7. Comparison of estimated actual corn ET from CWSI vs ET from the SAT method.

Below Figures 8 and 9, for data collected near Iliff, CO, depict similar results as the ones obtained from the Greeley area. In this study, the crop water use estimated with the CWSI method was 147 mm or 5.8 inches (actual crop water transpiration) while the SAT method ETa was 174 mm or 6.85 inches (actual crop/soil evapotranspiration) for a period between August 5th and September 2nd. While the potential corn ET (ETp) was 200.9 mm (8 inches) for the same period. Results indicate that there was a good agreement between the CWSI and the SAT ETa calculations in early August and then some discrepancies later on due to some soil background effects (stress plots with less biomass) and difference between Ta and ETa. These results indicate the need to better discriminate canopy temperature from surface radiometric temperature obtained with the IRT sensor.

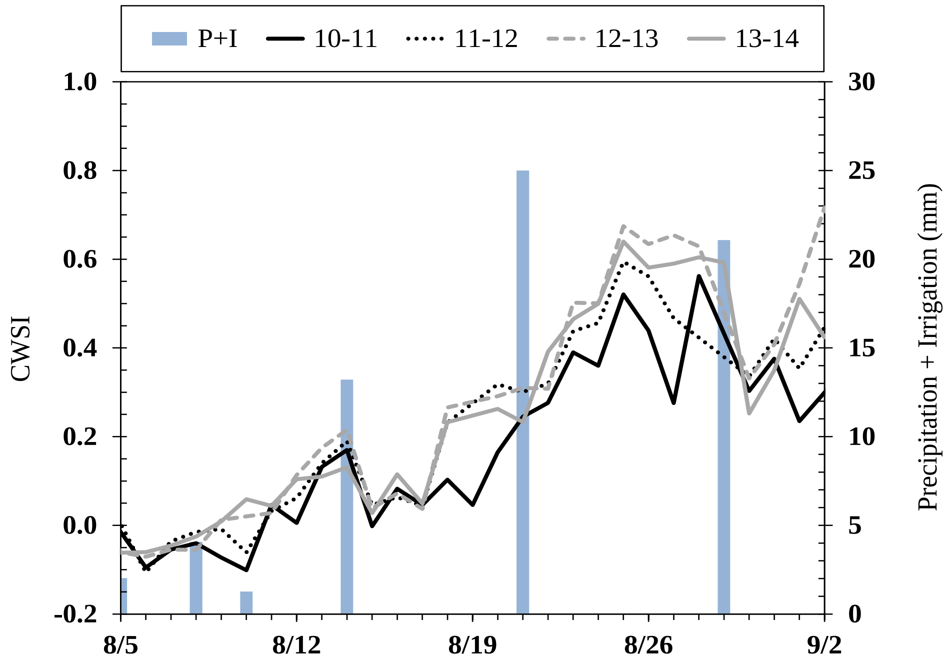


Figure 8. Corn CWSI calculations for four different periods in the day near Iliff, CO.

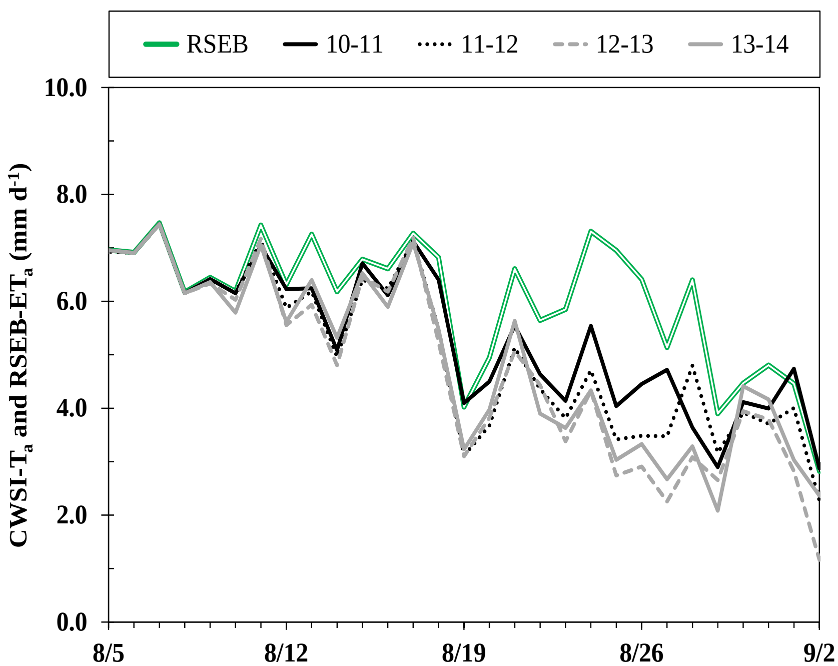


Figure 9. Corn water use (CWSI and SAT or RSEB) calculations for four different periods in the day near Iliff, CO.

Limitations:

The accuracy of the CWSI can be limited when **VPD** is low. As VPD decreases, the range of temperature limits becomes smaller, and the distances between points X, Y, and Z in graph decrease. The result is that small errors in $(T_C - T_A)_M$, $(T_C - T_A)_{LL}$, and $(T_C - T_A)_{UL}$ will lead to increasingly larger errors in CWSI, increasing the probability of out-of-bounds CWSI values; i.e., less than zero and greater than one. Colaizzi et al. (2012)

Somewhat related is the influence of incoming solar irradiance, where overcast skies also reduce the range of temperature limits. Both conditions are more prevalent in humid climates, but in arid and semiarid climates, low **VPD** is common in the morning (especially over irrigated fields) and greater cloud cover occurs frequently in the afternoon during summer months. Consequently, the CWSI is less responsive to plant and soil water conditions in humid locations, and has been found to be most responsive during clear skies and within a few hours of solar noon. Colaizzi et al. (2012)

Incomplete canopy cover is also a serious limitation of the CWSI, which exists during some (and perhaps all) of the irrigation season. The temperature of dry, sunlit soil is typically 30 °C greater than green, transpiring vegetation (Kustas and Norman, 1999).

Therefore, TC measurements can be greatly overestimated, resulting in overestimates of CWSI if soil appears in the radiometer field of view. The temperature of shaded soil is also usually different from vegetation, which may also introduce errors in CWSI calculations.

The view of vegetation can be maximized and soil minimized by pointing a radiometer at an angle and perpendicular to crop rows (e.g., Colaizzi et al., 2003a), and the radiometer can be designed to have a smaller field of view (e.g., O'Shaughnessy et al., 2011b). However, the radiometer view still may not be completely free of soil, especially early in the season. Colaizzi et al. (2012)

Ground-based NDVI approach

Kullberg (2015) investigated different crop water stress methods in her Master of Science Thesis entitled "EVALUATION OF STRESS COEFFICIENT METHODS TO ESTIMATE CROP EVAPOTRANSPIRATION" using data from the Limited Irrigation Research Farm (LIRF) near Greeley, CO, managed by the USDA ARS.

Below the ratios or coefficients evaluated are shown. Description on each method can be found in Kullberg, Emily (2015). "EVALUATION OF STRESS COEFFICIENT METHODS TO ESTIMATE CROP EVAPOTRANSPIRATION," M.S. Thesis, Civil and Environmental Engineering Department, Colorado State University, Fort Collins, CO. Published on-line at:
https://dspace.library.colostate.edu/handle/10217/167166

$$ET_a = (K_{cb}K_s + K_e)ET_{ref}$$

Crop Water Stress Methods

- CWSI: $CWSI = \frac{dT_m - dT_{LL}}{dT_{UL} - dT_{LL}}$ $\quad K_{S\ CWSI} = (1 - CWSI)$
- T_c ratio: $K_{s\ TcRatio} = \frac{T_{cNS}}{T_c}$ $\quad Ks$ = stress coefficient
- NDVI ratio: $K_{s\ NDVIratio} = \frac{NDVI_s}{NDVI_{ns}}$ $\quad NDVI = \frac{R_{nir} - R_{red}}{R_{nir} + R_{red}}$
- DANS (Degrees Above Non-Stressed): $DANS = T_c - T_{cNS}$

$$K_{S\ DANS} = \max\left(1 - \frac{DANS}{x}, 0\right)$$

- DACT (Degrees Above Canopy Threshold): $DACT = \max(0, T_c - T_{critical})$

$$K_{s\ DACT} = \max\left(1 - \frac{DACT}{y}, 0\right)$$

Collaboration with USDA ARS 45

Considering all treatments and both years, optimized values for “x” and “y” used in this study were 29.1 and 27.7, respectively.

$$ET_a = (K_{cb}K_s + K_e)ET_{ref}$$

Basal crop coefficient (K_{cb}) methods

- NDVI: $NDVI = \frac{R_{nir} - R_{red}}{R_{nir} + R_{red}}$

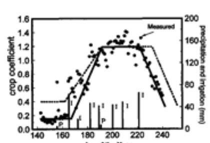
$$K_{cb\_refl} = 1.181(NDVI) - 0.026$$

- Crop percent cover (CC) or fractional vegetation (f_c) cover:

$$f_c = 1.22(NDVI) - 0.21$$

$$K_{cb\_refl} = 1.13 \cdot f_c + 0.14$$

- Tabulated K_{cb}: FAO paper 56



46

Evaluation (with neutron probe SWB ETa) of several temperature and reflectance based Ks and Kcb methods, as shown in Figures 10-13, indicated that the CWSI and DACT approaches were equivalent in estimating Ks and that a combination of Ks(CWSI) and Kcb(NDVI) estimates seems to contribute to a more accurate estimation of ETa. Therefore, based on ground measurements of corn canopy reflectance, the NDVI or reflectance based crop coefficient (Kc_refl) alone seems to not fully capture crop water stress but instead when it is combined with a crop water stress (Ks) derived from a CWSI calculation then the estimation of corn consumptive (water) use is more accurate (including deficit irrigation plots). This result was based on comparisons of plant water use measured with a neutron probe volumetric water content values.

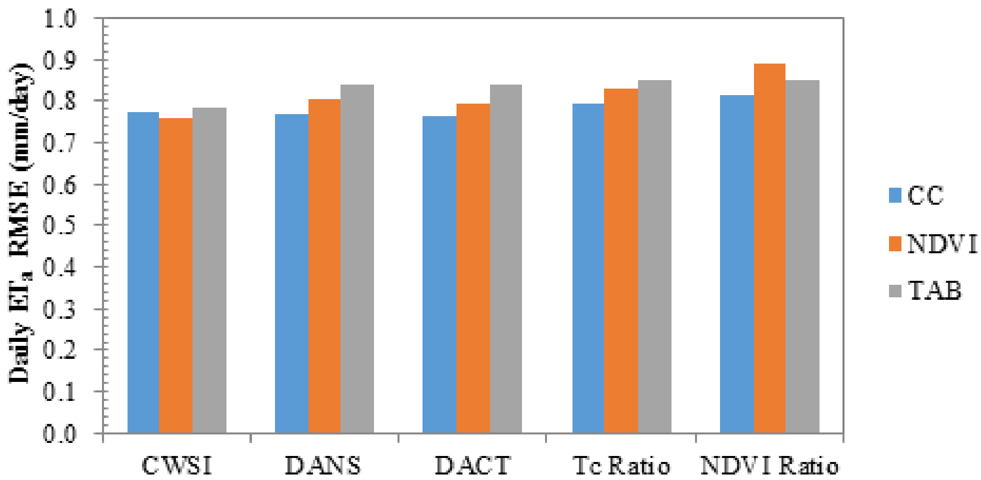


Figure 10. Daily ET_a estimate Root Mean Square Error or RMSE (mm/day) of each K_s and K_{cb} combination in 2013.

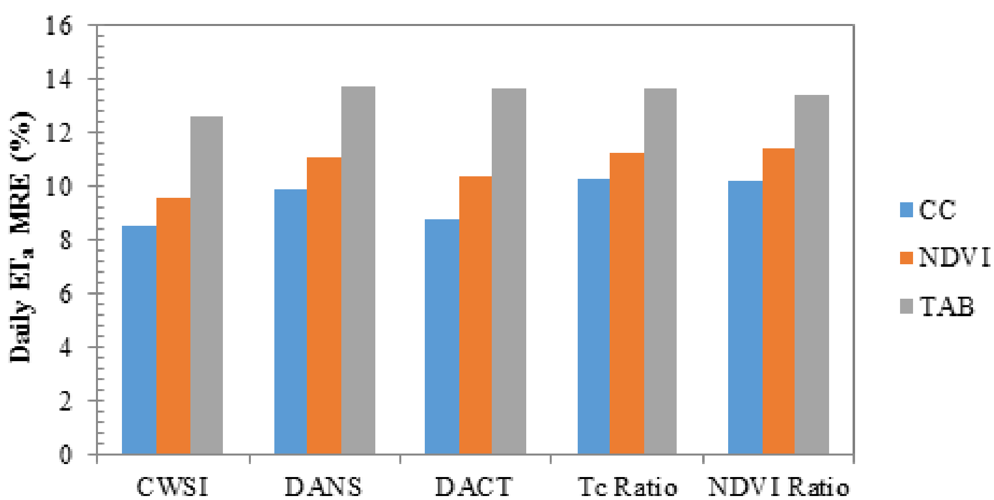


Figure 11. Daily ET_a estimate Mean Relative Error or MRE (%) of each K_s and K_{cb} combination in 2013.

Figure 12 below shows the good agreement between CWSI derived corn water use (ETa) and measure ETa values derived from a soil water balance using measure volumetric soil water content values obtained with a neutron probe/gauge.

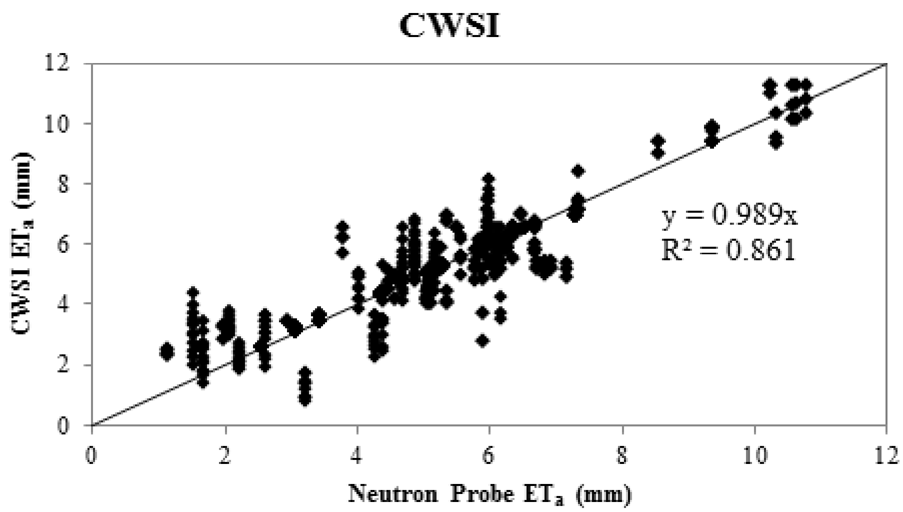


Figure 12. Scatterplot of CWSI ET_a vs. Neutron Probe ET_a (mm), R^2 = 0.86.

There seems to be evidence, in this study, that the crop stress coefficient (Ks) estimation can be improved when CWSI or DANS, DACT are used. Their use may help estimate better ETa.

In Figure 13 below, green shaded cells depict lower root mean square errors (RMSE). This is, when a given crop stress coefficient performed better. For instance, for a deficit irrigation treatment like number 3 where 80% of ET was irrigated during the crop vegetative growth period and also 80% of ET was irrigated during the maturity growth stage, the most favorable combination of coefficients was the NDVI based Kcb (basal crop coefficient) with the CWSI derived crop stress coefficient (Ks) and closely followed by the other approached including the NDVI ratio for Ks estimation.

		Irrigation Treatment (% ET applied in vegetation period/% ET applied in maturation period)					
		1 (100/100)	2 (100/50)	3 (80/80)	6 (80/40)	8 (65/40)	12 (40/40)
CC Kcb	CWSI Ks	0.54	0.57	0.64	0.93	0.89	0.95
	DANS Ks	0.52	0.58	0.67	0.87	0.86	1.00
	DACT Ks	0.51	0.53	0.63	0.85	0.87	1.04
	Tc Ratio Ks	0.52	0.59	0.68	0.92	0.87	1.05
	NDVI Ratio Ks	0.56	0.56	0.65	1.07	0.88	1.01
NDVI Kcb	CWSI Ks	0.65	0.58	0.59	0.91	0.82	0.93
	DANS Ks	0.64	0.60	0.63	0.94	0.82	1.08
	DACT Ks	0.65	0.57	0.62	0.91	0.84	1.08
	Tc Ratio Ks	0.64	0.61	0.64	1.01	0.82	1.12
	NDVI Ratio Ks	0.68	0.66	0.63	1.21	0.83	1.14
Tabulated Kcb	CWSI Ks	0.61	0.65	0.67	0.85	0.90	0.95
	DANS Ks	0.64	0.75	0.72	0.89	0.92	1.06
	DACT Ks	0.65	0.72	0.74	0.87	0.96	1.04
	Tc Ratio Ks	0.64	0.75	0.72	0.95	0.92	1.06
	NDVI Ratio Ks	0.64	0.75	0.72	0.95	0.92	1.06

Figure 13. Average daily ET_a RMSE (mm) by treatment.

Landsat NDVI approach

When ReSET was used to evaluate estimates of ETa using reflectance (NDVI or Normalized Difference Vegetation Index) based crop coefficients (Kcr), it was found that the Kcr method based on NDVI (and also SAVI) performed somewhat similar to ReSET starting around the mid vegetative growth stage and into the mid reproductive growth stage.

Three different Landsat NDVI (and SAVI or soil adjusted vegetation index) were evaluated with ReSET:

model **1**: Reflectance-based crop coefficient (grass ref.), kcbo.

Where: Kcbo =1.13 x fc+0.14, and fc = 1.22 x NDVI - 0.21.
fc = fractional cover
ETa = Kcbo x ETo;

model **2**: Reflectance-based crop coefficient (alfalfa ref.), Kcr1:

Where: Kcr1 =1.184 x NDVI - 0.026
ETa = Kcr1 x ETr

model **3**: Reflectance-based crop coefficient (alfalfa ref.), Kcr2:

Where: Kcr2 =1.416 x SAVI + 0.017
ETa = Kcr2 x ETr

Figure 14 shows the typical result obtained near Greeley, CO for corn fields, in 2015. Where models 2 and 3 (described above), purple and green lines respectively, agreed well with ETa from ReSET during the vegetative corn growth stage and beyond for a limited irrigated field.

Figure 15 shows a similar graph for an alfalfa field near La Salle, CO, in 2010. Thus, further evidence that the reflectance based crop coefficients (e.g., based on NDVI) may be an alternative to complex surface land energy balance methods for routine monitoring of crop water use or ET under different irrigation management strategies.

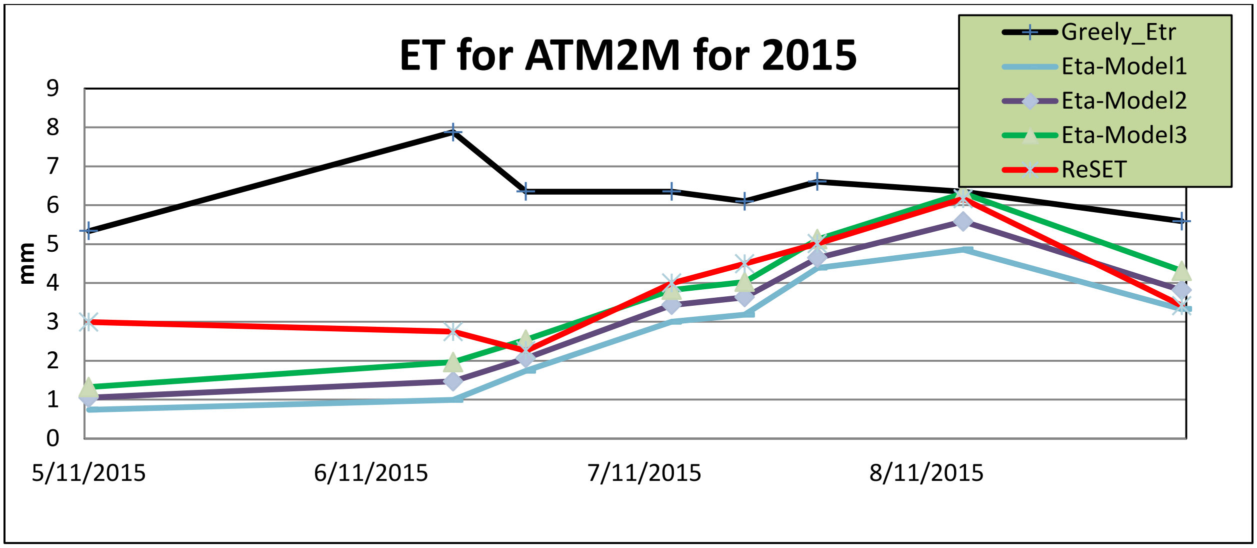


Figure 14. Corn ETa derived from Landsat satellite imagery for thee reflectance based methods and one energy balance based method (ReSET).

