Relating soil available water fraction to water stress indices

Steven R. Evett, Research Soil Scientist
USDA-ARS Conservation & Production Research Laboratory, Bushland, Texas, steve.evett@ars.usda.gov

Susan A. O'Shaughnessy, Research Agricultural Engineer
USDA-ARS Conservation & Production Research Laboratory, Bushland, Texas, susan.o'shaughnessy@ars.usda.gov

Paul D. Colaizzi, Research Agricultural Engineer
USDA-ARS Conservation & Production Research Laboratory, Bushland, Texas, paul.colaizzi@ars.usda.gov

Robert C. Schwartz, Research Soil Scientist
USDA-ARS Conservation & Production Research Laboratory, Bushland, Texas, robert.schwartz@ars.usda.gov

Abstract. *Thermometric infrared sensing of production agricultural fields is becoming more commonplace using satellite, aerial and proximal remote sensing platforms, including arrays of infrared thermometers mounted on moving irrigation systems. Using plant canopy temperature data for irrigation management has been thoroughly explored and working solutions have been implemented to trigger irrigations when plant water stress reaches a given threshold value. Using spatial canopy temperature data, maps of plant stress indices, such as the crop water stress index (CWSI), can be produced and used to trigger irrigation in those parts of a field in which the stress index exceeds the threshold, thus enabling variable rate irrigation (VRI). However, knowing the degree of plant water stress does not clearly translate into knowing the amount of irrigation to apply. Past research has shown a strong correlation between crop water stress index (CWSI) and stem water potential. The stem water potential is strongly correlated to the soil water potential in the root zone, although an exact analytical expression for the relationship is lacking, largely due to the dynamic nature of root growth and soil water redistribution in response to irrigation and precipitation. A strong relationship between CWSI and root zone soil water storage has been demonstrated during the latter part of the growing season in crops that were irrigated at different levels throughout the season, but the relationship earlier in the season was not strong in that earlier research, likely because the crop had not yet been severely stressed. At any rate, determining the soil water status before the onset of severe stress is the real objective and one not met by focusing only on soil water storage. Idso and Jackson demonstrated a relationship between the CWSI and the fraction of plant available soil water storage, not just the entire soil water storage. The present work involves a preliminary analysis of the relationship between fractional plant available soil water and CWSI measured at three levels of deficit irrigation of corn in 2016. The strength of correlations depended on the deficit level and the period of the season for which data were analyzed, and correlations were sometimes linear and sometimes nonlinear, particularly for stronger deficits later in the season. It appears that the effective soil water potential over the root zone will have to be computed in order to develop a stronger relationship with CWSI.*

Keywords. Fractional available soil water, variable rate irrigation, accuracy, management allowed depletion, canopy temperature, crop water stress index

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Soil Water Criteria for Irrigation Scheduling

Irrigation scheduling using soil water sensors is an exercise in maintaining the water content of the crop root zone soil above a lower limit defined by the management allowed depletion (MAD) for that soil and crop, but not so wet that too much water is lost to deep percolation, evaporation and runoff. The management allowed depletion for a corn crop on a clay loam soil is only about 0.06 inch/inch. To be useful for managing water to prevent over filling the soil or allowing it to dry so much that the crop yield is compromised more than acceptable, soil water sensors must be accurate. The accuracies needed are on the order of 0.02 to 0.04 inch/inch fractional soil water content (Table 1), which is better than many commercial soil water sensors are able to provide. This, plus the cost and practical problems associated with installing and maintaining soil water sensor networks in the field, motivates alternative approaches to irrigation scheduling based on canopy temperature sensing of crop water stress.

Values of field capacity and permanent wilting point for a particular field (needed for determining the available water holding capacity and MAD values) may be found from NRCS soil maps, at least to a close approximation. The values are, however, likely to change with depth in the soil and with position in the field, meaning that irrigation management should be site specific to be most effective, and to do that requires sensors be installed in the different soils of the field or some other means of mapping crop water stress be employed. NRCS soil maps are available on the Internet: http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm.

Plant root zones deepen during the growing season, often extending to five foot depth and sometimes deeper if the soil does not have a restrictive horizon and soil water content at depth is large enough to encourage root penetration. Since soil water sensors typically are sensitive only to the soil immediately around them, and since most sensors are small, it is typical that two or more sensors must be installed at different depths in order to gain acceptable understanding of how soil water content is changing in response to irrigation and crop water uptake. Depths of six and 18 inches or six and 24 inches are common. Seeing that the soil is above field capacity at 24 inches may indicate that deep percolation losses are occurring.