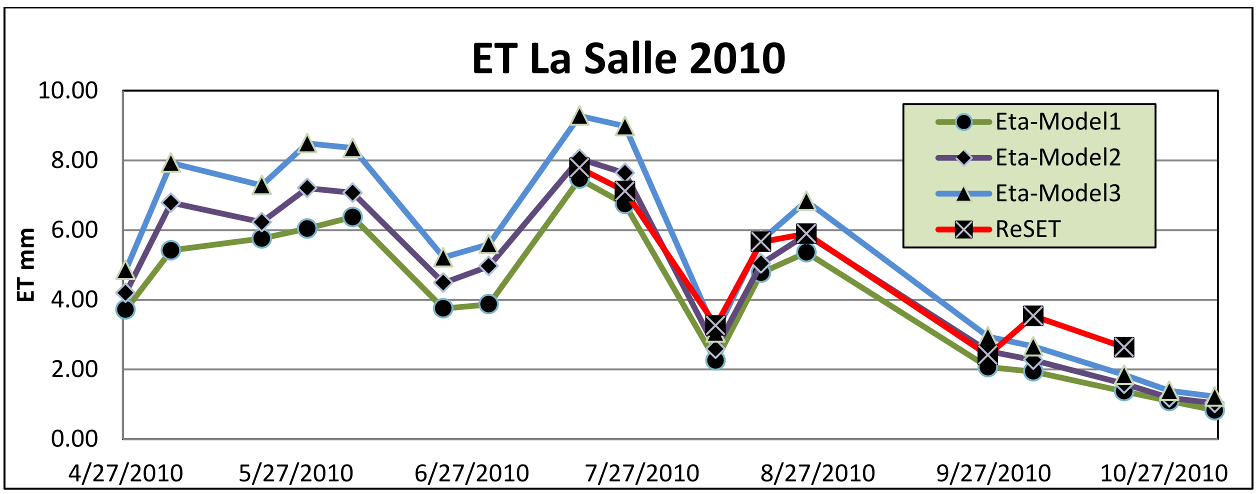


Figure 15. Alfalfa ETa near La Salle, CO, in 2010 derived using Landsat images and three reflectance based methods and one energy balance based method (ReSET).

Therefore, this results could be in indication that a simple reflectance based linear equation (combined with weather station data based reference ET) may be as effective as a full land surface energy balance approach/algorithm (as ReSET, METRIC, SEBAL) in estimating actual crop water use (ETa) for full and deficit irrigation regimes.

ReSET approach

In an independent study, Geli et al. (2014) evaluated several remote sensing based methods to estimate crop water use, including ReSET, METRIC, SEBS, DisALEXI/TSM, and SSEBop.

As shown in Figure 16 and Table 1 below, ReSET performed well as compared to actual ET measured with a Bowen Ratio energy balance flux station. The main crop was alfalfa (for the CA dataset).

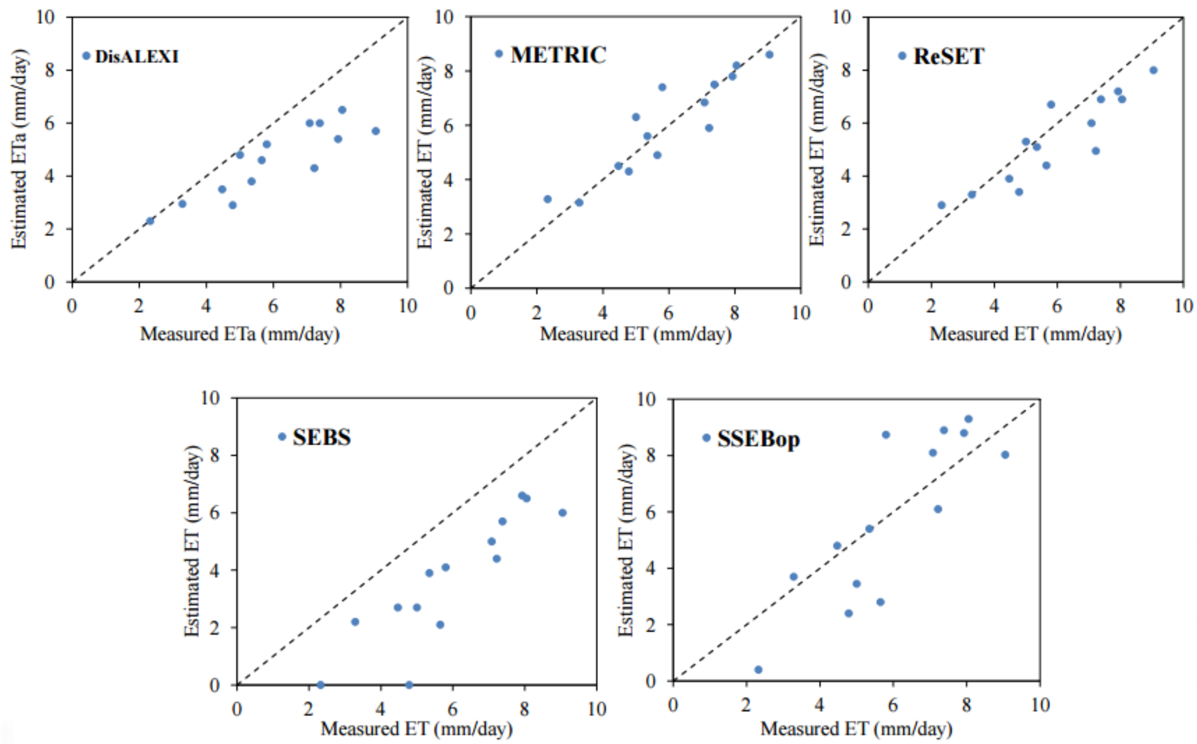


Figure 16. Scatter plots of estimated ETa using different remote sensing models vs. measured ETa with a Bowen ratio energy balance flux tower.

In Table 1, METRIC resulted with the lowest error in estimating ETa. However, ReSET was the second method more accurate. This result seems to validate the use of the approach to estimate and monitor crop water use under different irrigation regimes. Although, one has to consider that ReSET uses METRIC with the difference that instead of using a single weather station data and a “dT” function for most of the Landsat imagery, ReSET uses grids of weather data generated from a network of weather stations and produces a set of “dT” function. In theory ReSET should have resulted with less error than METRIC. One potential reason why METRIC and ReSET did not yield similar ETa values could be the way the extreme cold and hot pixels are selected. Thus, one potential limitation to this method is the existence (or not) of the extreme pixels in the Landsat imagery and the skills/abilities of the user (or system) to select such pixels.

Table 1. Summary of errors on ETa estimation from several remote sensing methods.

	RMSE	BIAS	BIAS (%)	MAE	Sample	Mean	Std. Dev.
Measured					16	6.55	2.4
SSEBop	1.5	-0.2	-7.2%	1.3	16	6.35	2.8
SEBS	2.7	-2.5	-42.0%	2.5	16	4.09	2.1
METRIC	0.9	-0.1	1.6%	0.6	16	6.45	1.9
ReSET	1.3	-0.8	-9.8%	1.1	16	5.70	1.7
DisALEXI	1.8	-1.4	-18.9%	1.7	16	5.20	1.4

Conclusion

Some lessons learned include:

The infra-red thermometer (IRT) sensor should be reading only canopy temperature and avoid sampling the soil background in order to more appropriately apply the Crop Water Stress Index (CWSI), for instance. Users of IRTs have to make sure that the sensor is reading canopy temperature only. If that is not the case, then a model is needed to remove the bias/contamination of soil background temperature.

A commercially available IRT (Ryobi) was evaluated. Inexpensive handheld IRTs are not accurate and need a thorough calibration. The sensor underestimated true target temperature as they are affected by sensor body heating, air temperature, etc. A calibration equation was developed for this particular sensor.

IRTs need sensor body temperature and thermal emissivity corrections. IRT sensors should be reading only canopy temperature and avoid sampling the soil background.

Estimates of ETa with the surface aerodynamic temperature (SAT energy balance) model was found to be equivalent to ETa estimates with the remote sensing method METRIC for corn (which is a well-established method). Therefore, the SAT method is one energy balance – remote sensing method that has potential to monitor corn water use under different irrigation regimes.

When the CWSI was used to estimate ETa and was evaluated with ETa from the SAT method, it was found that some underestimation of ETa by the CWSI method occurred. Since the stress was overestimated due to soil temperature in the field of view (FOV) of the IRT sensor then canopy temperature or Tc modeling is needed. Furthermore, the user of the CWSI method in several occasions had to adjust the upper limit of dT (non- transpiring boundary) to contain values in the range 0-1. Other potential impediments to the application of this method include: taking readings under windy conditions, cloud cover conditions prevent the use of the method, restricted to a period of the day between noon and 2 to 3 pm local time, requires proximity to the plant (within 1-2 feet), requires in-situ air temperature and relative humidity readings. Thus, results indicate that further work is needed on the method before routine operations for monitoring deficit irrigation effectively.

Using soil water content sensor data in the soil water balance, to estimate crop actual ET (ETa), demands well calibrated and well installed sensors throughout the soil root zone. Estimates of ET and soil water deficit only represent a very small area of the field because the sensor only samples a small soil volume.

Evaluation (with neutron probe SWB ETa) of several temperature and reflectance based Ks and Kcb methods indicated that the CWSI and DACT approaches were equivalent in estimating Ks and that a combination of Ks(CWSI) and Kcb(NDVI) estimates seems to contribute to a more accurate estimation of ETa. This suggests that the inclusion of remote sensing vegetation indices may improve the estimation of crop water stress and thus be a valid tool to monitor reduced CU under limited irrigation regimes.

Regarding estimating ETa using remote sensing images from Landsat (both reflectance and thermal), it has been shown that the ReSET algorithm performed well in estimating ETa. However, a limitation (as it is for all methods that use extreme pixels in satellite imagery) is the existence (or lack of) true Ag extreme pixels (hot/cold) in the satellite scene and the ability of the user or system/code to select those pixels. The method seems accurate but it is resourceful intensive (both, in regards to data input and user interaction).

A simpler approach may be the reflectance based crop coefficient (Kc_refl) to estimate ETa. When ReSET was used to evaluate estimates of ETa using reflectance based crop coefficients, it was found that the Kc_refl method based on NDVI (and also SAVI) performed somewhat similar to ReSET starting around the mid vegetative growth stage and into the mid reproductive growth stage. This method is a straight forward method and has shown potential for practical implementation of remote sensing to monitor (document) deficit/limited irrigation over a crop growth season.

Field Days, Workshop and related Publications

During this project, two field days were held at the LIRF USDA ARS farm near Greeley, CO, to show field data (results) and the different instrumentation needed to monitor crop water stress under different irrigation strategies (full, low frequency deficit irrigation, and high frequency deficit irrigation). Figures 17 and 18 show a portion of the activities held during both field days in 2014 and 2015, respectively.

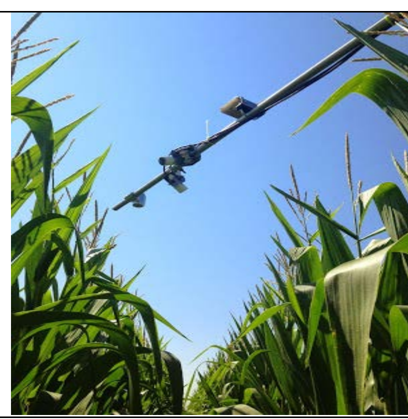
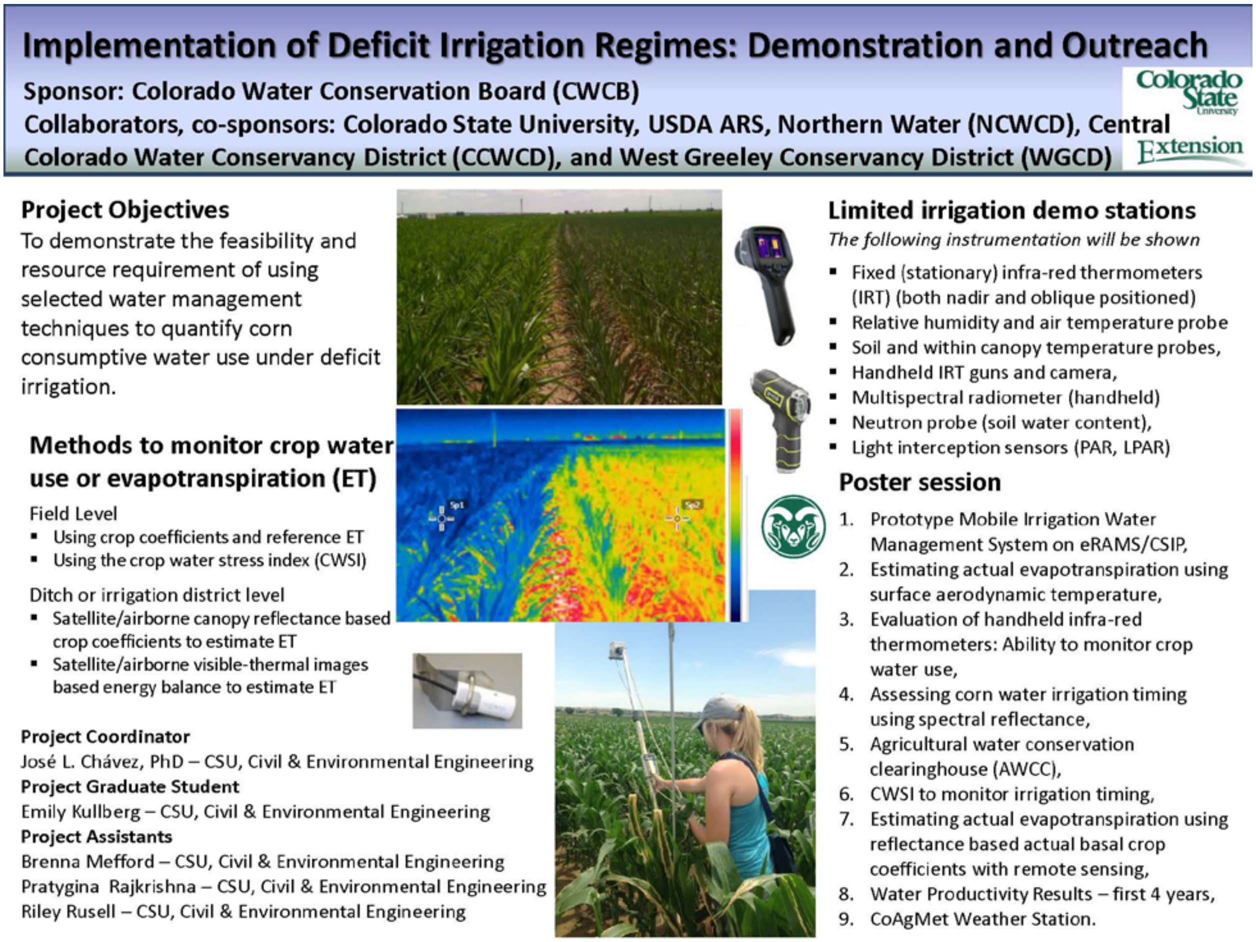


Figure 17. Field day on August 8 of 2014 near Greeley, CO.

Figure 18. Field day on August 21 of 2016 near Greeley, CO.

Below is the Field day brochure indicating activities and poster presentations.



Samples of posters can be found in Appendix E.

Material presented at the Workshop held on April 21st, 2016.

Brochure developed with assistance from the Fort Morgan CSU County Extension office.

SPEAKERS

Dr. José L. Chávez is an Associate Professor in the Civil and Environmental Engineering Department at Colorado State University. He earned his B.S. in Agricultural Engineering from the Universidade Federal da Paraiba in Brazil in 1992. In 1999 Dr. Chávez received his M.S. degree in Irrigation Engineering from Utah State University. His Ph.D. was in Biological and Agricultural Engineering from Utah State University, in 2005. His expertise is in irrigation water management, crop/vegetation water consumptive use (evapotranspiration, ET) determination and modeling, use of remote sensing for mapping ET, irrigation scheduling, irrigation systems design, drainage and wetlands engineering, and precision irrigation.

Joel Schneekloth is the Regional Water Resource Specialist for CSU since 2000. Prior to that, he held a Water Resource Extension Educator position with the University of Nebraska. Joel conducts research and educational programs relating to irrigation and crop production with a primary emphasis upon limited water supplies. He has conducted research and education programs on drought tolerant corn, tillage and residue management for irrigated corn production, irrigation timing impacts on crop production.

Dr. Allan A. Andales is an Associate Professor and Extension Specialist of Irrigation and Water Science in the Department of Soil and Crop Sciences, Colorado State University (CSU). He has degrees from the University of the Philippines (BS Agricultural Engineering) and Iowa State University (MS and PhD Agricultural Engineering and Water Resources). His primary focus is on conserving soil and water resources. Research activities include the measurement of evapotranspiration using precision weighing lysimeters, development of irrigation scheduling tools, precision irrigation, and computer modeling of agricultural systems (cropland and rangeland) to help make management decisions. He teaches undergraduate classes in Irrigation Principles and Irrigation of Field Crops; supervises MS and PhD students; and mentors international scholars. He is a member of the CSU Extension Water Resource Management Team that engages the public in addressing agricultural and urban water issues in Colorado.

Dr. Aymn Elhaddad is a Research Scientist in the Civil Engineering Department at Colorado State University. His research at CSU focused on regional-scale hydrological modeling, developing GIS/Remote Sensing based applications, and providing geospatial analysis tools to assist in earth surface monitoring. Aymn's work can be found in several peer-reviewed publications, including the Journal of Irrigation and Drainage Engineering and the Journal of Hydrological Processes. Aymn is the main developer of the ReSET model (Remote Sensing of Evapotranspiration). Aymn has a Ph.D in Civil and Environmental Engineering and an M.S. in Forestry Sc, GIS and remote sensing both from Colorado State University.

Colorado State University Extension,
U.S. Department of Agriculture and
Colorado Counties cooperating.

Colorado State University Extension

Morgan County Extension
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Fort Morgan, Co 80701

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2016 Irrigation Water Management Continuing Education Credits

Alternative Agricultural Water Transfer Methods: Deficit irrigation monitoring

April 21, 2016
8:30 am to 3:30 pm

Country Steak Out
19592 East 8th Avenue
Fort Morgan, CO 80701

2016

Water Management

Technologies for monitoring crop water use: full to deficit irrigation

8:30- 9:00	Registration
9:00 - 9:10	Welcome José Chávez CSU Extension Specialist
9:10 - 9:40	Limited Irrigation: Principles, Pros, Cons Joel Schneekloth, CSU Extension Specialist
9:40 - 10:15	CO Irrigation Scheduler WISE Allan Andales CSU Extension Specialist
10:15—10:30	Break
10:30 - 11:30	Estimating ET and Water Stress: Methods José Chávez CSU Extension Specialist
11:30 to 12:00	Remote Sensing of ET (Satellite Based) Aymm Elhaddad CSU Research Scientist
12:00 - 1:30	Lunch *"CWCB's Alternative Transfer Methods Grant Program: Past, Present and Future"* Craig Godbout CWCB

This Program is sponsored by

Colorado Water Conservation Board

The Northern Colorado Water Conservancy District

Central Colorado Water Conservancy District

Lunch is provided by sponsors

Register by April 15, 2016

Hands on workshop
(Bring your laptop computer)*

2:00 - 3:30

- CO Irrigation Scheduler WISE, (on-line tool, Wi-Fi connection**). Bring the location (coordinates: latitude, longitude) of your field
- Calculating Crop Water Stress and Water Use (ET) (Excel)
- Remote Sensing of ET***

3:30 Adjourn

* Laptop computer software requirement: MS Office Excel 2010 or above.

** Have in your laptop a web browser (FireFox preferred) to use WISE

*** Requires ArcGIS version 10 installed. We will have one laptop with the soft ware and data loaded.

Please RSVP as soon as possible, space and hand-outs are limited.

Register by April 15, 2016 to:
Morgan County Extension at 970 542-3540
or by email to Dr. Wilma Trujillo
Wilma.Trujillo@colostate.edu

If you have a disability for which you seek an accommodation, please notify Morgan County Extension (970 542-3540) 5 days before the event.

CSU Extension programs are available to all without discrimination.

Individual presentations can be found in the Appendix F.

Published material:

Chávez, J.L. and E. Kullberg, 2015, Handheld Infra-Red Thermometry Calibration: Monitoring Crop Water Stress. In Proceedings of the 2015 ASCE EWRI World Congress, May 17-21, Austin, TX, pp. 2024-2034.

Chávez, J.L., 2015, "Using canopy temperature as an indicator of plant stress." In Proceedings of the 26th Annual Central Plains Irrigation Conference (CPIC), Colby, KS, February 17-18, 2015, CPIA, 760 N. Thompson, Colby, KS.

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.

DeJonge K., Mefford*, B.S., and J.L. Chávez. 2016. "Assessing corn water stress using spectral reflectance," International Journal of Remote Sensing. Submitted on 02 Feb 2015, re-submitted on 11 Feb 2016. Accepted on 16 March 2016. In Press.

DeJonge, K.C., Kullberg, E.G. and J.L. Chávez. “Evaluation of stress coefficient methods to estimate crop evapotranspiration.” *Agricultural Water Management*. Submitted on 15 Feb 2016. In Review.

Kullberg, E. (2015). “EVALUATION OF STRESS COEFFICIENT METHODS TO ESTIMATE CROP EVAPOTRANSPIRATION,” M.S. Thesis, Civil and Environmental Engineering Department, Colorado State University, Fort Collins, CO. Published on-line at: https://dspace.library.colostate.edu/handle/10217/167166

Mefford, B. (2014). Assessing corn water stress using spectral reflectance. M.S. Thesis. Retrieved from Colorado State University Libraries Digital Collections. , Civil and Environmental Engineering Department, Colorado State University, Fort Collins, CO. Published on-line at: https://dspace.library.colostate.edu/bitstream/handle/10217/84002/Mefford_colostate_0053N_12586.pdf?sequence=1

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Colaizzi, Paul; Susan O’Shaughnessy; Steve Evett; and Terry Howell. 2012. USING PLANT CANOPY TEMPERATURE TO IMPROVE IRRIGATED CROP MANAGEMENT. In Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, Kansas, Feb. 21-22, 2012, pp. 203-223.

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Geli H., C.M.U. Neale, and JJ. Verdim (2014). Intercomparison of remote sensing based models for evapotranspiration. In Proceedings of the 2014 ASA-CSSA-SSSA International Annual Meeting, Long Beach, CA.

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.

Jackson, R. D. 1982. Canopy temperature and crop water stress. In: Advances in Irrigation (D. Hillel, ed)., Academic Press, New York, NY. 1: 43-85.

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Kustas, W. P., and J. M. Norman. 1999. Evaluation of soil and vegetation heat flux predictions using a simple two source model with radiometric temperatures for partial canopy cover. Agric. For. Meteorol. 94: 13-29.

Neale, C.M.U., Bausch, W.C., and Heerman, D.F. (1989). Development of reflectance-based crop coefficients for corn. *Trans. ASAE,* 32(6): 1891-1899.

O'Shaughnessy, S. A., M. A. Hebel, S. R. Evett, and P. D. Colaizzi, 2011b. Evaluation of a wireless infrared thermometer with a narrow field of view. Comp. Elec. Agric. 76: 59-68.

Appendices

APPENDIX A. Water Irrigation Scheduler for Efficient Application (WISE): Instructions

Instructions using a Web Browser (Firefox preferred)

Homepage

1. Navigate to http://wise.colostate.edu and click on the "eRAMS Platform" link near the bottom of the page. Alternately, you can navigate directly to https://erams.com/

Create a New User

1. Click on the "Sign Up" link at the upper right corner of the Home screen.

2. Enter your required and optional user information and click "Create Account."

3. Open a new browser window. Login to the email account associated with the email address provided in the previous step, and open the email confirmation message sent to you by eRAMS. (Note: It may take a short time for the email to arrive, and it's possible that this message could be placed in your spam folder. Be sure to check this folder if the email confirmation doesn't appear in your inbox.)

4. Click on the link provided in the email confirmation message. You'll be logged into eRAMS after clicking on this link.

Add Irrigation Project

1. On the left hand side of the page, click on the "Projects" box.

2. When the Projects page opens, click on "Create Project."

a. Enter a name for your project, such as "My Irrigation Project."

b. Under “Project Type,” select “Irrigation Scheduler.”

c. Click “Okay.” The newly-created project should appear in the Projects list. Click on the project name to open the project in the WISE user interface.

Create a Crop Field

1. On the left side of the screen, you will see two tabs: “Map” and “Fields.” A Google map will also be visible on the right side of the screen.

2. Use your mouse wheel or the zoom tool above the map to zoom to a particular location or field on the map. If you know the coordinates of your field, enter it in the “Zoom to:” box at the upper left corner of the map (example: 40.6525, -105.000). Note that locations in Colorado should have a negative (-) longitude value.

a. To use the zoom tool, click on the zoom tool button then click and drag your mouse across the map. Once you let go of your mouse, the map will zoom to the extent of the box that was previously drawn.

b. To pan through the map, click on the Pan tool, click and hold while panning the map.

3. Hover over the “Draw” button which is located below the “Select Field” dropdown box.

a. Select “Draw Circle,” “Draw Polygon,” or “Import.”

b. For a polygon, draw your crop field by making successive clicks on the map at each corner of your crop field. Double click to complete. To draw a circle, click and hold your mouse in the center of the circle you wish to draw, then drag your mouse to the perimeter of the circle. Release your mouse to complete.

4. Provide a name for your crop field in the dialog box that appears, such as “My Alfalfa Field,” and click OK. WISE will take a moment to extract soil properties and locate the weather stations closest to your field.

View Weather Stations

Weather stations may have already been collected for your crop field, but if not you can use the following steps to find weather stations nearest your crop field.

1. Click on the “Weather Stations” panel below the “Fields” tab on the left side of the screen, if the panel has not already been opened.

2. Click on the “Collect Closest Weather Stations” icon (open magnifying glass) to find closest applicable weather stations for your crop field. (Note: Currently only CoAgMet and Northern Water weather stations are available.) If more than one station is selected, WISE will perform an inverse distance-weighted average calculation of crop evapotranspiration (ETc) and rain.

3. Click on a weather station to see it on the map.

4. Click on the “View All Weather Stations” button to see all of the weather stations displayed on the map. Hover your mouse over a weather station marker on the map to see details about the weather station.

Activate or Deactivate Weather Stations

1. Activate or deactivate a weather station in the left column by clicking on the power button that appears next to a weather station name when you hover your mouse over the station. Inactive weather stations are grayed and crossed out and will not be used for estimating ETc and rainfall on your field.

View Weather Data for a Weather Station

1. Click on a weather station in the list of search results

2. From the popup box displayed on the map that represents this weather station, click “See Current Weather”

Set Crop Field Attributes

1. Click on the “Set Up/Modify” button (gear icon) in the “Fields” tab on the left hand side of the screen.

2. Enter a Crop Type, Planting Date, and Emergence Date for your crop field in the dialog that is displayed. Est. Harvest Date can be left blank, unless available.

3. Enter Irrigation system information. The efficiency will be used to estimate the applied water that is effectively stored in the soil root zone. You can move the slider button on the Efficiency bar to change the irrigation system efficiency.

4. If known, enter an “Initial Soil Water Deficit (%)” in the root zone.

5. Click on the “Update” button to save any changes.

6. Click “Done” on the bottom right corner of the dialog box.

View Irrigation Schedule

1. Click on the “View Your Crop Irrigation Schedule” button (calendar icon) in the “Fields” tab on the left hand side of the screen. WISE will take a moment to calculate a daily water balance for your field.

2. A summary of your crop field’s irrigation needs, as well as a table and graph of irrigation scheduling results can be viewed by clicking on their corresponding tabs.

Enter your actual Irrigation, Rain, or Deficit

1. Click on the “Table” tab in “Crop Irrigation Schedule” dialog box.

2. Double click on one of the gray boxes under the Gross Irrigation, Rain, or Observed Soil Deficit columns. A text box will appear allowing you to enter a value. Type in your actual value and hit “Enter”

on your keyboard. At a minimum, you should enter your actual Gross Irrigation each time that you apply irrigation water. WISE will use rain amounts from the selected weather stations, if you do not enter your own values.

3. Click on the “Update” button to save this updated value to your irrigation schedule.

View Graphs

1. Click on the “Graph” tab in “Crop Irrigation Schedule” dialog box. A graph of plant available water (PAW) will appear to display a time series of PAW up to the current date.

2. Click on the “Select Graph” dropdown box on the right hand side of the “Crop Irrigation Schedule” dropdown box. Select the “Water Deficit” graph to see the estimated net irrigation requirement (Root Zone Deficit). Irrigation is advised when the deficit (blue line) approaches or falls below the Management Allowed Depletion (red line).

Export

1. Click on the “Export” button. Select print or export format to print or display the report of your crop irrigation schedule for the current field.

APPENDIX B. Soil moisture sensors

Soil moisture sensors are used to take volumetric soil water content and water potential measurements. The use of such instruments to schedule irrigation dates back over 80 years. Figure A1 below shows graphically some sensor technologies available nowadays.

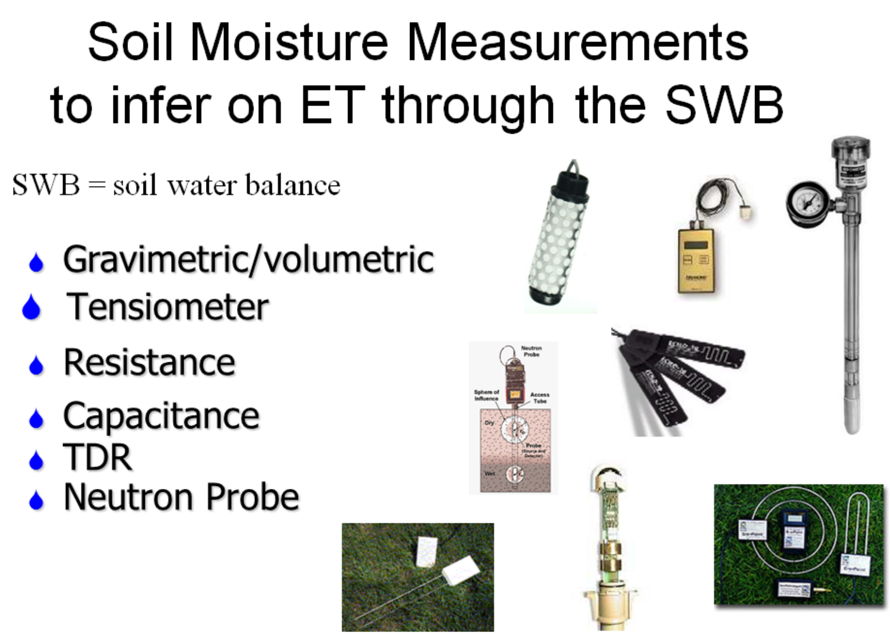


Figure A1. Different technologies (sensors) to infer on soil water content/potential.

Tensiometers are the only Direct means of measuring Soil Water Tension. All other methods are Indirect, in that they actually measure something other than soil water and then are converted to a soil water characteristic via some method of calibration. Irrometer's Watermark granular matrix sensor, measures electrical resistance and equate that to soil water tension with a calibration of ohms of resistance to centibars of tension. Other sensors relate their measurement to soil water content, as opposed to tension, which tells how much water is in the soil by volume. Capacitance or Frequency Domain Reflectometry (FDR) sensors detect changes in soil dielectric properties and convert these readings to soil water content. Time Domain Reflectometry (TDR) sensors measure the time it takes for an electromagnetic wave to be transmitted through the soil. The presence of water in the medium affects the speed of the electromagnetic wave. This is then calibrated to a soil water content. Neutron probes measure the speed of neutron travel, which is slowed by hydrogen. Since hydrogen is a part of water, this can be related to water content.

http://www-pub.iaea.org/mtcd/publications/PubDetails.asp?pubId=7801

All sensors measure a *surrogate property* that is then related to the soil volumetric water content (θ_v) through a calibration. The major surrogate properties are:

a) Capacitance – variable resonant frequency

b) Phase delay – constant frequency

c) Transmission time

d) Water content reflectometer, e.g., CS616

e) Quasi travel time, e.g. Trime

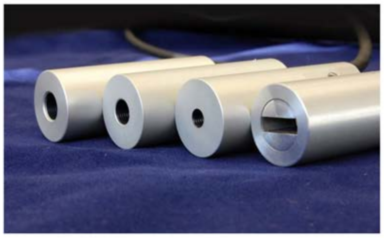
f) Time domain reflectometry (TDR), waveform interpretation

g) Thermal neutron count – neutron probe

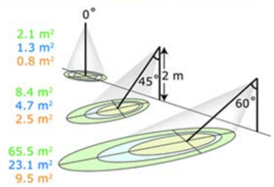
APPEDIX C. Procedure to calibrate IRTs (Apogee)

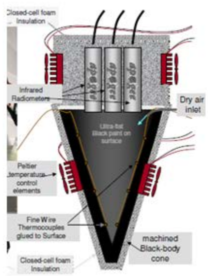
Ts calibration for surface emissivity and background temperature follows.

IRTs need calibration before collected data can be used



Type	Model	Half Angle
Standard	SI-111	22°
Narrow	SI-121	18°
Ultra-Narrow	SI-131	14°





Use of a blackbody

Sensor calibration sheet provided by the manufacturer

Certificate of Calibration

APOGEE INSTRUMENTS INFRARED RADIOMETER
SI SERIES

Calibration Overview		
Model/Serial Number	:	**SI-111_EXAMPLE**
Calibration Date	:	8-Jul-2013
Recommended Recalibration Date	:	8-Jul-2015
Mean of Differences from Target	:	0.001 °C
Target Temperature Uncertainty (95% confidence) from -30 to 65 °C	:	**0.133 °C**
Maximum Difference from Target	:	0.148 °C
Minimum Difference from Target	:	-0.119 °C
Maximum Detector Response	:	1.379 mV
Minimum Detector Response	:	-0.804 mV
Average Output Sensitivity	:	66.794 µV / °C

Custom Calibration Coefficients

CRBasic

	C2	C1	C0
m	81170.5	7187980	1334780000
b	2295.07	245405	-6557540

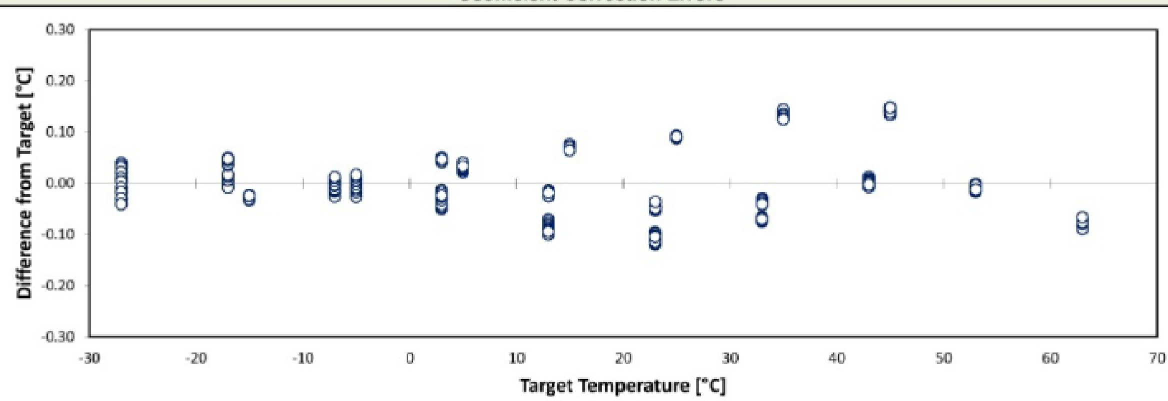
See the SI-100 series manual for how to apply these coefficients in determining target temperatures.

Edlog

	C2	C1	C0
m(SB)	0.81171	71.88052	13347.93348
b(SB)	0.02295	2.45407	-65.57606

Use these coefficients in Edlog programs for older Campbell Scientific dataloggers.

Coefficient Correction Errors



Calibration procedure

Target Temperature Measurement:

The detector output from SI-100 series radiometers follows the fundamental physics of the Stefan-Boltzmann Law, where radiation transfer is proportional to the fourth power of absolute temperature. A modified form of the Stefan-Boltzmann equation is used to calibrate sensors, and subsequently, calculate target temperature:

$$T_T^{\,4} - T_D^{\,4} = m \cdot S_D + b \qquad (1)$$

where T_T is target temperature [K], T_D is detector temperature [K], S_D is the millivolt signal from the detector, m is slope, and b is intercept. The mV signal from the detector is linearly proportional to the energy balance between the target and detector, analogous to energy emission being linearly proportional to the fourth power of temperature in the Stefan-Boltzmann Law.

During the calibration process, m and b are determined at each detector temperature set point (10 C increments across a -15 C to 45 C range) by plotting measurements of $T_T^4 - T_D^4$ versus mV. The derived m and b coefficients are then plotted as function of T_D and second order polynomials are fitted to the results to produce equations that determine m and b at any T_D:

$$m = C2 \cdot T_D^{\,2} + C1 \cdot T_D + C0 \qquad (2)$$

$$b = C2 \cdot T_D^{\,2} + C1 \cdot T_D + C0 \qquad (3)$$

Where C2, C1, and C0 are the custom calibration coefficients listed on the calibration certificate (shown above) that comes with each SI-100 series radiometer (there are two sets of polynomial coefficients, one set for m and one set for b). Note that T_D is converted from Kelvin to Celsius (temperature in C equals temperature in K minus 273.15) before m and b are plotted versus T_D.

To make measurements of target temperatures, Eq. (1) is rearranged to solve for T_T [C], measured values of S_D and T_D are input, and predicted values of m and b are input:

$$T_T = \left(T_D^{\,4} + m \cdot S_D + b\right)^{\frac{1}{4}} - 273.15 \qquad (4)$$

Sensor body temperature calibration example

- Calibration coefficients for a SI-111 IRT:

	C2	C1	C0
m =	6.6104E+04	8.1115E+06	1.3876E+09
b =	2.3018E+04	-4.8556E+05	9.4958E+05

- Calibrate the IRT readings (mV) to obtain target temperatures (T_{target} °C)

Signal (mV)	R_T (Ω)	SBTempC (°C)
-0.5	10880	23.1
0	12500	20.0
1.5	14000	17.5

- Where SBTempC is sensor body temperature or detector temperature (T_D) and Signal is the millivolt signal from the detector (S_D).

$$m = C2 \cdot T_D^2 + C1 \cdot T_D + C0$$

$$b = C2 \cdot T_D^2 + C1 \cdot T_D + C0$$

- For first data point: S_D = -0.5 mV, and SBTempC = T_D = 23.1 °C.

- m = 6.6104E+04 x $(23.1)^2$ + 8.1115E+06 x 23.1 + 1.3876E+09 = 1.61E+09
- b = 2.3018E+04 x $(23.1)^2$ + -4.8556E+05 x 23.1 + 9.4958E+05 = 2.01E+06

$$T_T = \left(T_D^4 + m \cdot S_D + b\right)^{\frac{1}{4}} - 273.15$$

- T_{target} (°C) = $((23.1+273.15)^4$ + 1.61E+09 x (-0.5) + 2.01E+06$)^{0.25}$ – 273.15
- T_{target} = 15.0 °C.

Signal (mV)	R_T (Ω)	SBTempC (°C)	m	b	T_{Target} (°C)
-0.5	10880	23.1	1.61E+09	2.01E+06	15.0
0	12500	20.0	1.58E+09	4.41E+05	20.0
1.5	14000	17.5	1.55E+09	-4.99E+05	38.7

IRT surface thermal emissivity and background correction

Appropriate correction for surface emissivity is required for accurate surface temperature measurements. The simple (and commonly made) emissivity correction, dividing measured temperature by surface emissivity, is incorrect because it does not account for reflected infrared radiation.

The radiation detected by an infrared radiometer includes two components: 1. radiation directly emitted by the target surface, and 2. reflected radiation from the background. The second component is often neglected. The magnitude of the two components in the total radiation detected by the radiometer is estimated using the emissivity (ε) and reflectivity (1 - ε) of the target surface:

$$E_{Sensor} = \varepsilon \cdot E_{Target} + (1 - \varepsilon) \cdot E_{Background} \qquad (1)$$

where E_{Sensor} is radiance [W m^{-2} sr^{-1}] detected by the radiometer, E_{Target} is radiance [W m^{-2} sr^{-1}] emitted by the target surface, $E_{Background}$ is radiance [W m^{-2} sr^{-1}] emitted by the background (when the target surface is outdoors the background is generally the sky), and ε is the ratio of non-blackbody radiation emission (actual radiation emission) to blackbody radiation emission at the same temperature (theoretical maximum for radiation emission). Unless the target surface is a blackbody (ε = 1; emits and absorbs the theoretical maximum amount of energy based on temperature), E_{sensor} will include a fraction (1 – ε) of reflected radiation from the background.

Since temperature, rather than energy, is the desired quantity, Eq. (1) can be written in terms of temperature using the Stefan-Boltzmann Law, $E = \sigma T^4$ (relates energy being emitted by an object to the fourth power of its absolute temperature):

$$\sigma \cdot T_{Sensor}^{\ 4} = \varepsilon \cdot \sigma \cdot T_{Target}^{\ 4} + (1-\varepsilon) \cdot \sigma \cdot T_{Background}^{\ 4} \qquad (2)$$

where T_{Sensor} [K] is temperature measured by the infrared radiometer (brightness temperature), T_{Target} [K] is actual temperature of the target surface, $T_{Background}$ [K] is brightness temperature of the background (usually the sky), and σ is the Stefan-Boltzmann constant (5.67 x 10^{-8} W m^{-2} K^{-4}). The power of 4 on the temperatures in Eq. (2) is valid for the entire blackbody spectrum.

Note: T_{target} = true target temperature, T_{sensor} = target temperature uncorrected for emissivity effects.