Table 1. Example calculation of available water holding capacity†, θ_{AWHC}, which is defined as the difference in water content between field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}), in three soils with widely different textures. Also shown is the management allowed depletion (MAD, inch/inch or $m^3\ m^{-3}$). The small range of MAD severely tests the abilities of most soil water sensors, particularly for the loamy sand soil.

Horizon	θ_{PWP}	θ_{FC}	θ_{AWHC}		MAD		MAD
	----------- $m^3\ m^{-3}$ or in/inch	---------			fraction		$m^3\ m^{-3}$
silt loam	0.086	0.295	0.209	×	0.6	=	0.126
loamy sand	0.066	0.103	0.037	×	0.6	=	0.022
clay	0.190	0.332	0.142	×	0.6	=	0.085

† θ_{FC}, θ_{PWP}, and θ_{AWHC} are soil water contents at field capacity, at the permanent wilting point, and the plant-available water holding capacity (designated as AWHC).

Spatial Variability of Soil Properties

Center pivots are sometimes placed on sloping land and on land that changes from one soil type to another across the area covered by the pivot. Sometimes soil type changes are unrelated to slope and aspect, for example in glacial till soils, flood plains, salt affected soils, etc. Figure 2 illustrates a situation with both slope and soil type variations. There are four soil types irrigated by this pivot, the Lazbuddie clay and Loften clay (LcA and LoA) are in irrigation capability class 2 due to their small slopes and deep profiles. They represent the margins of a playa. The Pullman clay loam (PuB) under the pivot is in class 3 due to its greater slope and potential for runoff. The Pep clay loam has slopes of 3 to 5% and so is in class 4 due to very high runoff potential. Site-specific, variable rate irrigation could be used to reduce irrigation rates on the areas with high runoff potential.

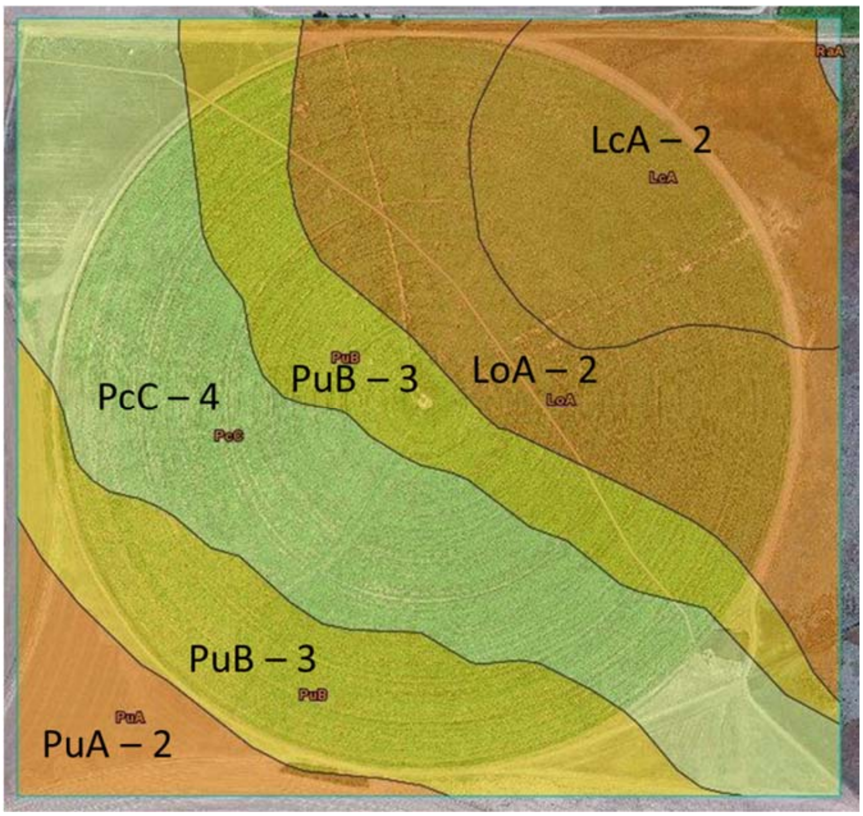

Figure 1. Soil and irrigation capability classification map from the NRCS soil survey web site for a center pivot in the Texas Panhandle. Letter codes indicate soil type; numbers indicate irrigation capability class. See Table 2 for details.