- T_{sensor} = 28.2 °C, (equivalent to uncorrected T_{target})
- Target or surface emissivity (ε)= 0.98 (full cover, green, healthy plant, ε_v). For bare soil is 0.93 or ε_s,
- $T_{background}$ = sky temperature = 31.9 °C

Rearrangement of Eq. (2) to solve for T_{Target} yields the equation used to calculate the actual target surface temperature (i.e., measured brightness temperature corrected for emissivity effects):

$$T_{Target} = \sqrt[4]{\frac{T_{Sensor}^{\ 4} - (1-\varepsilon) \cdot T_{Background}^{\ 4}}{\varepsilon}} \qquad (3)$$

- $T_{target} = [((28.2+273.15)^4 - (1-0.98)x\ (31.9+273.15)^4)/0.98]^{0.25}$

- T_{target} = 301.27 K or 28.1 °C, (corrected for emissivity, true temperature)

Note: For computing the sky temperature in the emissivity correction the following equation can give an approximation: Tsky = Tair + 50*fc - 60

where Tsky and Tair are in degrees Celsius and fc is the fraction of cloud cover.

Please see the video in the following link by Mark Blonquist of Apogee Instruments (http://www.decagon.com/en/education/virtual-seminars/virtual-seminars/infrared-thermometer-plant-science/) for more information.

The introduction of the equation above is at around 9:00 in the video.

The REF-ET calculator can be used in order to estimate the fraction of cloud cover. REF-ET can be found at: http://extension.uidaho.edu/kimberly/2015/06/ref-et-reference-evapotranspiration-calculator/

Surface thermal emissivity calculation can be obtained by following Brunsell and Gillies procedure.

Details can be found at: https://www.researchgate.net/publication/225090720_Incorporating_Surface_Emissivity_into_a_Thermal_Atmospheric_Correction

Assume NDVImax = 0.89, NDVImin = 0.15. Assume Emissivity of vegetation Ev = 0.98 and of soil Es = 0.92.

APPENDIX D. CWSI Method

The CWSI method relies on the temperature difference (dT, °C) 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.

$$CWSI = (dT - dT_{min})/(dT_{max} - dT_{min}) \quad \text{(B1)}$$

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):

$$dT_{min} = a\,(VPD) + b \quad \text{(B2)}$$

$$dT_{max} = a\,(VPG) + b \quad \text{(B3)}$$

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.

<u>Vapor Pressure Deficit (VPD) Calculation</u>

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

$$VPD = e_s - e_a \qquad \text{(B4)}$$

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).

$$e_s = 0.6108 \times \exp\left(\frac{17.27 \times T_a}{237.3 + T_a}\right) \qquad \text{(B5)}$$

$$e_a = (RH/100) \times e_s \qquad \text{(B6)}$$

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

<u>Vapor Pressure Gradient (VPG) Calculation</u>

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:

$$VPG = \left[0.6108 \times \exp\left(\frac{17.27 \times T_a}{237.3 + T_a}\right)\right] - \left[0.6108 \times \exp\left(\frac{17.27 \times (T_a + b)}{237.3 + (T_a + b)}\right)\right] \quad \text{(B7)}$$

Once the corn CWSI was computed, the next step is to compute an actual crop water use or evapotranspiration (ETa). Which can be used to monitor deficit/limited irrigation fields seasonal water consumption by accumulating daily estimates of ETa throughout the crop growing season.

$ETa = (1 – CWSI)\ ET_p$ (B8)

$ET_p = Kc \times ET_{ref}$ (B9)

The term (1-CWSI) is similar to the crop stress coefficient (Ks) discussed before. The variable ETref is the reference ET. ET_p is referred as to the potential crop ET or ETc.

Note: computation of the CWSI has been implemented in a Excel Spreadsheet.

Appendix E

Sample of field days' posters presented:

Estimating Actual Evapotranspiration Using reflectance based actual basal crop coefficients with remote sensing

José L. Chávez[1] and Tom Trout[2]

[1]Department of Civil and Environmental Engineering, Colorado State University, and [2]USDA ARS, Water Management Unit, Fort Collins, CO

Project Overview:

Research has shown that remote sensing can be used to obtained actual crop coefficients (basal) from vegetation indices (e.g., from the normalized difference vegetation index (NDVI) or from fractional vegetation cover (fc). Briefly, NDVI or fc is linearly related to basal crop coefficients (Kcb ini = 0.15, Kcb_full = 1.01 for corn) between initial (fc = 0) and full (fc = 0.8 for corn) canopy cover. Vegetation indices such as NDVI and SAVI (see definitions below) are very sensitive to vegetation growth in the vegetative growth stage of crops (from emergence to full cover) and to crop water stress. Basal crop coefficients derived from remote sensing sensors can be paired with reference crop (e.g., alfalfa) water use or evapotranspiration (derived from weather station data such as COAGMET) to infer spatially distributed basal crop water use (ETcb). This ETcb can be used in a soil water balance approach to schedule irrigation.

Vegetation indices to crop coefficient to estimate ETcb with remote sensing

$$ETa = K_{cr} \times ET_r$$

where K_{cr} is reflectance based crop coefficient and ET_r is alfalfa reference ET

For Corn: Neale et al. (1989) $K_{cr} = 1.092 \times NDVI - 0.053$, (for Fruita, CO)

$K_{cr} = 1.181 \times NDVI - 0.026$, (for Greeley, CO)

Bausch (1993) $K_{cr} = 1.416 \times SAVI + 0.017$

$$NDVI = (R_{NIR} - R_{RED}) / (R_{NIR} + R_{RED})$$

$$SAVI = (R_{NIR} - R_{RED}) (1+L) / (R_{NIR} + R_{RED} + L)$$

where R_{NIR} is reflectance in the near infra-red band, R_{RED} is reflectance in the red band and L is an adjusting factor to minimize soil background effects (function of soil type and crop growth stage).

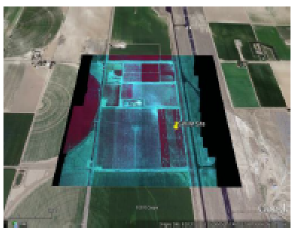


Fig. 1. Example of a high resolution multispectral surface reflectance remote sensing imagery overlaid on a Google Earth RGB photo. The false color composite image (near infra-red, red, and green bands stack) shows the green vegetated areas in shades of red color. The more intense the red color (larger pixel value) the more plant biomass is present and therefore the NDVI value is larger and so is the fractional cover and derived Kcb values.

Vegetation fraction of ground cover (fc) based crop coefficient and ETcb with remote sensing

The basal crop coefficient Kcb (equivalent to crop water transpiration) can be inferred with canopy reflectance from remote sensing or from other estimates of fc.

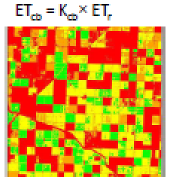
Kcb = Kcb ini + ((Kcb full – Kcb ini)*Fc full)*fc, where Kcb ini = 0.15 for corn. And, Kcb full = Fr(min(1+0.1h,1.2))+[0.04(u-2)-.004(RH-45]*(h/3)0.3), or 1.01 for corn. Where, h is canopy height (m), u is wind speed (m/s), and RH is relative humidity (%).

According to Trout et al. (2008) and Johnson & Trout (2012) fc and Kcb can be estimated as:

$$f_c = 1.22 \times NDVI - 0.21$$

$$K_{cb} = 1.13 \times f_c + 0.14$$

$$ET_{cb} = K_{cb} \times ET_r$$



	NDVI, fc	Kcb	ETcb (mm/day)
(red)	<0.2	<0.3	<2
(orange)	0.2-0.4	0.3-0.6	2-4
(yellow)	0.4-0.6	0.6-0.9	4-6
(green)	>0.6	>0.9	>6

Fig.2. ETcb map from Landsat 30 m pixel size imagery.

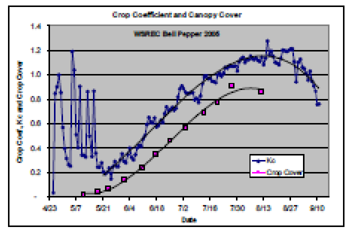


Fig. 3. Daily crop coefficient, Kc, and canopy cover for a bell pepper crop grown on a weighing lysimeter on the west side of the San Joaquin Valley, CA in 2005.

This process should be carried out in two steps rather than attempting to directly link Kcb to NDVI. The intermediate step allows interpolation and extrapolation of fc between and beyond NDVI measurements, ground truthing of fc estimates, and crop specific Kcb:fc relationships.

References: Johnson, L.F. and T.J. Trout. (2012). Satellite-assisted monitoring of vegetable crop evapotranspiration in California's San Joaquin valley. Remote Sens. 4: 439-455.

Trout, T.J. , L.F. Johnson, and J. Gartung. (2008). Remote sensing of canopy cover in horticultural crops. HortScience 43(2):333-337.

Estimating Actual Evapotranspiration Using Surface Aerodynamic Temperature

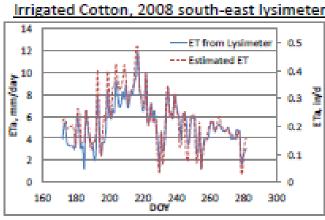
P.I. José L. Chávez with the assistance of Brenna Mefford
Department of Civil and Environmental Engineering, Colorado State University

Method Overview:

In the calculation of sensible heat flux surface aerodynamic temperature (T_{aero}) is often assumed to be equal to surface temperature on the ground. Using models developed to estimate T_{aero} using plant biophysical characteristics and weather data allows for crop consumptive use or ET to be calculated more accurately. Twenty six different equations for T_{aero} were tested on a variety of crops and climates. Estimating T_{aero} with equations 05 and 06 (T_{aero} 05, T_{aero} 06) resulted in an accurate ET value similar to measured ET values from large weighing lysimeters. In the equations, Ts is surface temperature (°C), Ta is air temperature (°C), LAI is leaf area index, U is wind speed (m/s), and hc is crop height (m). In the figures and tables below: R^2 is the goodness of fit, RMSE is root mean square error , MBE is mean bias error, and MAE is mean absolute error . ETa is actual crop evapotranspiration calculated using an energy balance algorithm and Taero. DOY = day of the year.

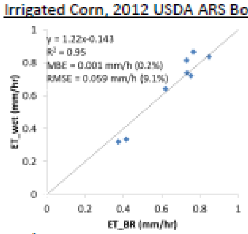
$$T_{aero}\,05 = 0.49 \cdot T_s + 0.31 \cdot T_a + 0.5 \cdot LAI - 0.19 \cdot U - 0.85 \cdot h_c + 5.5$$

Irrigated Cotton, 2008 south-east lysimeter, Bushland, TX:



RMSE	1.06 mm/d	0.042 in/d
MBE	0.38 mm/d	0.015 in/d
MAE	0.76 mm/d	0.03 in/d
Slope	0.77	0.77
Intercept	0.94	0.94
R^2	0.84	0.84

Irrigated Corn, 2012 USDA ARS Bowen ratio field, in Greeley, CO:



Equations:

$$LE = Rn - G - H$$
$$H = \rho \times c_p \times (T_{aero} - T_a) / r_{ah}$$

$$ET_i = 3{,}600 \frac{LE}{\lambda_v \, \rho_w}$$

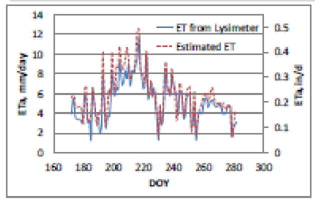
$$ETa = \frac{ET_{ref\_i}}{ET_{ref\_d}} \times ET_i$$

LE = latent heat flux (W/m²),
Rn = net radiation, G = soil heat flux, and H = sensible heat flux (all in W/m²),
r_{ah} = the aerodynamic resistance to heat transport (s/m),
c_p is the specific heat capacity of the air (1004 J/kg/K),
ρ is air density (kg/m³),
T_{aero} = surface aerodynamic temperature (K),
T_a = air temperature (K)

ETi is instantaneous ET (mm/h)
λv is latent heat of vaporization of water (MJ/Kg),
ρ_w is water density (1 Mg/m³)
ET_{ref_i} is hourly reference (e.g., alfalfa) ET , (mm/h),
ET_{ref_d} is reference daily ET, (mm /d)

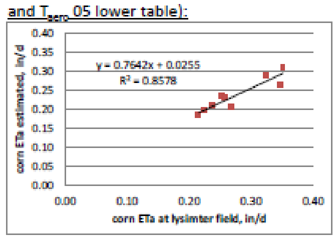
$$T_{aero}\,06 = 0.534 \cdot T_s + 0.39 \cdot T_a + 0.224 \cdot LAI - 0.192 \cdot U + 1.68$$

Irrigated Cotton , 2008 south-east lysimeter, in Bushland, TX:



RMSE	1.07 mm/d	0.042 in/d
MBE	0.67 mm/d	0.026 in/d
MAE	0.80 mm/d	0.032 in/d
Slope	0.83	0.83
Intercept	0.36	0.36
R^2	0.87	0.87

Irrigated Corn, 2013 lysimeter field, in Rocky Ford, CO (T_{aero} 06 upper table and T_{aero} 05 lower table):



RMSE	1.12 mm/d	0.044 in /d
MBE	-1.00 mm/d	-0.04 in/d
MAE	1.00 mm/d	0.04 in/d
Slope	0.76	0.76
Intercept	0.63	0.63
R^2	0.86	0.86

RMSE	0.661 mm/d	0.026 in/d
MBE	-0.328 mm/d	-0.013 in/d
MAE	0.572 mm/d	0.023 in/d
Slope	0.73	0.73
Intercept	1.39	1.39
R^2	0.79	0.79

Conclusion:

Estimating corn water consumptive use (or evapotranspiration) in eastern Colorado is feasible using a modeled aerodynamic surface temperature (T_{aero}) in an energy balance method.
Results from method T_{aero} 05 model seem to indicate the model performs well for irrigated corn in eastern Colorado.
The model data input needs include air temperature, wind speed, crop height, crop leaf area index, and corn canopy temperature which can be measured with an infra-red thermometer.

The Water Irrigation Scheduler for Efficient Application (WISE) Online Tool

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Opportunity

- Improved irrigation water management (IWM) can play a key role in water conservation, prevention of water pollution, and enhanced crop productivity.
- Irrigation scheduling advisory tools that track irrigation requirements for each field can improve IWM at the farm or irrigation distribution scale.
- The development of IWM tools on widely available mobile devices can increase the adoption of improved IWM practices.
- The availability of cloud services enables the widespread deployment of IWM tools through the internet and wireless networks.

Objective

Develop, pilot, and disseminate a scalable device-independent mobile system for improved IWM.

User inputs (by irrigated field)

- Field boundaries using eRAMS online mapping tool.
- Soil water holding capacity automatically extracted for mapped field from SSURGO database
- Online weather station(s) selected from Colorado Agricultural Meteorological (CoAgMet) network
- Irrigation system characteristics (type, efficiency)
- Crop type, planting/emergence date, managed root zone
- Management allowed depletion (MAD)
- Actual irrigation amounts

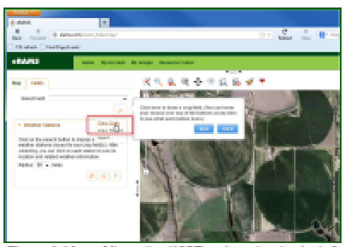

Figure 1. View of the online WISE system showing tools for drawing field boundaries on a map.

WISE outputs (by irrigated field)

- Irrigation water requirement (based on daily soil water balance)
- Daily soil water deficit:

$$D_c = D_p + ET_c - P - Irr + SRO + DP$$

where D_c is the soil water deficit (net irrigation requirement) in the root zone on the current day, D_p is the soil water deficit on the previous day, ET_c is the crop evapotranspiration rate for the current day, P is the gross precipitation for the current day, Irr is irrigation amount for the current day, SRO is surface runoff, and DP is deep percolation or drainage. Note that this equation cannot be applied to fields with upward flow of shallow ground water into the root zone.

- Evapotranspiration (ET) from previous time periods (days or week) calculated by CoAgMet
- Short-term (5-day) forecast of soil water deficit and ET
- Testing of WISE for corn in north east Colorado (2010 – 2012) gave an average soil water deficit error of 13.6%.

Go to http://wise.colostate.edu for more information.

Figure 2. Example graph showing soil water deficit in the root zone (blue line; inches of water) in relation to management allowed depletion (MAD, red line). Irrigation is recommended when the deficit approaches or falls below the MAD.

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National Institute of Food and Agriculture

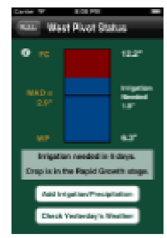
eRAMS/CSIP

- eRAMS web-based GIS is used to map irrigated field boundaries, obtain soil water characteristics from Soil Survey Geographic (SSURGO) Database, and select CoAgMet weather stations.
- Modeling services are used to calculate the daily soil water balance for each field and estimate irrigation requirements.
- Cloud Services Innovation Platform provides cloud services to manage multiple users of WISE.

WISE app

- Provides WISE outputs for each irrigated field to help make irrigation decisions
- Allows inputs of actual irrigation or precipitation amounts
- Stand-alone versions for the Apple or Android smart phone or tablet platforms will synch with eRAMS when a network connection is available.

Figure 3. iPhone® app showing a "water bucket" representation of soil moisture status of a field. Field capacity (FC) and wilting point (WP) show the upper and lower limits of plant available water (inches of water) in the root zone, respectively. The red bar shows the estimated amount of depletion relative to management allowed depletion (MAD).



Acknowledgements

Major funding for WISE was provided by USDA-NIFA. Additional funding was provided by Colorado Water Conservation Board, Colorado Agricultural Experiment Station, Western Sugar Cooperative, and Coca Cola. CSIP is supported by USDA-NRCS (Information Technology Center), USDA-ARS (Agricultural Systems Research Unit), and CSU (Dept. of Civil and Environmental Engineering). Programming of the web-based tool was done by Kyle Traff. Programming of the iPhone app was done by Andrew Bartlett. Troy Bauder, Erik Wardle, Joel Schneekloth, and Perry Cabot helped coordinate outreach activities.

Assessing Corn Water Irrigation timing Using Spectral Reflectance

Brenna Mefford[1], José L. Chávez[1], Kendall DeJonge[2], and Tom Trout[2]
[1]Department of Civil and Environmental Engineering, Colorado State University and [2]USDA-ARS, Agricultural Research Service , Fort Collins, CO

Project Overview:

In this project it is proposed to use corn canopy spectral reflectance to trigger irrigations and avoid stress and yield loss. This method requires only two sets of data (1) vegetation index value (NDVI, GNDVI, or OSAVI) for the field (2) Growth stage data from the field. This method was determined from data taken during the 2013 growing season in Greeley, CO at the Limited Irrigation Research Facility (LIRF) managed by the Agricultural Research Service Water Management Unit.

Project Objective:

Evaluate if corn spectral reflectance can be used as an indicator of water stress and as a trigger for irrigation.

Figure 1. "High boy" tractor driving through the corn field at LIRF in Greeley, CO. Boom with sensors is kept over the center of the stress treatment plots.

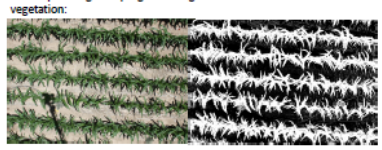
Figure 2. Sensor platform on top of boom.

Methods and Materials

A "high boy" tractor that has a 10 foot boom which is held over the middle of the corn plots is driven through the field. On the top of the boom is a platform that has a Canon 50d digital camera, and two multispectral SKYE sensors. One SKYE sensor measures incoming light, the other measures light reflected from the corn canopy. Images from the Canon 50d were processed by a program to calculate fractional vegetation cover in each plot. A water balance was built using soil moisture measurements obtained using a Neutron Probe for each treatment of deficit irrigation. Three different vegetation indices were calculated for each treatment using multispectral data, from the SKYE sensors, acquired around local noon hours (standard time). The three indices calculated were (1) Normalized Difference Vegetation Index (NDVI), (2) Green Normalized Difference Vegetation Index (GNDVI), and (3) Optimized Soil Adjusted Vegetation Index (OSAVI). These indices were compared to the crop water stress coefficient (Ks) to determine sensitivity to water stress. Fractional vegetation and growth stage data from a fully irrigated treatment were used to create a table linking corn growth stage to fractional vegetation to vegetation indices.

Calculation of Fractional Vegetation Cover:

Raw imagery from the Cannon 50d camera, and the output image after running the image through the fractional vegetation program, along with the output image the program also gives a numerical value for fractional vegetation:



Cannon 50d Image Output Image

Calculation of Vegetation Indices:

Multispectral data from the SKYE sensors were used to calculate three different vegetation indices:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

$$GNDVI = \frac{NIR - Green}{NIR + Green}$$

$$OSAVI = \frac{(NIR - Red)}{(NIR + Red + 0.16)} \times (1.16)$$

Calculation of Vegetation Ratios:

Vegetation ratios were developed in order to get the vegetation indices on a scale of 1 to 0 to be able to compare to K_s (crop water stress coefficient)

$$N_{ratio} = \frac{NDVI_{stressed}}{NDVI_{no\ stress}}$$

$$G_{ratio} = \frac{GNDVI_{stressed}}{GNDVI_{no\ stress}}$$

$$O_{ratio} = \frac{OSAVI_{stressed}}{OSAVI_{no\ stress}}$$

Comparison of Vegetation Ratios to K_s:

Comparing the vegetation ratios to K_s resulted in small root mean square error (RMSE) and mean bias error (MBE) values. Thus, suggesting that the vegetation ratios could be used to monitor corn water stress.

	RMSE	MBE	R^2
N_{ratio}	0.076	0.029	0.535
G_{ratio}	0.062	0.024	0.463
O_{ratio}	0.076	0.031	0.448

Steps for Proposed Method to Schedule Irrigations:

1.) Determine NDVI, GNDVI, or OSAVI values from field using a handheld sensor or surface reflectance data from airborne or satellite imagery.

2.) Determine average growth stage of corn in farmers field.

3.) Use below table and average growth stage to determine corresponding vegetation index value of a fully irrigated field with no stress occurring.

Growth Stage	Fractional Vegetation	NDVI	GNDVI	OSAVI
Emergence	0.01	-0.03	0.02	-0.07
V1	0.02	-0.02	0.02	-0.06
V3	0.03	-0.01	0.03	-0.05
V5	0.10	0.07	0.09	0.04
V7	0.28	0.25	0.25	0.26
V9	0.65	0.64	0.57	0.73
V11	0.75	0.75	0.66	0.85
V14	0.88	0.89	0.77	1.01
V16	0.89	0.90	0.78	1.03
V18 (VT)	0.90	0.91	0.80	1.05
R1	0.86	0.87	0.76	1.00
R2	0.82	0.83	0.73	0.94
R3	0.77	0.77	0.68	0.88
R4	0.75	0.75	0.66	0.86
R5	0.68	0.67	0.60	0.76
R6	0.09	0.06	0.09	0.03

4.) Using the vegetation index value from the farmers field of interest and the vegetation index value for a fully irrigated field from the above table, calculate the vegetation ratio of choice.

5.) If vegetation ratio is less than a value of 0.93 an irrigation needs to occur to keep the corn from experiencing a large stress event that could effect the yield.

Conclusion:

Corn spectral reflectance could be used to monitor water stress and trigger irrigations. Using vegetation ratios allows for irrigation events to be triggered using five steps. With technology continually improving hand held multispectral sensors that are cost effective are becoming more readily available making the proposed method easier to use.

CROP WATER STRESS INDEX METHOD EVALUATION

José L. Chávez[1], Emily Kullberg[1], Kendall DeJonge[2], Tom Trout[2], and Jon Altenhofen[3]
[1]Department of Civil and Environmental Engineering, Colorado State University, [2]USDA ARS, [3]Northern Water

Introduction

CWSI (Crop Water Stress Index) is a method used to monitor crop water use. Governing equation relates the temperature difference (dT) between canopy and air (Tc – Tair) and lower limit non-water-stressed difference (dT_{min}) and upper limit severely-stressed difference (dT_{max}). Maximum and minimum dT can be calculated through equations shown below. Parameters "a" and "b" are slope and intercept of the linear relationship. VPG is estimated as the difference between saturated vapor pressure at air temperature and at a higher temperature equal to air temperature plus the coefficient "b". VPD, or vapor pressure deficit, is estimated as the difference between saturated vapor pressure at air temperature and the actual vapor pressure. For eastern CO, the coefficients for corn are "a" -1.99 and "b" 3.04.
Data requirements for the CWSI include: Relative humidity (RH), Ambient air temperature (T_a), and Crop canopy temperature (T_c).

Objective

The objective was to evaluate the accuracy of the CWSI method to estimate crop water stress through comparison to volumetric water content.

Temperature data

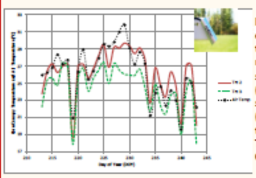
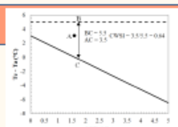


Figure 1. Plot of canopy temperature for non-water stressed treatment (Trt 3), for water stressed treatment (Trt 2), and of air temperature (Air Temp) in degrees Celsius (°C).

Method



$$CWSI = \frac{dT - dT_{min}}{dT_{max} - dT_{min}}$$

dT_{min} = a (VPD) + b

dT_{max} = a (VPG) + b

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 °C). VPD = es – ea

$e_a = (RH/100) \times e_s$ where, RH is relative humidity in percent (%).

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

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

Infrared Thermometer Instrumentation

Figure 3. IRT Sensor (SI-111)

Apogee Infrared Temperature Sensor (model SI-111)

- Measures surface temperature by converting thermal energy radiated from any surface in its field- of-view (FOV) to an electrical signal with a response time of 0.6 seconds
- 8-14 µm germanium atmospheric window
- Uncertainty of 0.2°C (95% confidence)
- Calibrated target temperature range from -30 to 65°C

Results

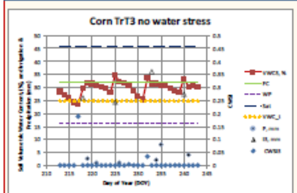


Figure 2. Plots of corn water stress (CWSI3) and soil volumetric water content (VWC3) for non-water stressed treatment (Trt 3).

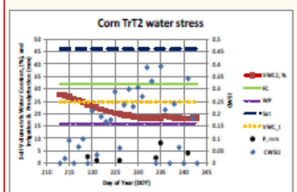


Figure 3. Plots of corn water stress (CWSI2) and soil volumetric water content (VWC2) for the deficit irrigated or water stressed treatment (Trt 2).

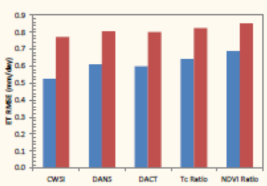


Figure 4. Weekly ET estimate RMSE (mm/week) for each combination of Ks and Kcb

$ET = (1 - CWSI) \cdot ET_C$

Where ET_c is the reference evapotranspiration developed with local weather data and using the Penman-Monteith Evapotranspiration Equation and tabulated corn crop coefficients.

Results (contd.)

CWSI vs. Volumetric Soil Water Content: There is a strong correlation between CWSI and soil volumetric water content (VWC). Taghvaeian et al. (2012), found that VWC would be equal to or greater than 28.3% at no stress for a clay loam soil texture in Iliff, CO. To avoid crop water stress and therefore yield loss, a CWSI of 0.20 – 0.23 was recommended.

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.

$$SWSI = \frac{VWC_t - VWC_a}{VWC_t - VWC_{WP}}$$

where, VWC_a is the actual VWC or current measured soil moisture level.

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.

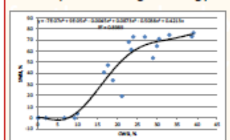


Figure 5. Relationship between CWSI and SWSI for the sandy clay loam soil near Greeley, CO.

Conclusions

- ❑ The CWSI captures corn water stress. The associated error on derived ET values were 0.52 mm/d (RMSE) which is an acceptable error.
- ❑ The CWSI closely follows soil moisture deficit and is therefore a good indicator of soil moisture depletion and crop water status.
- ❑ If minimal yield reduction is desired then CWSI should not decrease below 0.20-0.23.

Thanks to the following funding and collaborating agencies: Colorado Water Conservation Board (CWCB), Central Colorado Water Conservancy District (CCWCD), West Greeley Conservancy District (WGCD), Northern Water (NW), USDA ARS, USDA NRCS CIG, and CSU Extension.

Estimating Actual Evapotranspiration, Crop Water Stress Index and NDVI using Unmanned Aerial System (UAS) remote sensing

CPT Jeffrey C. Hathaway and José L. Chávez
Department of Civil and Environmental Engineering, Colorado State University

Project Overview:

The ability to have access to accurate and timely crop water requirements is extremely important in the modern era, where the demands on our limited water resources are ever increasing. Utilizing airborne and satellite remote sensing platforms, it is possible to determine the Actual Evapotranspiration (ET_a), Crop Water Stress Index (CWSI) and NDVI, which all are commonly used in planning for precision irrigation. Colorado State University has begun researching using UAS platforms as a remote sensing platform for frequent, cost effective data collection at the field level.
Research has shown that remote sensing can be used to obtain ET_a, CWSI and general crop health using the Thermal, Near-Infrared (NIR), and Red bands of the Electromagnetic Spectrum. Spatially distributed Canopy Temperature (T_c) derived from remote sensing sensors can be paired weather data derived from weather station data (such as COAGMET) to estimate the CWSI. Using the estimated CWSI and Reference ET (ET_r), it is possible to estimate the spatially distributed ET_a. The overall health of the crop can be estimated using NDVI, which is a ratio of the plants reflectance of the NIR and Red wavelengths.

NDVI estimate with remote sensing:

$NDVI = (R_{NIR} - R_{RED}) / (R_{NIR} + R_{RED})$ Neale et al. (1989)

where R_{NIR} is reflectance in the near infra-red band, R_{RED} is reflectance in the red band and L is an adjusting factor to minimize soil background effects (function of soil type and crop growth stage).

Fig. 1. Example of a high resolution multispectral surface reflectance remote sensing imagery. The false color composite image (near infra-red, red, and green bands stack) shows the green vegetated areas in shades of red color. The more intense the red color (larger pixel value) the more plant biomass is present and therefore the NDVI value is larger.

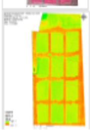


Fig. 2. Example of a high resolution, spatially distributed NDVI remote sensing imagery. The false color composite image (Red=0 to Green=1) shows the higher NDVI values (healthy vegetation) as shades of green, and soil as red. The north west plot is fully irrigated and has an average NDVI of 0.593 while the south east plot is in drought condition has a NDVI of 0.5217.

Fig. 3. Example of a high resolution, RGB imagery from the Tempest UAS A6000 Digital Camera.

Fig. 4. CSU Tempest UAS. The Tempest is equipped with a Tetracam SNAP ADC Multi-Spectral Cameral, FLIR Tau 2 640 Thermal Camera, Sony A6000 Digital Camera, CropScan MSR5 Multi-Spectral Scanner and a Exergen IRT. The Tempest flies at 400 ft AGL at 18 m/s. The endurance for a standard flight is 1.5 hrs, allowing data to be collected over ~1,000 acres with a 60% image overlap. Spatial resolutions: Thermal camera of approx. 12 cm pixel size, multispectral camera with approx. 6.5 cm.

Fig. 5. CSU Tempest UAS conducting remote sensing operations at CSU ARDEC on August 13, 2015.

Funding provided by:
Colorado Water Conservation Board (CWCB)
Colorado Water Institute
Borland Hydrology Fund
CSU Extension

References: Christopher M. U. Neale, H. Jayanthi, J.L. Wright. Irrigation water management using high resolution airborne remote sensing. *Journal of Irrigation and Drainage System*; Volume 19; 2005; 321-336.
E. R. Hunt,C.S.T. Daughtry, S.B. Mirsky, W.D Hively. Remote sensing with unmanned aircraft systems for precision agriculture applications. *Second International Conference on Agro-Geoinformatic*; 2013.

CWSI estimate with remote sensing

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

where dT is the difference between the Canopy Temperature (Tc (c)) and the Air Temperature (Ta (c)). $dT_{\max}$ is assumed to be 4.5 C (for corn in Northern Colorado) and $dT_{\min}$ is:

$dT_{\min} = -1.99 * (VPD) + 3.04$

where VPD is the Vapor Pressure Difference, which is a function of Ta (c), and Relative Humidity (RH (%)).

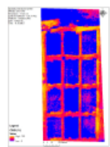


Fig. 6. Example of a high resolution, spatially distributed CWSI remote sensing imagery. The false color composite image (Blue = 0% stress, Red= 100% stress) shows the amount of water stress that the crop is exhibiting. The bluer the color the less stress the crop is under. The north west plot is fully irrigated (under no stress (0.008%)), while the south east plot is at drought conditions (exhibiting stress (7.12%)).

Fig. 9. Conducting joint flight operations with Utah State University.

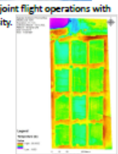


Fig. 7. Example of a high resolution, spatially distributed thermal remote sensing imagery. The false color composite image shows the amount of surface/canopy temperature (Drought – 27.68 C / Full – 25.09 C).

ETa estimate with remote sensing

$ET_a = (1 - CWSI) * ET_r$

Where ET_r is the Reference Evapotranspiration developed with local weather data and using the Penman-Monteith Evapotranspiration Equation.

Fig. 10. Conducting remote sensing data collection at CSU ARDEC August 13, 2015.

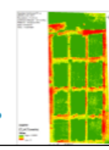
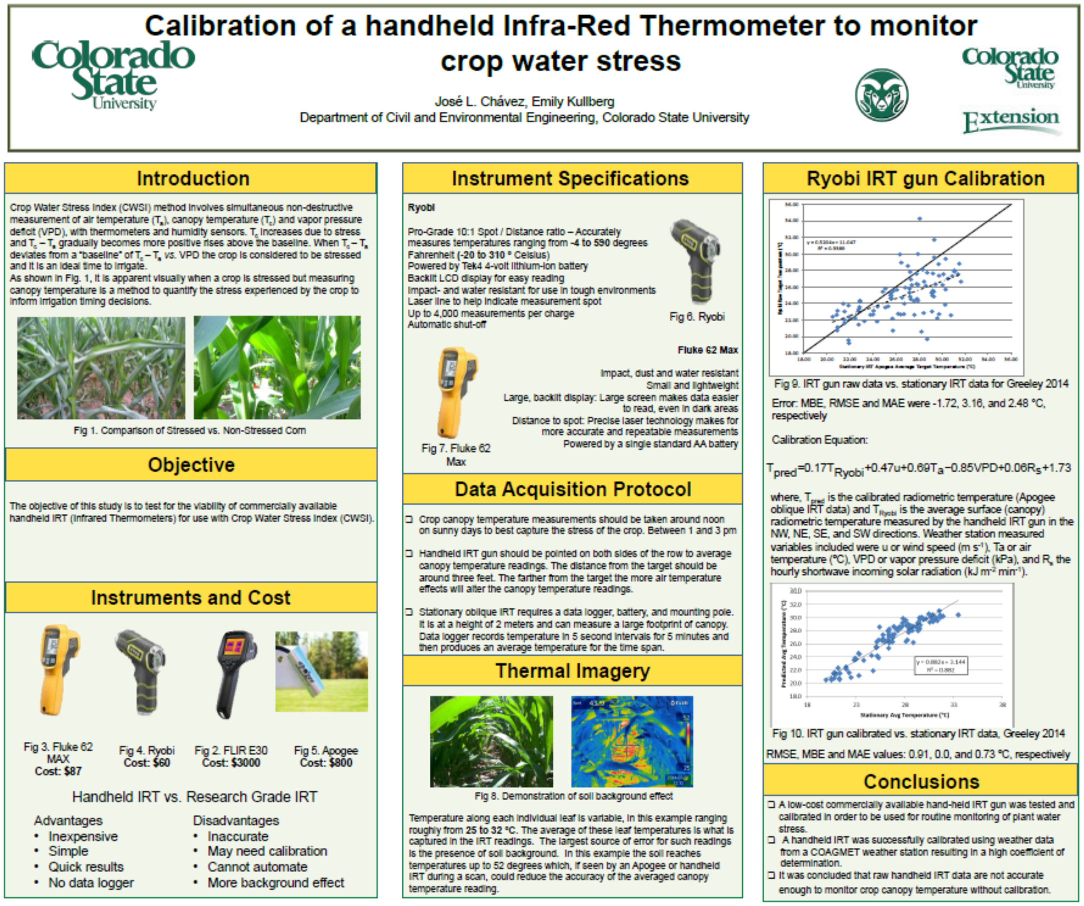


Fig. 8. Example of a high resolution, spatially distributed ET_a remote sensing imagery. The false color composite image shows the amount of hourly ET (how much water the plants are using. The greener the crop the larger amount of water that the crop is using. This is significant for both irrigation planning and crop health monitoring. A lower ET_a can show both water deficits as well as possible crop health issues.



Appendix F

Workshop presentations

Joel Schneekloth's presentation:

Limited Irrigation: Principles, Pros and Cons

Joel P. Schneekloth
Colorado State Extension
ATM's

Why Limited Irrigation?

- In the High Plains Aquifer
  - Declining water resources
  - Compact obligations – Reduce consumptive use
- In the South Platte Basin
  - Low snow pack
  - Competition with urban uses
  - ATM's

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Deficit Irrigation:

Applying less water than is required for full ET

Low capacity systems – Inability to meet maximum crop ET without stress

To many acres for the water supply.

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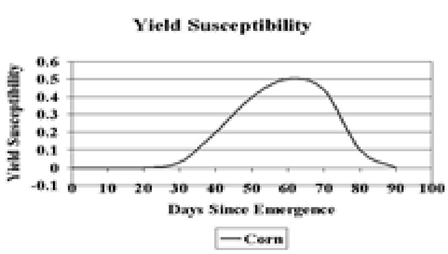
Limited Irrigation:

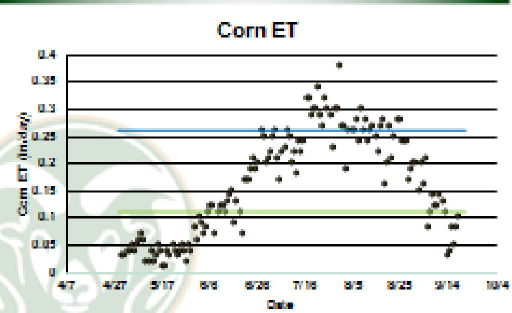
Use crop rotations with different water use patterns and/or lower water use crops to maximize the available water supply.

Grow fewer acres of a single crop but grow multiple crops.

Colorado State University

Growth Stage and Stress Impacts





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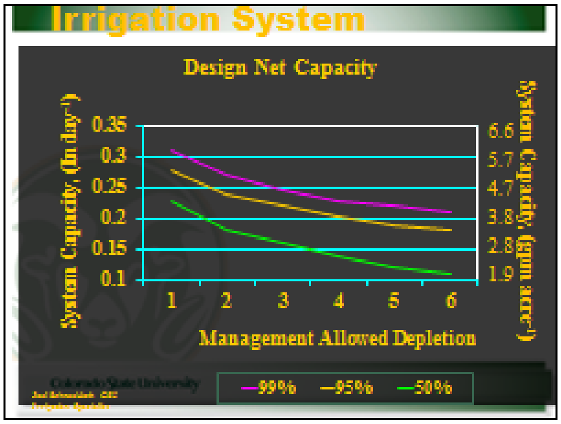

Deficit vs Limited

- Producer has 13 inches per acre to utilize
- Limited capacity or diversion capabilities
  - Deficit strategy – apply 1 inch per 8 days over growing season – all acres
  - Limited strategy – apply 1 inch per 3 days in a shortened window (reproductive time period) – limited acres

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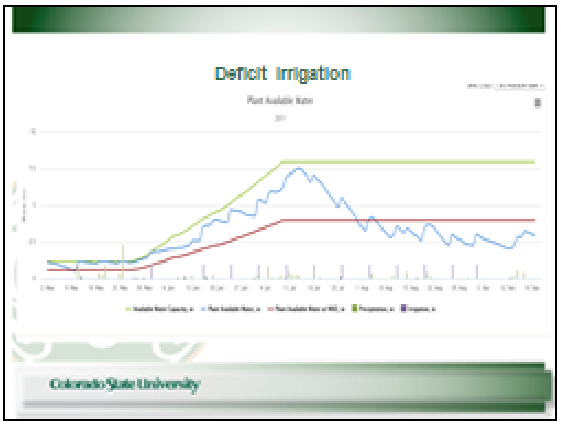

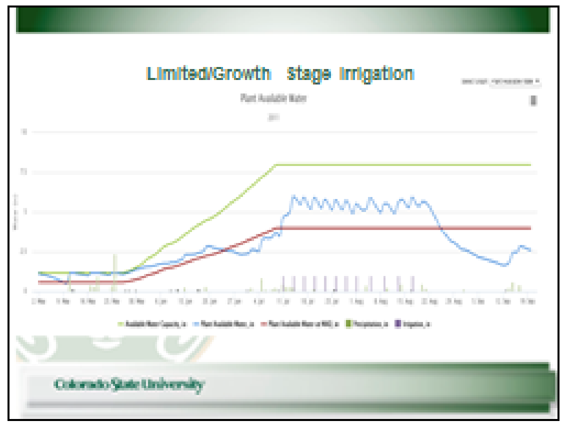

Impact of Stress

Same Irrigation Amounts
13 inches

Similar ET

What happened to grain yields?