The soils illustrated in Figure 1 are all clays or clay loams, but do differ somewhat in available water holding capacity (Table 2). The most important difference between them is their slope, in particular the greater slopes of the Pep clay loam. One could lump the Lofton, Lazbuddie and Pullman soils together in terms of soil water sensing, leaving only the Pep soil to be sampled separately. However, the interpretation of soil water content data should be viewed in light of the FC and PWP values for each soil type, which means that a given water content will have different meaning in different soils. Depending on the degree of lumping, sensors in eight locations may be necessary to guarantee that soil water content variations are adequately captured.

Table 2. Summary by Map Unit of Classifications in the Area of Interest (AOI) in Figure 2.

Map unit symbol	Map unit name	Rating	AWHC* (in/in)	Acres in AOI	Percent of AOI
LcA	Lazbuddie clay, 0 to 1 percent slopes	2	0.161	40.4	17.1%
LoA	Lofton clay loam, 0 to 1 percent slopes	2	0.140	46.5	19.7%
PcC	Pep clay loam, 3 to 5 percent slopes	4	0.170	68.7	29.1%
PuA	Pullman clay loam, 0 to 1 percent slopes	2	0.165	14.3	6.1%
PuB	Pullman clay loam, 1 to 3 percent slopes	3	0.158	65.3	27.7%
RaA	Randall clay, 0 to 1 percent slopes, frequently ponded			0.5	0.2%
Totals for Area of Interest (the square, not the circle)				235.7	100.0%

***AWHC is available water holding capacity, the water that the soil holds between field capacity and permanent wilting point. In this case it is given in inch per inch for the top 40 inches of soil.**

Canopy Temperature and Soil Water Sensing – Relationship to Crop Water Stress

Factors Influencing Crop Spatial Variability

Crop variations in space are influenced by other factors in addition to soil type, texture, salinity, depth and depth to restricting layers. Slope and aspect affect runoff and evaporative demand. In hilly terrain, evaporative demand is typically greater on south facing slopes than on north facing slopes. Disease and insect pressure can create field variability, as can temporary ponding due to runoff, or lack of sufficient infiltration of applied irrigation due to runoff from steeper slopes. Of course, agronomic mistakes in planting, spraying and fertilization can also create variability in the crop, which will translate into variability in crop water uptake rates and soil water content variability. Several of these factors cannot be ameliorated by irrigation, but irrigation can be varied in response to save water. For example, irrigation of areas of a field hard hit by disease or insect pressure may no longer be economically viable, in which case a Site-Specific VRI (SSVRI) system prescription can be written to stop irrigation in those areas. Irrigation can be reduced on field areas in which slope is causing runoff problems, thus ameliorating parts of the field prone to ponding and water logging. Soil water sensors placed in these two areas (sloping and prone to water logging) will detect problems of lack of soil water on slopes and excess of soil water on areas that pond. Reducing irrigation rates on sloping areas will, however, likely lead to crop water stress there, which can only be addressed by extra irrigations on those areas. While an SSVRI system may allow this site-specific irrigation to occur, there may not be time in the irrigation schedule to allow these extra irrigations on sloped areas. Also, it should be recognized that evaporative loss is a greater fraction of smaller irrigations than of larger irrigations (Tolk et al., 2014).

Plant Water Status Mapping – Connection to ET & Soil Water Status

In dry climates, greater crop canopy temperatures (Fig. 2) indicate greater crop water stress because crops with sufficient soil water availability are cooled by transpiration. Irrigation scheduling based on crop water stress can be accomplished automatically (or manually) using crop water stress data from infrared temperature sensors mounted on moving irrigation systems (Peters and Evett, 2008). An empirical crop water stress index (eCWSI) based on georeferenced data from sensors on a center pivot lateral can be mapped to show spatial changes in crop water stress that develop over time. Crop leaf temperature data from infrared thermometers (IRTs) can be combined with on-site measured weather data from inexpensive weather stations to calculate a crop water stress index that is integrated over the daylight hours to improve stability, resulting in maps of the integrated Crop Water Stress Index (iCWSI) for an entire field (O’Shaughnessy et al., 2010). The iCWSI is well correlated with plant stem water potential, which is a direct indicator of plant water stress. Automated VRI irrigation using a supervisory control and data acquisition (SCADA) system has been demonstrated to produce yields and crop water use efficiencies as good as or better than those resulting from irrigation scheduling using the best scientific irrigation scheduling method – the neutron probe used weekly in many access tubes spread over a field (Evett et al., 2006; O’Shaughnessy et al., 2012a), and has been recently patented (Evett et al., 2014a). These methods are being transferred to commercial center pivot irrigation systems for eventual sale to producers. The wireless IRTs eliminate initial and maintenance costs of wiring (O’Shaughnessy et al., 2012b, 2013); and this IRT technology has been transferred to a manufacturer who offers it for sale (model SapIP-IRT, Dynamax, Inc., Houston, TX).

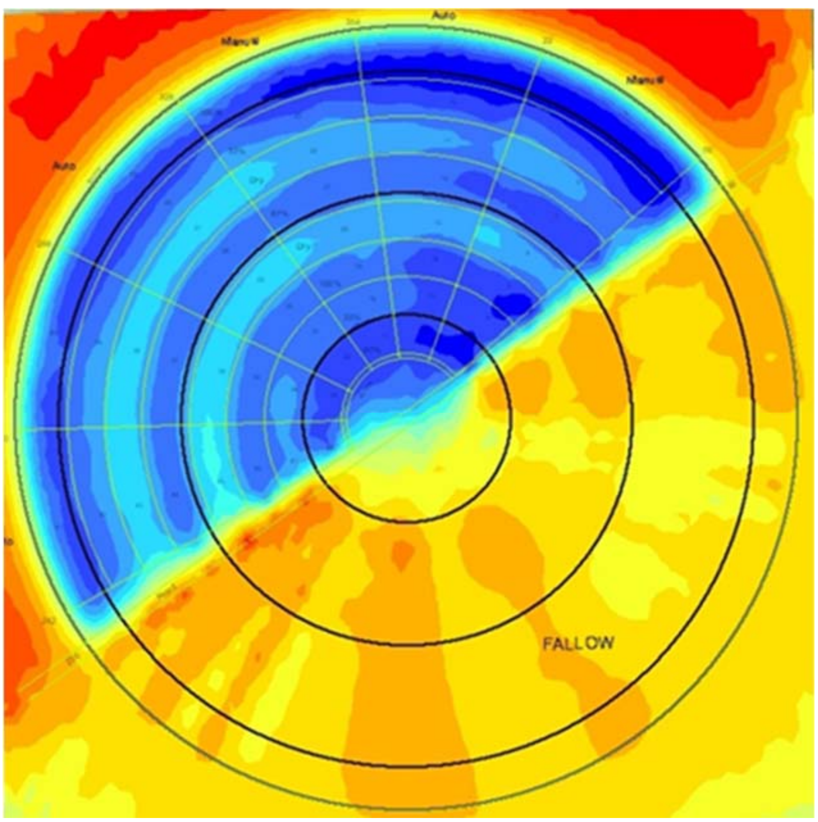

Figure 2. False color image of a center pivot irrigated field showing increasing canopy temperature as irrigation deficit increased from full irrigation (coolest temperature, dark blue) to more deficit irrigation (lighter blue) and to a non-irrigated (dryland) treatment (yellow, brown and red, hottest temperature).

Planting a crop can be seen as the installation of many thousands of sensitive biological soil water sensors per acre. Crop water stress is well correlated with leaf water potential, which in turn is correlated with soil profile water content.

Knowing how much water a soil can accept can be determined from soil water sensors at the locations where those sensors are installed, but is unknown elsewhere in the field. Soil water content is spatially variable horizontally and vertically in all soils and temporally variable over the irrigation season (e.g., Padhi et al., 2011). Spatial variation in soil water content occurs even in level fields (e.g., Longchamps et al., 2015). Spatio-temporal dependence of soil water content can vary with respect to soil types, but the variable that is important for irrigation management is the fractional plant available soil water (fPASW) in the root zone. For example,

fPASW = (SWC-PWP)/(FC-PWP)

Where SWC is the soil water content, FC is soil water content at field capacity and PWP is the soil water content at permanent wilting point. Fractional PASW has a range of 0 to 1. Rab et al. (2009) found that PASW was strongly correlated with wheat yield in Australia.