Trial in Akron – 2011

1 inch every 8 days 140 bu $acre^{-1}$ Deficit
1 inch every 8 days 200 bu $acre^{-1}$ Limited

Impact of water stress – 60 bu with similar water applied

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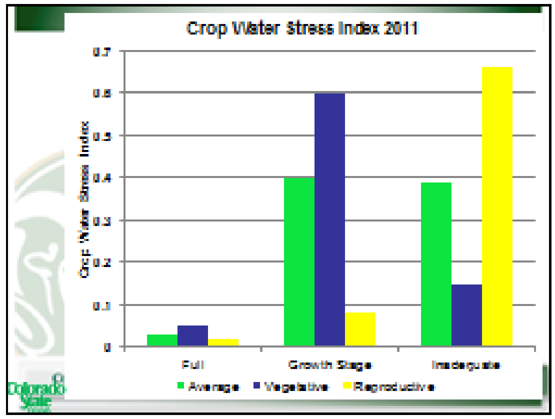
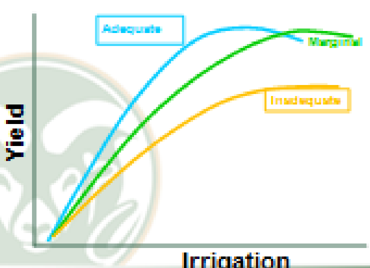


Yield vs Irrigation Capacity



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Economics

- Economics important
  - Deficit Irrigation - \$356 $acre^{-1}$
  - Growth Stage/Limited - \$599 $acre^{-1}$
  - 1 acre of Growth Stage/Limited equals 1.7 acres of Deficit – Not including land cost
  - 9.1 inches of saved water

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Cutting back further

- Previous research
  - 50% of water applied for full irrigation
  - 70 to 80% of maximum yield
- Previous example
  - 6.5 inches of water applied during a 5 week window
  - Key period for yield impact
  - Estimated yields of 140 to 160 bu $acre^{-1}$

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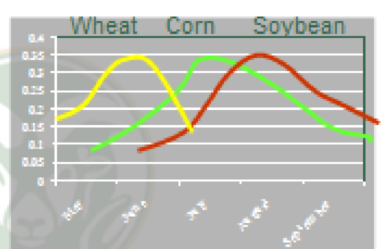
ET During Growing Season



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Water Use For Crops
Growing Season Use

Alfalfa	35 inches
Sugar Beets	29 inches
Corn	25-27 inches
Soybeans	23 inches
Dry Beans	17-18 inches
Winter Wheat	18-20 inches
Sunflowers	20-22 inches
Spring Grains	14-16 inches

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Water savings

Depending upon past cropping history, inclusion of lower water use crops can save water compared to continuous corn.

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Pros and Cons

No system is fail safe and 100%

There are issues with limited/deficit irrigation but there are some definite potential positives.

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Pros

Potential to maximize returns to water and stretch limited water resources.

Incorporating all aspects can spread time demands around rather than single cropping.

Potential for average or even better than average crops
- Excessive early season precipitation
- Leaching of nutrients

Increased precipitation use efficiency

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Cons

More management decisions
- Herbicide – rotation intervals
- Tolerance to some visible water stress

Generally splitting fields into smaller sections

With extremely dry years
- More potential for yield variability

Low water holding capacity soils
- Not as much opportunity for water savings potential

Increased precipitation use efficiency

Rotational fallowing is easier
- Potential economics not maximized

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Dr. Allan Andales' presentation/poster:

The Water Irrigation Scheduler for Efficient Application (WISE) Online Tool

Allan A. Andales[1] and Mazdak Arabi[2]

[1]Department of Soil and Crop Sciences and [2]Department of Civil and Environmental Engineering, Colorado State University

Opportunity

•Improved irrigation water management (IWM) can play a key role in water conservation, prevention of water pollution, and enhanced crop productivity.
•Irrigation scheduling advisory tools that track irrigation requirements for each field can improve IWM at the farm or irrigation distribution scale.
•The development of IWM tools on widely available mobile devices can increase the adoption of improved IWM practices.
•The availability of cloud services enables the widespread deployment of IWM tools through the Internet and wireless networks.

Objective

Develop, pilot, and disseminate a scalable device-independent mobile system for improved IWM.

User inputs (by irrigated field)

•Field boundaries using eRAMS online mapping tool.
•Soil water holding capacity automatically extracted for mapped field from SSURGO database
•Online weather station(s) selected from Colorado Agricultural Meteorological (CoAgMet) network
•Irrigation system characteristics (type, efficiency)
•Crop type, planting/emergence date, managed root zone
•Management allowed depletion (MAD)
•Actual irrigation amounts

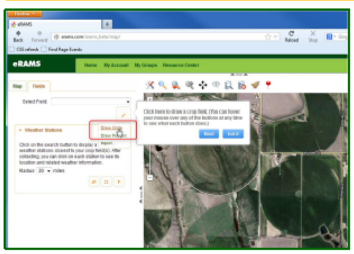


Figure 1. View of the online WISE system showing tools for drawing field boundaries on a map.

WISE outputs (by irrigated field)

•Irrigation water requirement (based on daily soil water balance)
•Daily soil water deficit:

$$D_c = D_p + ET_c - P - Irr + SRO + DP$$

where D_c is the soil water deficit (net irrigation requirement) in the root zone on the current day, D_p is the soil water deficit on the previous day, ET_c is the crop evapotranspiration rate for the current day, P is the gross precipitation for the current day, Irr is irrigation amount for the current day, SRO is surface runoff, and DP is deep percolation or drainage. Note that this equation cannot be applied to fields with upward flow of shallow ground water into the root zone.

•Evapotranspiration (ET) from previous time periods (days or week) calculated by CoAgMet
•Short-term (5-day) forecast of soil water deficit and ET
•Testing of WISE for corn in north east Colorado (2010 – 2012) gave an average soil water deficit error of 13.6%.

Go to http://wise.colostate.edu for more information.

Figure 2. Example graph showing soil water deficit in the root zone (blue line; inches of water) in relation to management allowed depletion (MAD, red line). Irrigation is recommended when the deficit approaches or falls below the MAD.

United States Department of Agriculture
National Institute of Food and Agriculture

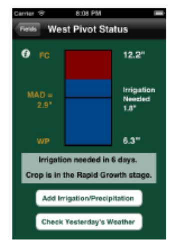
eRAMS/CSIP

•eRAMS web-based GIS is used to map irrigated field boundaries, obtain soil water characteristics from Soil Survey Geographic (SSURGO) Database, and select CoAgMet weather stations.
•Modeling services are used to calculate the daily soil water balance for each field and estimate irrigation requirements.
•Cloud Services Innovation Platform provides cloud services to manage multiple users of WISE.

WISE app

•Provides WISE outputs for each irrigated field to help make irrigation decisions
•Allows inputs of actual irrigation or precipitation amounts
•Stand-alone versions for the Apple or Android smart phone or tablet platforms will synch with eRAMS when a network connection is available.

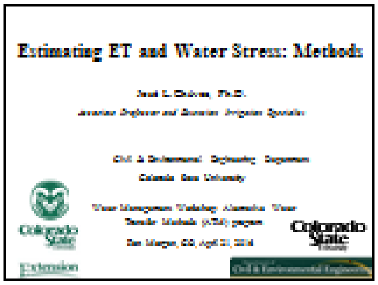
Figure 3. iPhone® app showing a "water bucket" representation of soil moisture status of a field. Field capacity (FC) and wilting point (WP) show the upper and lower limits of plant available water (inches of water) in the root zone, respectively. The red bar shows the estimated amount of depletion relative to management allowed depletion (MAD).



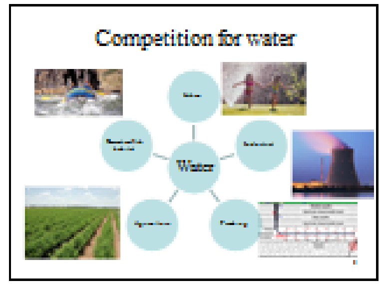
Acknowledgements

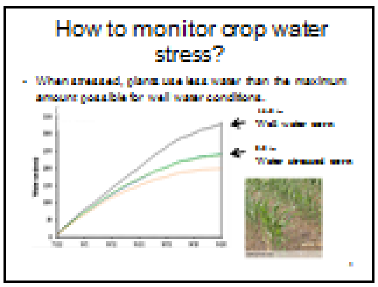
Major funding for WISE was provided by USDA-NIFA. Additional funding was provided by Colorado Water Conservation Board, Colorado Agricultural Experiment Station, Western Sugar Cooperative, and Coca Cola. CSIP is supported by USDA-NRCS (Information Technology Center), USDA-ARS (Agricultural Systems Research Unit), and CSU (Dept. of Civil and Environmental Engineering). Programming of the web-based tool was done by Kyle Traff. Programming of the iPhone app was done by Andrew Bartlett. Troy Bauder, Erik Wardle, Joel Schneekloth, and Perry Cabot helped coordinate outreach activities.

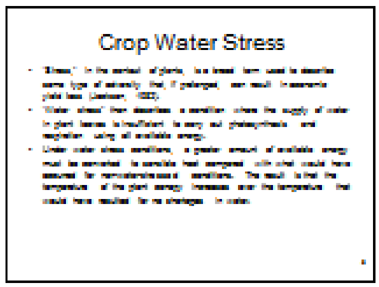
Dr. José L. Chávez's presentation:

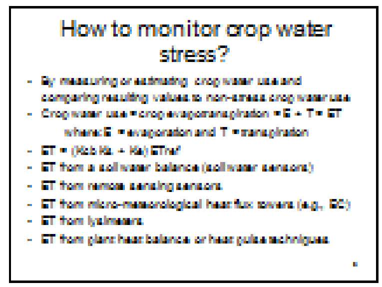

Estimating ET and Water Stress: Methods

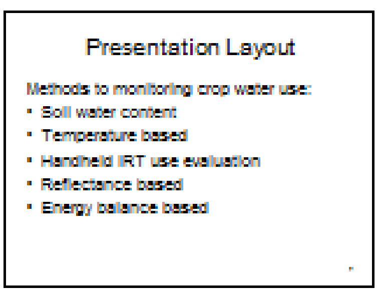

Acknowledgement
CCWCD

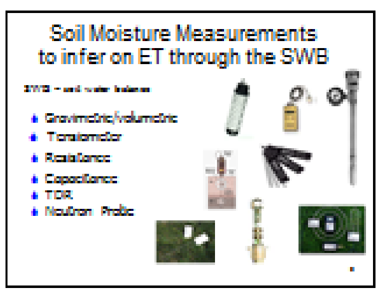

Competition for water
Water

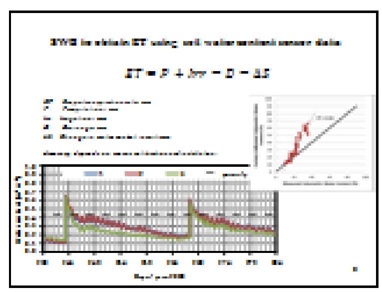

How to monitor crop water stress?
When stressed, plants use less water than the maximum amount possible for well water conditions.

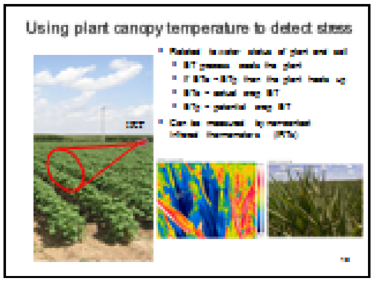

Crop Water Stress

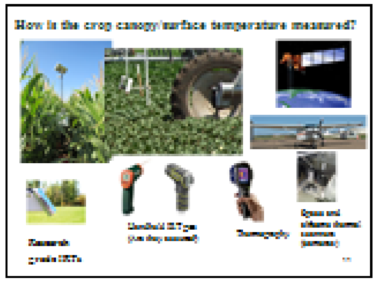

How to monitor crop water stress?
By measuring or estimating crop water use and comparing resulting values to non-stress crop water use
Crop water use = crop evapotranspiration = E + T = ET
where E = evaporation and T = transpiration
ET = (Kcb Ks + Ke) ETref
ET from a soil water balance (soil water sensors)
ET from remote sensing sensors
ET from micro-meteorological heat flux towers (e.g., EC)
ET from lysimeters
ET from plant heat balance or heat pulse techniques

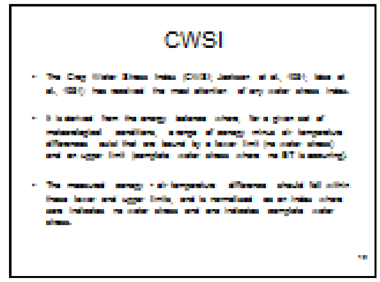

Presentation Layout
Methods to monitoring crop water use:
Soil water content
Temperature based
Handheld IRT use evaluation
Reflectance based
Energy balance based

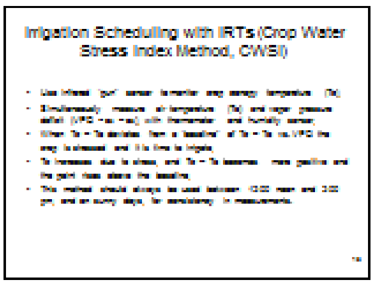

Soil Moisture Measurements
to infer on ET through the SWB
Gravimetric/volumetric
Tensiometer
Resistance
Capacitance
TDR
Neutron Probe

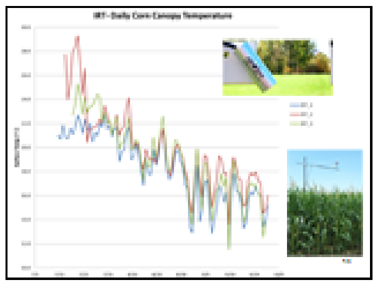

ET = P + Irr − D − ΔS

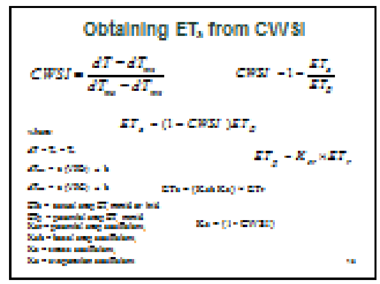

Using plant canopy temperature to detect stress

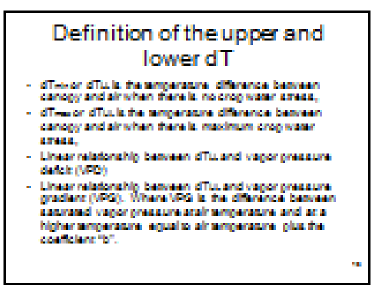

How is the crop canopy/surface temperature measured?

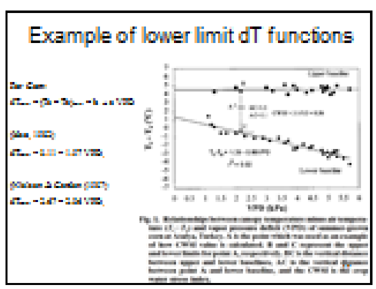

CWSI

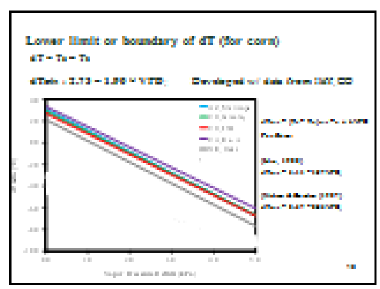

Irrigation Scheduling with IRTs (Crop Water Stress Index Method, CWSI)

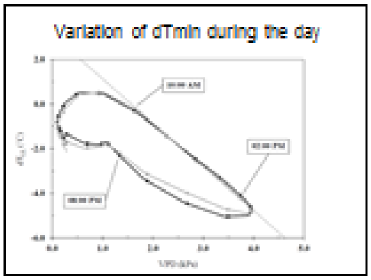


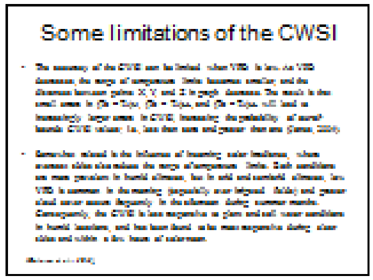

Obtaining ET from CWSI

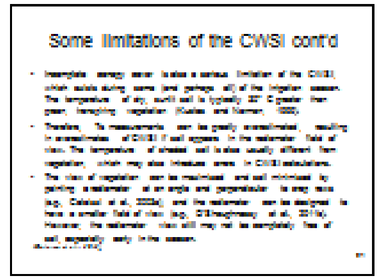

Definition of the upper and lower dT

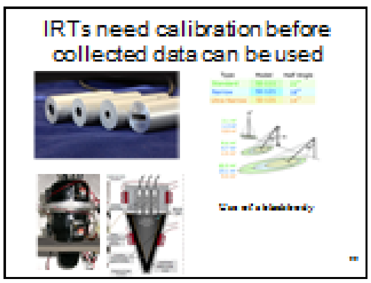

Example of lower limit dT functions

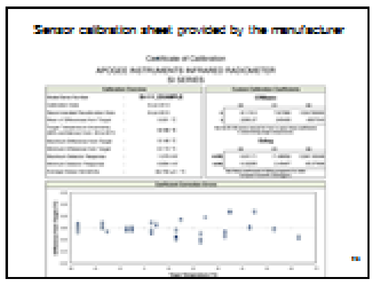

Lower limit or boundary of dT (for corn)

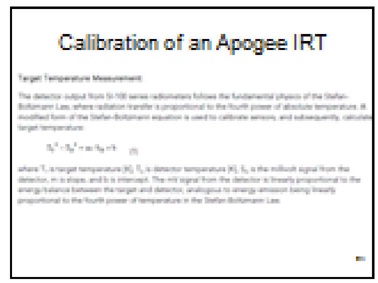

Variation of dTmin during the day
VPD (kPa)

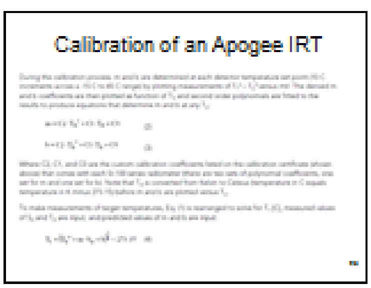

Some limitations of the CWSI

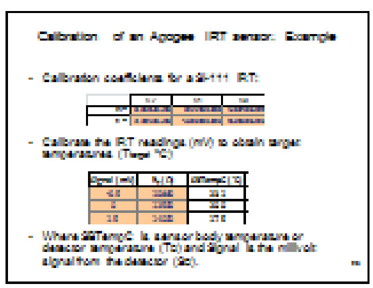

Some limitations of the CWSI cont'd

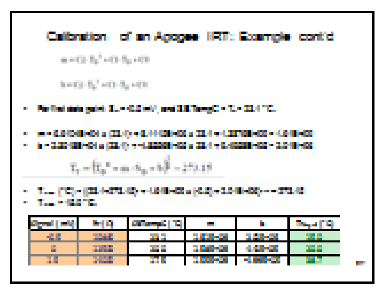

IRTs need calibration before collected data can be used
Use of a blackbody

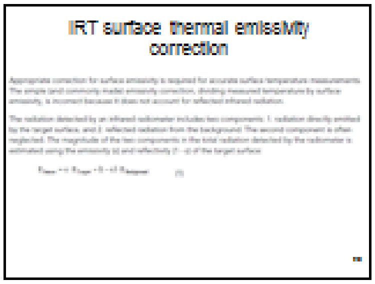

Sensor calibration sheet provided by the manufacturer
Certificate of Calibration
APOGEE INSTRUMENTS INFRARED RADIOMETER
SI SERIES

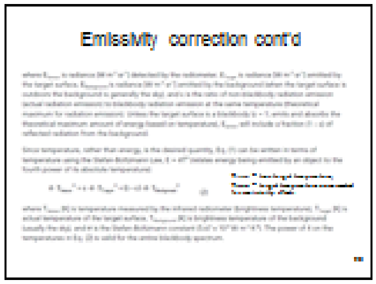

Calibration of an Apogee IRT
Target Temperature Measurement

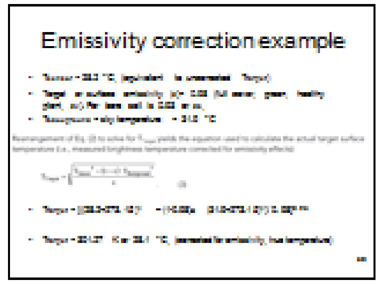

Calibration of an Apogee IRT

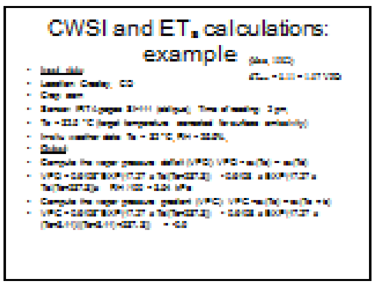

Calibration of an Apogee IRT sensor: Example
Calibration coefficients for a SI-111 IRT:
Calibrate the IRT readings (mV) to obtain target temperatures (Ttarget °C)
Where SBTempC is sensor body temperature or detector temperature (Td) and Signal is the millivolt signal from the detector (Sd).

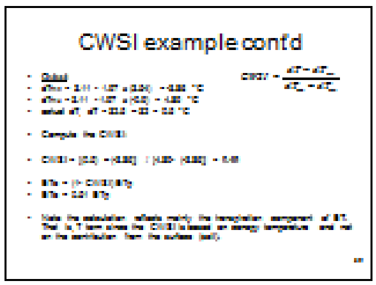

Calibration of an Apogee IRT: Example cont'd

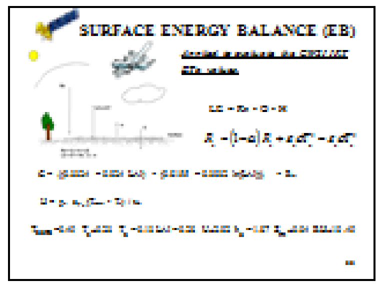

IRT surface thermal emissivity correction

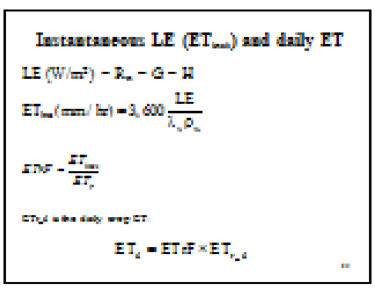

Emissivity correction cont'd

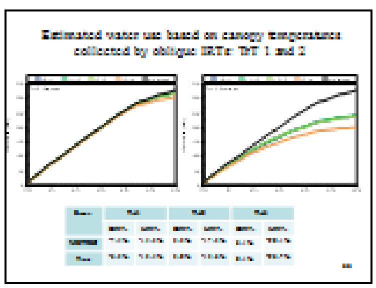

Emissivity correction example

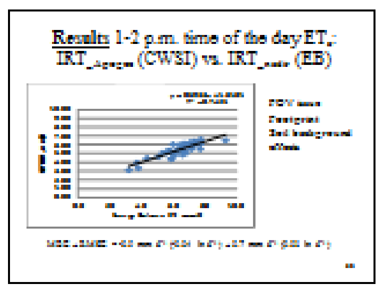

CWSI and ET_a calculations: example

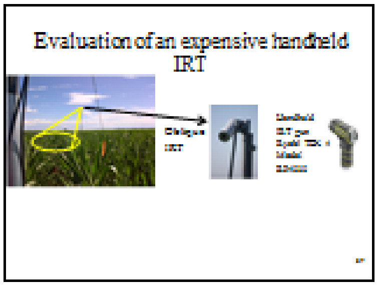

CWSI example cont'd

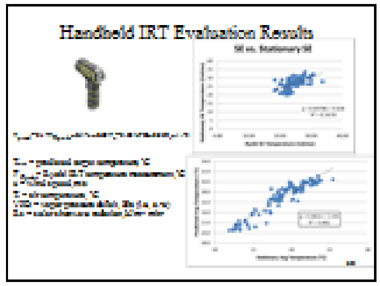

SURFACE ENERGY BALANCE (EB)


Instantaneous LE (ET_inst) and daily ET
LE (W/m²) = R_n − G − H
ET_inst (mm/hr) = 3,600 LE/(λ_v ρ_w)
ETrF = ET_inst / ET_r
ET_d = ETrF × ET_r_d

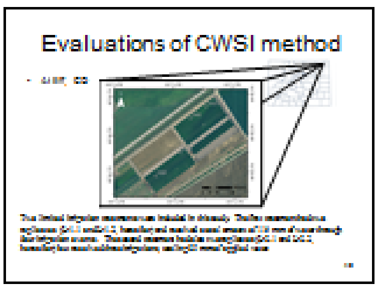

Estimated water use based on canopy temperatures collected by oblique IRTs: IRT 1 and 2

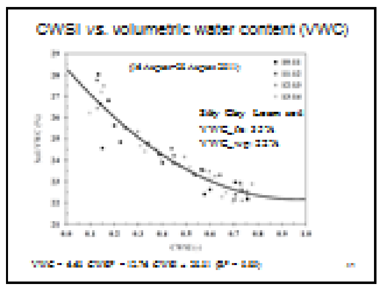

Results 1-2 p.m. time of the day ET_c:
IRT_Apogee (CWSI) vs. IRT (EB)

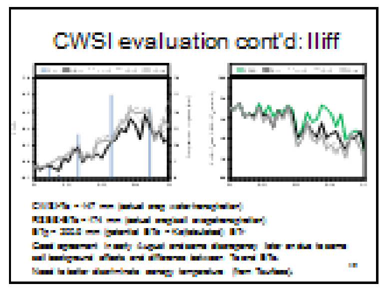

Evaluation of an expensive handheld IRT

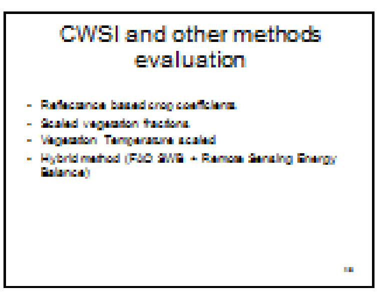

Handheld IRT Evaluation Results

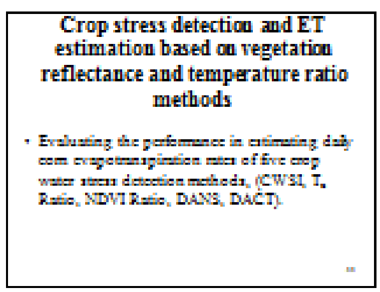

Comments on handheld IRT

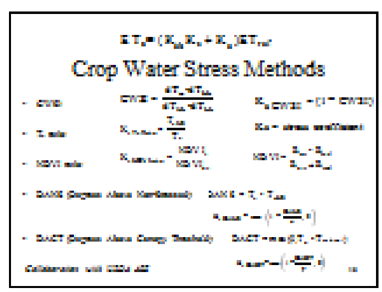

Evaluations of CWSI method

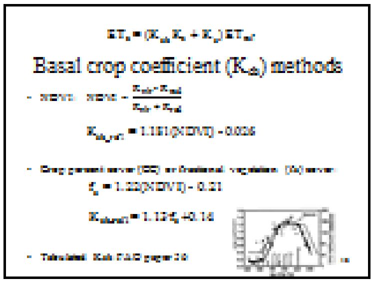

CWSI vs. volumetric water content (VWC)

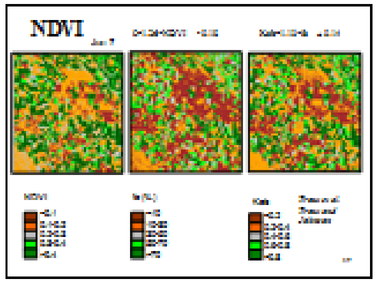

CWSI evaluation cont'd: Iliff

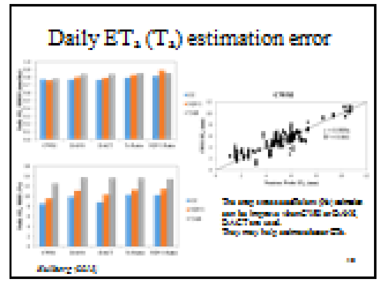

CWSI and other methods evaluation
Reflectance based crop coefficients
Scaled vegetation fractions
Vegetation Temperature scaled
Hybrid method (FAO 56 + Remote Sensing Energy Balance)

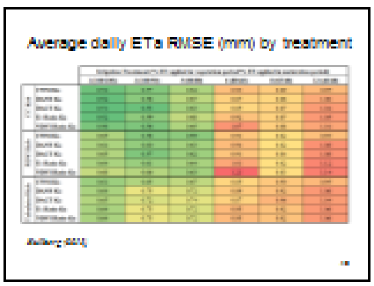

Crop stress detection and ET estimation based on vegetation reflectance and temperature ratio methods
Evaluating the performance in estimating daily corn evapotranspiration rates of five crop water stress detection methods, (CWSI, Tc Ratio, NDVI Ratio, DANS, DACT).

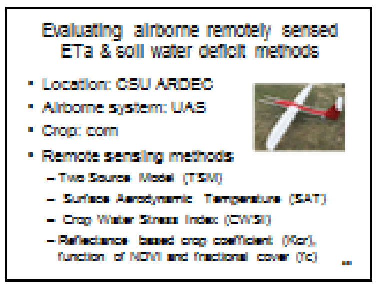

Crop Water Stress Methods

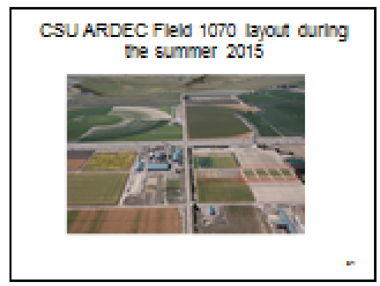

Basal crop coefficient (K_{cb}) methods
Tabulated Kcb FAO paper 56

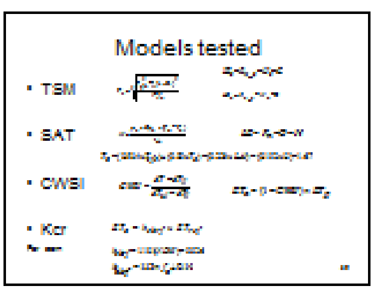

NDVI

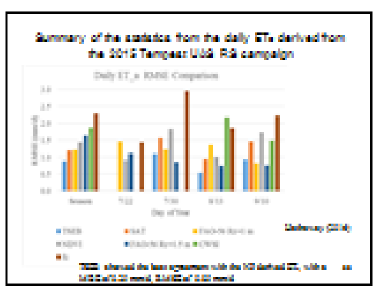

Daily ET_a (T_a) estimation error

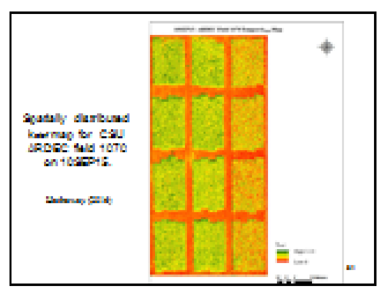

Average daily ETa RMSE (mm) by treatment

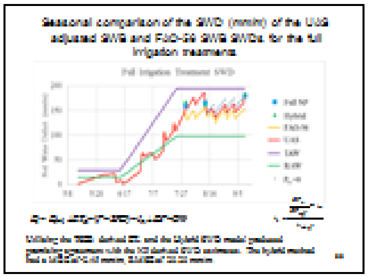

Evaluating airborne remotely sensed ETa & soil water deficit methods
Location: CSU ARDEC
Airborne system: UAS
Crop: corn
Remote sensing methods
– Two Source Model (TSM)
– Surface Aerodynamic Temperature (SAT)
– Crop Water Stress Index (CWSI)
– Reflectance based crop coefficient (Kcr), function of NDVI and fractional cover (fc)

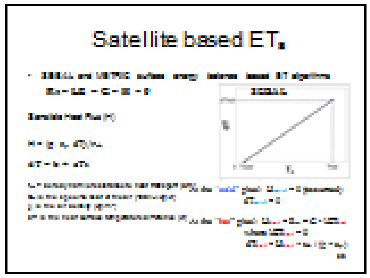

CSU ARDEC Field 1070 layout during the summer 2015

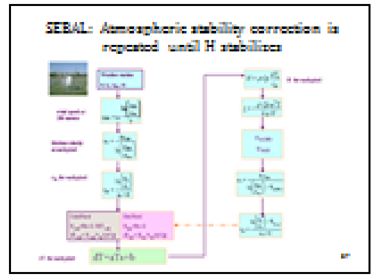

Models tested
TSM
SAT
CWSI
Kcr

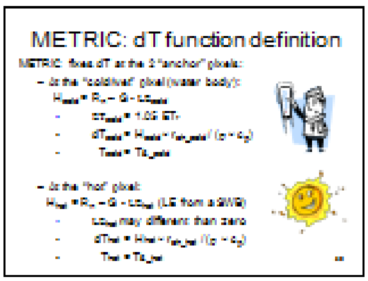

Summary of the statistics from the daily ETa derived from the 2015 Tempest UAS RS campaign

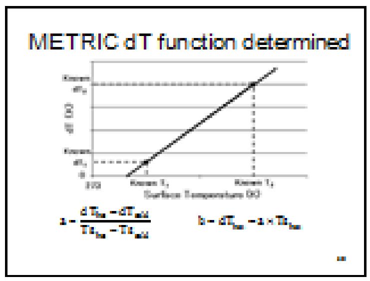

Spatially distributed Kcr map for CSU ARDEC field 1070

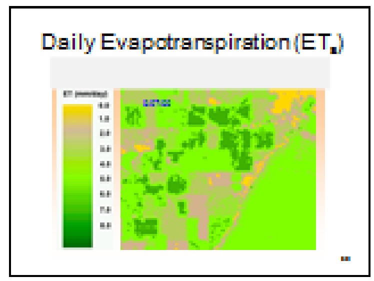

Seasonal comparison of the SWD (mm/m) of the UAS adjusted SWB and FAO-56 SWB SWDs for the full irrigation treatment

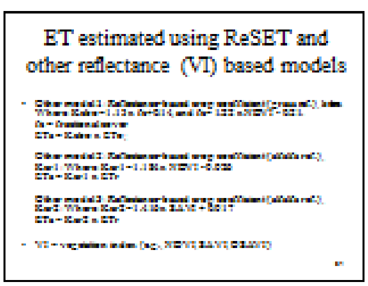

Satellite based ET$_a$
SEBAL

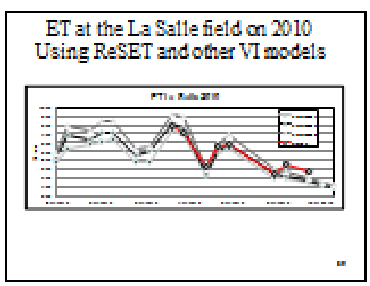

SEBAL: Atmospheric stability correction is repeated until H stabilizes

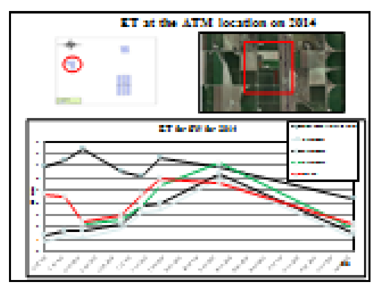

METRIC: dT function definition
METRIC fixes dT at the 2 "anchor" pixels:
At the "cold/wet" pixel (water body):
At the "hot" pixel:

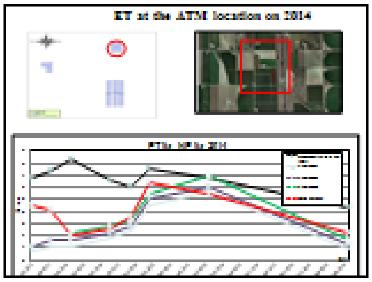

METRIC dT function determined
Surface Temperature (K)

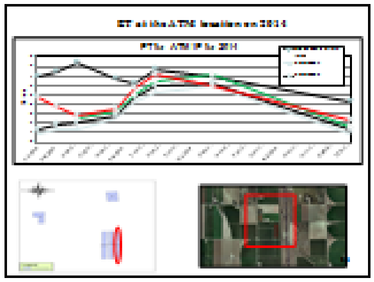

Daily Evapotranspiration (ET$_a$)

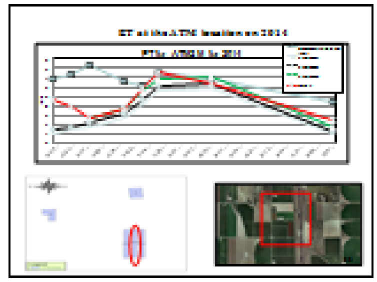

ET estimated using ReSET and other reflectance (VI) based models

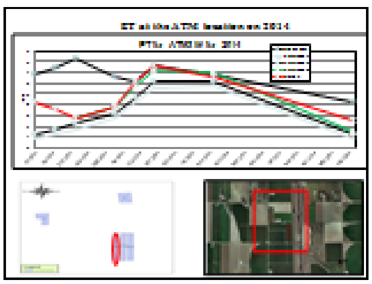

ET at the La Salle field on 2010
Using ReSET and other VI models

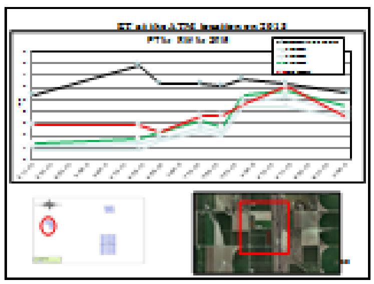

ET at the ATM location on 2014

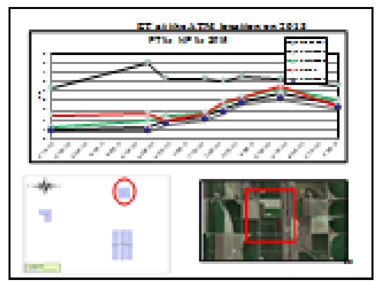

ET at the ATM location on 2014

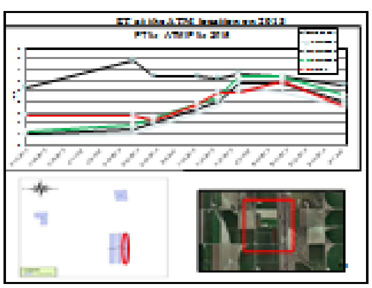


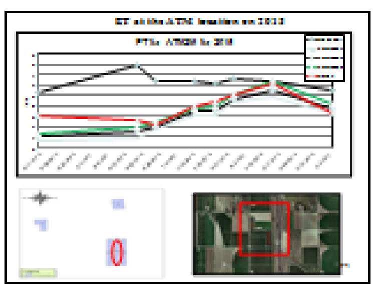


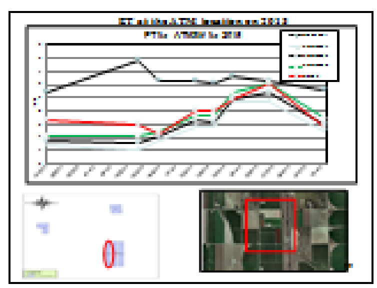


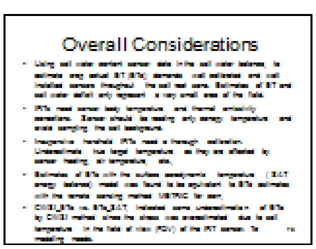


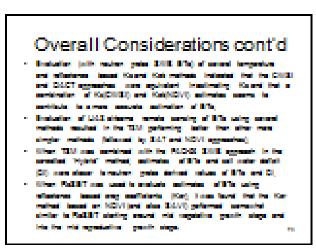






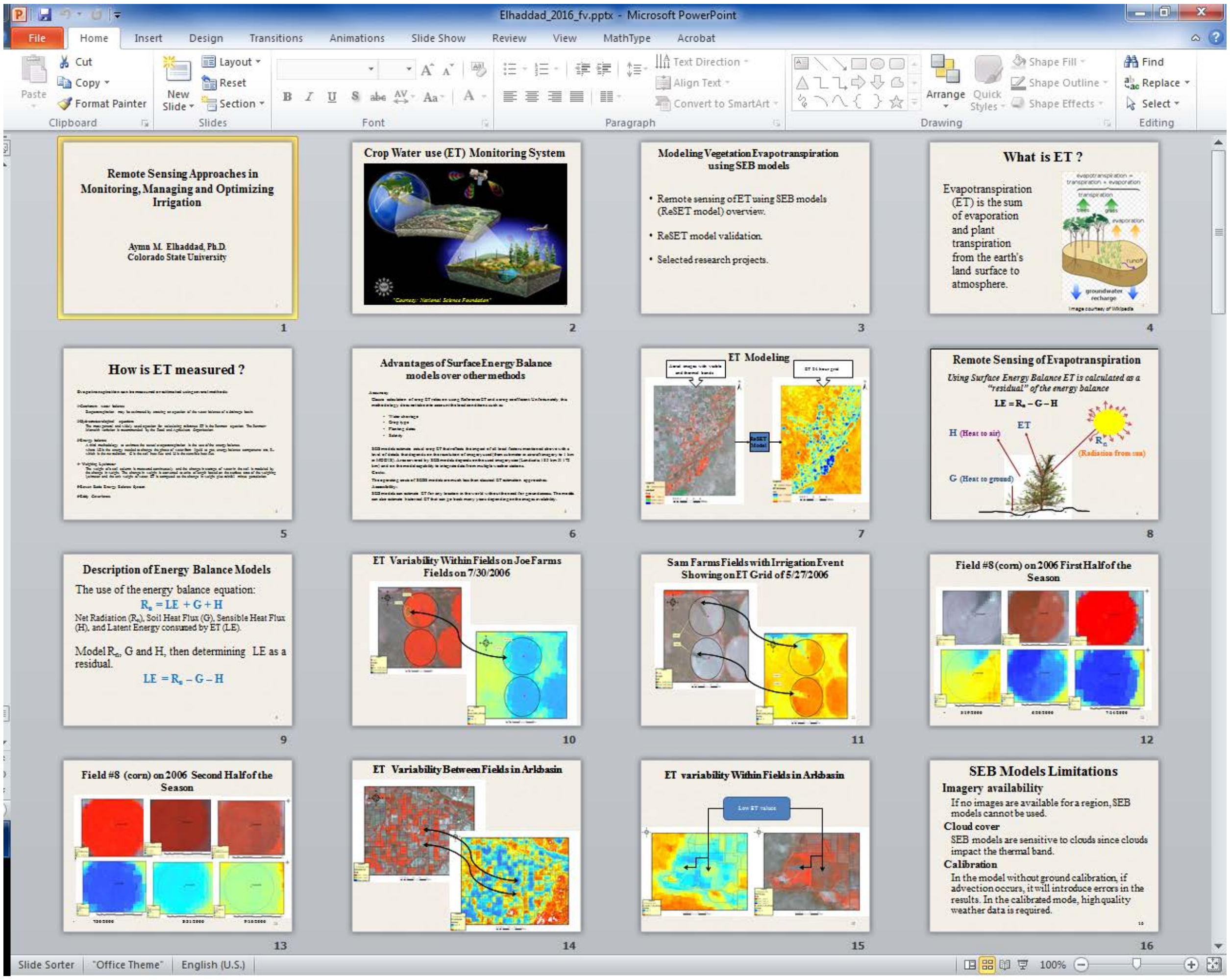


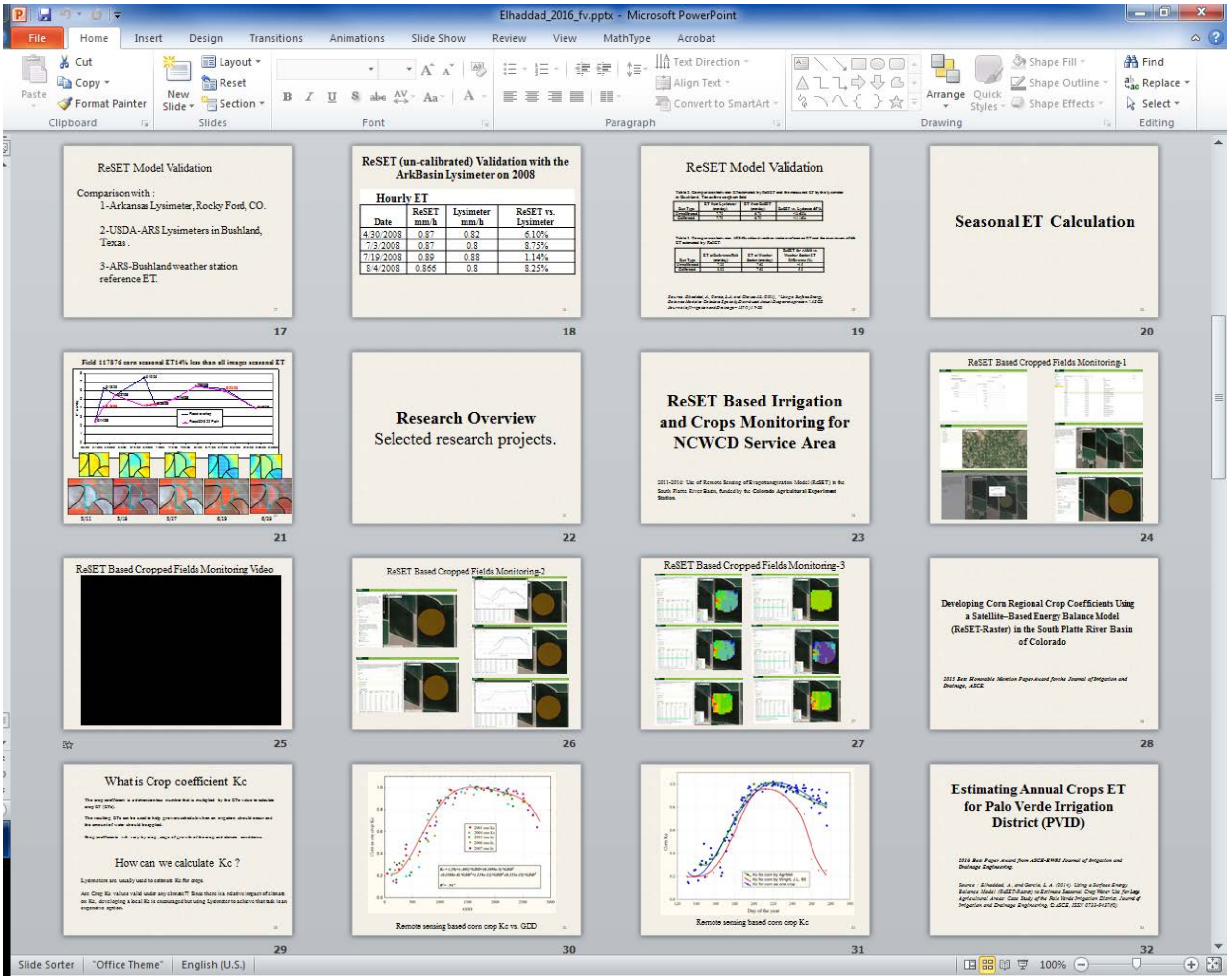

Overall Considerations


Overall Considerations cont'd


Contact Information

Dr. Aymn ElHaddad's presentation:




Elhaddad_2016_fv.pptx - Microsoft PowerPoint
ReSET Model Validation
Comparison with :
1-Arkansas Lysimeter, Rocky Ford, CO.
2-USDA-ARS Lysimeters in Bushland, Texas .
3-ARS-Bushland weather station reference ET.
17
ReSET (un-calibrated) Validation with the ArkBasin Lysimeter on 2008
Hourly ET
Date | ReSET mm/h | Lysimeter mm/h | ReSET vs. Lysimeter
4/30/2008 | 0.87 | 0.82 | 6.10%
7/3/2008 | 0.87 | 0.8 | 8.75%
7/19/2008 | 0.89 | 0.88 | 1.14%
8/4/2008 | 0.866 | 0.8 | 8.25%
18
ReSET Model Validation
19
Seasonal ET Calculation
20
21
Research Overview
Selected research projects.
22
ReSET Based Irrigation and Crops Monitoring for NCWCD Service Area
23
ReSET Based Cropped Fields Monitoring-1
24
ReSET Based Cropped Fields Monitoring Video
25
ReSET Based Cropped Fields Monitoring-2
26
ReSET Based Cropped Fields Monitoring-3
27
Developing Corn Regional Crop Coefficients Using a Satellite-Based Energy Balance Model (ReSET-Raster) in the South Platte River Basin of Colorado
28
What is Crop coefficient Kc
How can we calculate Kc ?
29
Remote sensing based corn crop Kc vs. GDD
30
Remote sensing based corn crop Kc
31
Estimating Annual Crops ET for Palo Verde Irrigation District (PVID)
32
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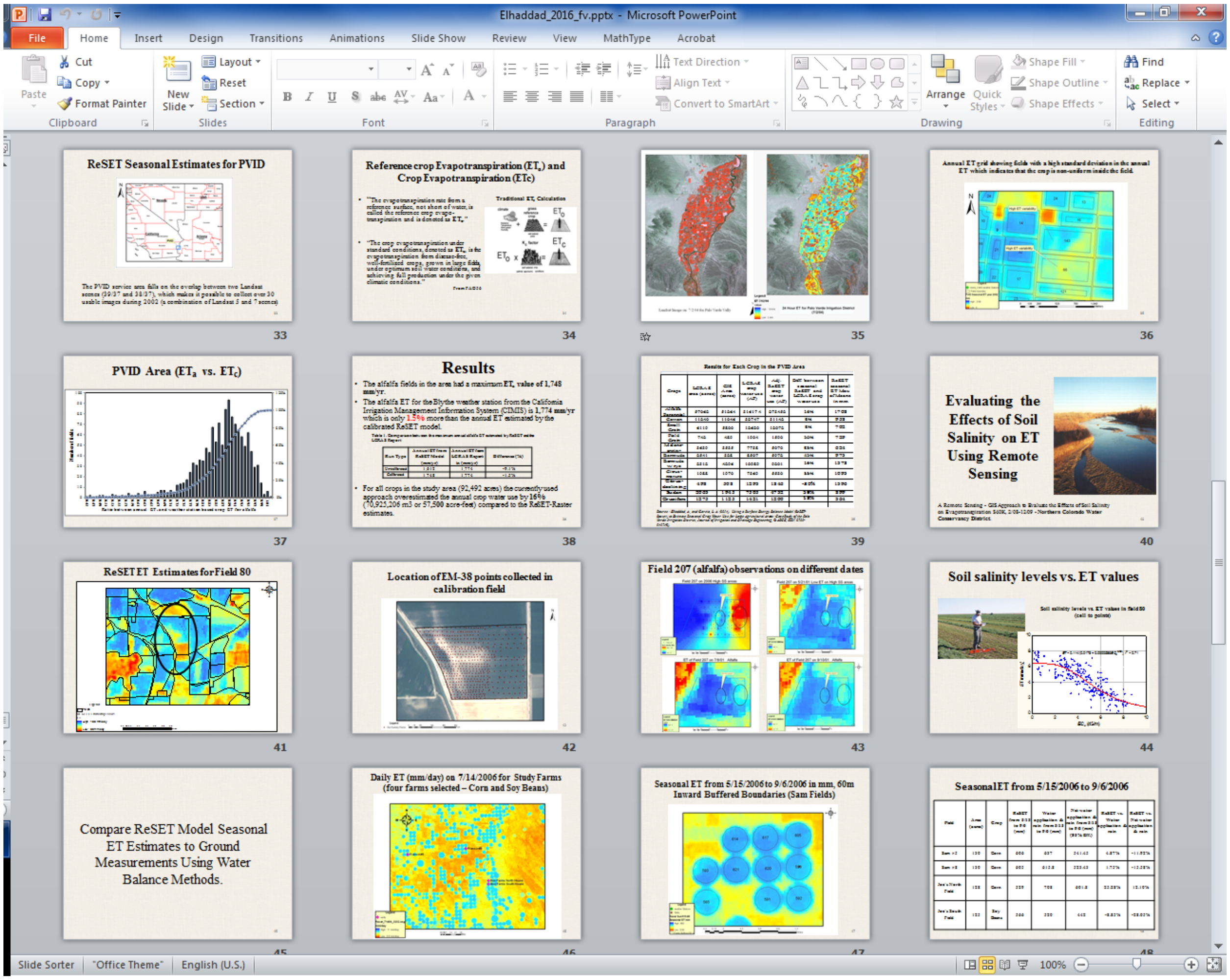
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ReSET Seasonal Estimates for PVID
33
34
35
Annual ET grid showing fields with a high standard deviation in the annual ET which indicates that the crop is non-uniform inside the field.
36
Results
37
38
Results for Each Crop in the PVID Area
39
Evaluating the Effects of Soil Salinity on ET Using Remote Sensing
40
ReSET ET Estimates for Field 80
41
Location of EM-38 points collected in calibration field
42
Field 207 (alfalfa) observations on different dates
43
Soil salinity levels vs. ET values
44
Compare ReSET Model Seasonal ET Estimates to Ground Measurements Using Water Balance Methods.
Daily ET (mm/day) on 7/14/2006 for Study Farms (four farms selected – Corn and Soy Beans)
Seasonal ET from 5/15/2006 to 9/6/2006 in mm, 60m Inward Buffered Boundaries (Sam Fields)
Seasonal ET from 5/15/2006 to 9/6/2006
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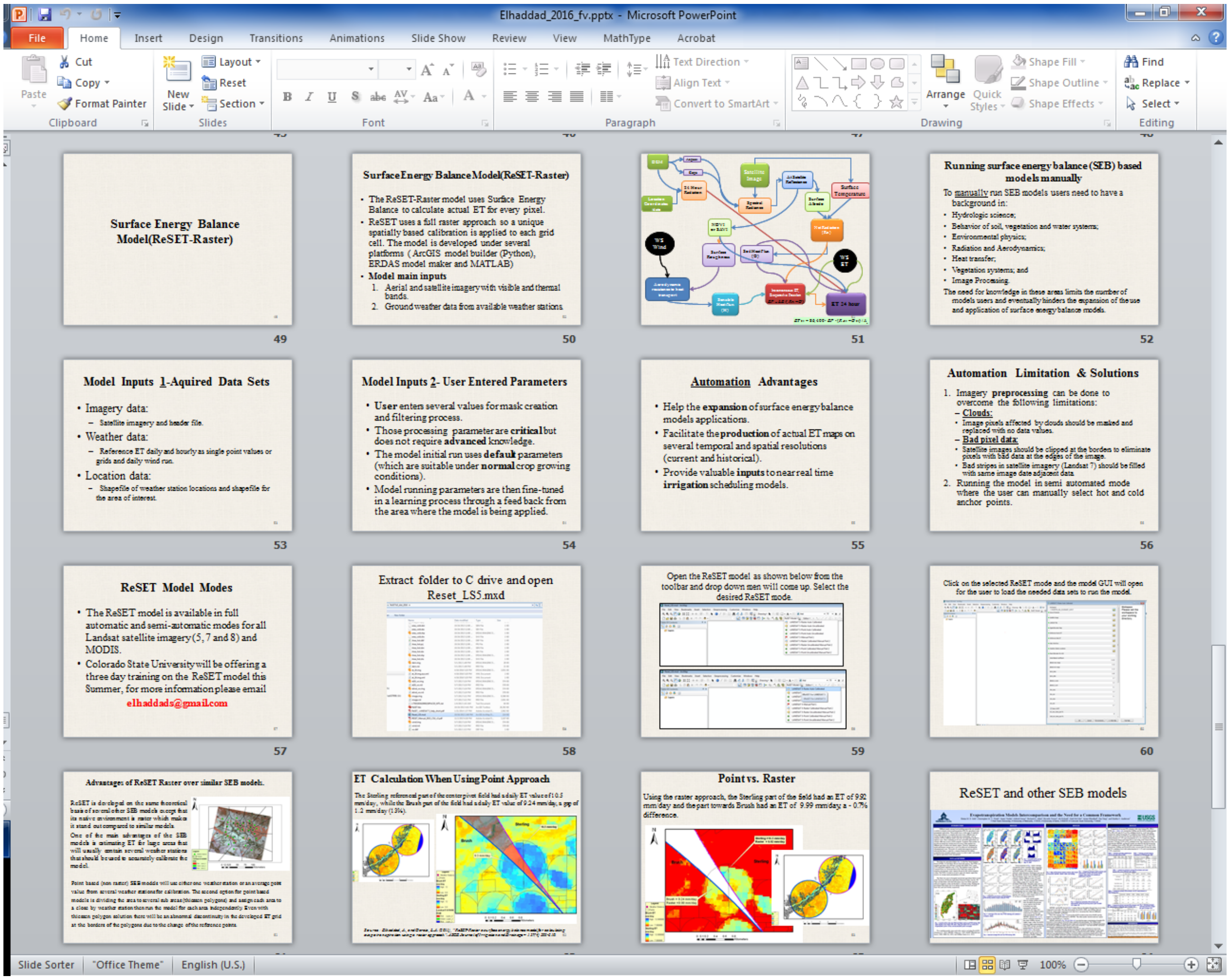
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Surface Energy Balance Model(ReSET-Raster)
Surface Energy Balance Model(ReSET-Raster)
The ReSET-Raster model uses Surface Energy Balance to calculate actual ET for every pixel.
ReSET uses a full raster approach so a unique spatially based calibration is applied to each grid cell. The model is developed under several platforms (ArcGIS model builder (Python), ERDAS model maker and MATLAB)
Model main inputs
1. Aerial and satellite imagery with visible and thermal bands.
2. Ground weather data from available weather stations.
Running surface energy balance (SEB) based models manually
To manually run SEB models users need to have a background in:
Hydrologic science;
Behavior of soil, vegetation and water systems;
Environmental physics;
Radiation and Aerodynamics;
Heat transfer;
Vegetation systems; and
Image Processing.
The need for knowledge in these areas limits the number of models users and eventually hinders the expansion of the use and application of surface energy balance models.
49
50
51
52
Model Inputs 1-Aquired Data Sets
Imagery data:
Satellite imagery and header file.
Weather data:
Reference ET daily and hourly as single point values or grids and daily wind run.
Location data:
Shapefile of weather station locations and shapefile for the area of interest.
Model Inputs 2- User Entered Parameters
User enters several values for mask creation and filtering process.
Those processing parameter are critical but does not require advanced knowledge.
The model initial run uses default parameters (which are suitable under normal crop growing conditions).
Model running parameters are then fine-tuned in a learning process through a feed back from the area where the model is being applied.
Automation Advantages
Help the expansion of surface energy balance models applications.
Facilitate the production of actual ET maps on several temporal and spatial resolutions (current and historical).
Provide valuable inputs to near real time irrigation scheduling models.
Automation Limitation & Solutions
1. Imagery preprocessing can be done to overcome the following limitations:
Clouds:
Image pixels affected by clouds should be masked and replaced with no data values.
Bad pixel data:
Satellite images should be clipped at the borders to eliminate pixels with bad data at the edges of the image.
Bad stripes in satellite imagery (Landsat 7) should be filled with same image date adjacent data.
2. Running the model in semi automated mode where the user can manually select hot and cold anchor points.
53
54
55
56
ReSET Model Modes
The ReSET model is available in full automatic and semi-automatic modes for all Landsat satellite imagery (5, 7 and 8) and MODIS.
Colorado State University will be offering a three day training on the ReSET model this Summer, for more information please email
elhaddads@gmail.com
Extract folder to C drive and open Reset_LS5.mxd
Open the ReSET model as shown below from the toolbar and drop down men will come up. Select the desired ReSET mode.
Click on the selected ReSET mode and the model GUI will open for the user to load the needed data sets to run the model.
57
58
59
60
Advantages of ReSET Raster over similar SEB models.
ET Calculation When Using Point Approach
Point vs. Raster
ReSET and other SEB models
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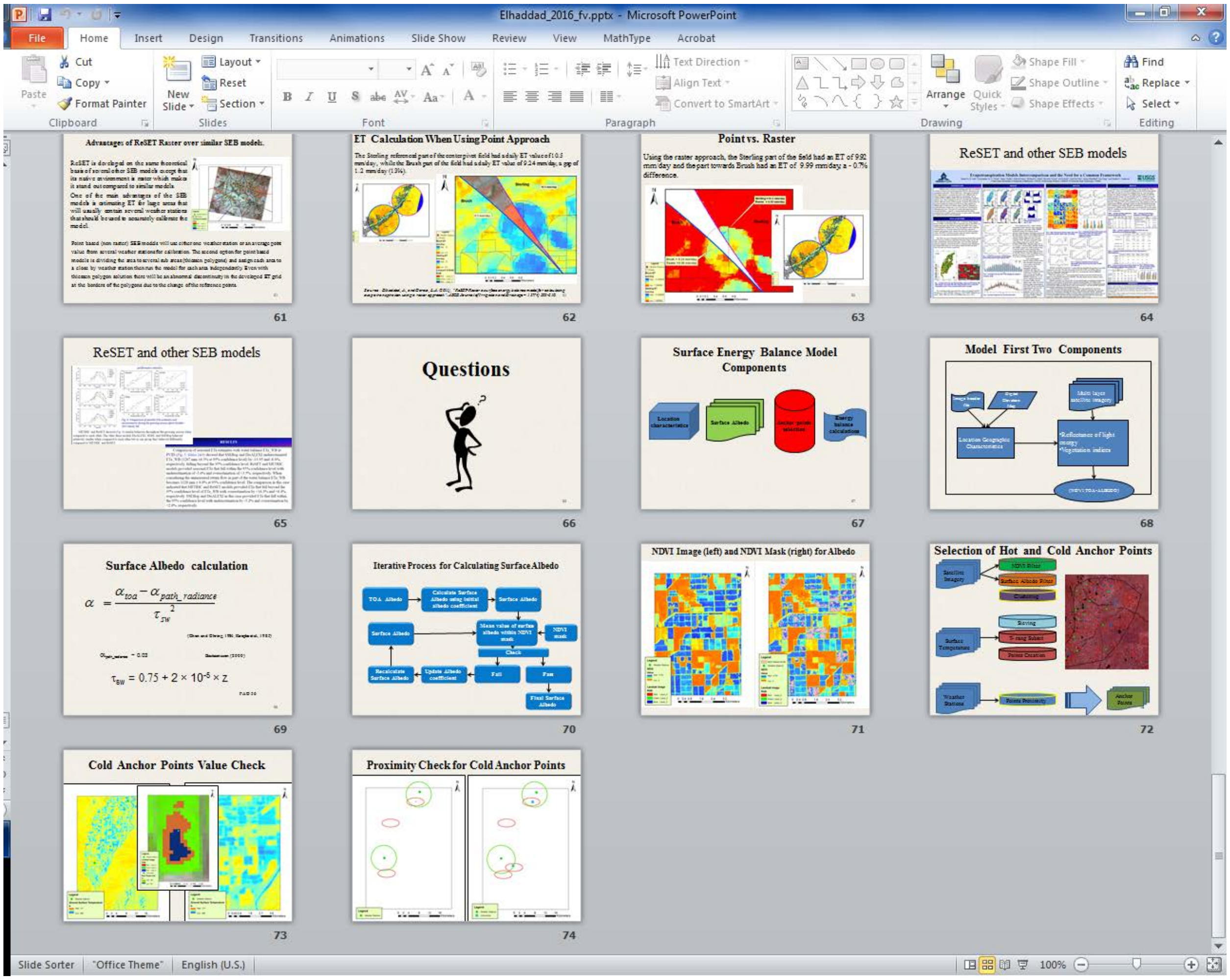
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Advantages of ReSET Raster over similar SEB models.
61
ET Calculation When Using Point Approach
62
Point vs. Raster
63
ReSET and other SEB models
64
ReSET and other SEB models
65
Questions
66
Surface Energy Balance Model Components
67
Model First Two Components
68
Surface Albedo calculation
69
Iterative Process for Calculating Surface Albedo
70
NDVI Image (left) and NDVI Mask (right) for Albedo
71
Selection of Hot and Cold Anchor Points
72
Cold Anchor Points Value Check
73
Proximity Check for Cold Anchor Points
74
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