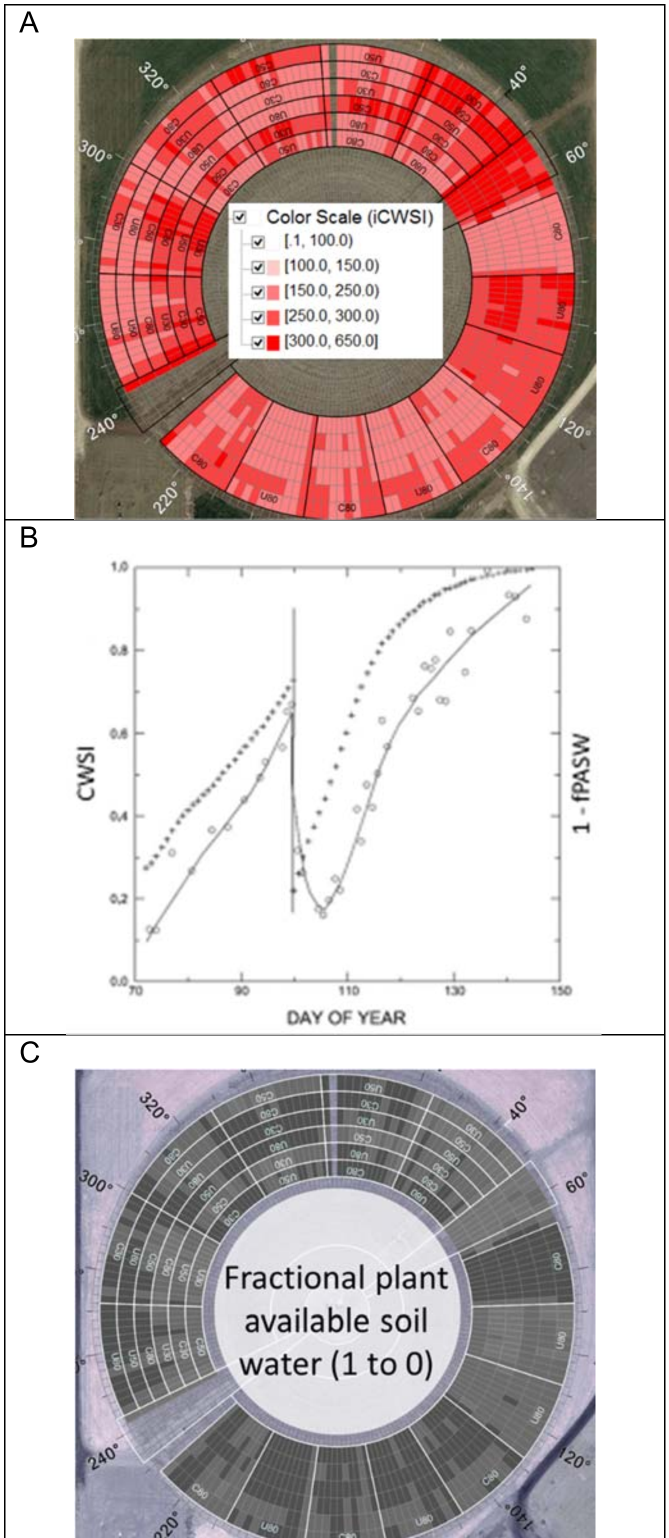

Figure 3. (A) Map of CWSI, (B) Relationship between CWSI and 1 – fPASW (Jackson et al., 1981), (C) Illustrative map of fPASW.

While in-situ soil water sensors provide frequent soil water content measurements, it often is not feasible to install an adequate number of sensors to accurately represent soil water content variability in producers' irrigated fields (Hedley and Yule, 2009). However, it is possible to map the CWSI (Fig. 3, A) using data from a plant feedback ISSCADA system moving across the field (Peters and Evett, 2008; O'Shaughnessy et al., 2016). Since a strong relationship exists between the CWSI (range of 0 to 1) and the fractional PASW (0 to 1) (Fig. 3, B) (Jackson et al., 1981), data on the fractional PASW in the root zone obtained at a few locations could be cokriged with a map of

CWSI to produce a map of fractional PASW (Fig. 3, C). Studies have demonstrated how cokriging can be used to reduce the required intensity of expensive soil sampling or sensing methods by building a relationship between the sampled property and an easily measured one, and then repeating the easy sampling over space to achieve strong representation of the spatial variability of the less easily measured property (e.g., Goovaerts, 1998; Rab et al., 2009). Indeed, Yates (1986) and Yates and Warrick (1987) estimated the surface soil water content by cokriging using more numerous measurements of the soil surface temperature. A model that maps fraction of PASW is needed to overcome the infeasibility of installing numerous soil water sensors in a single field and to aid in mapping the fraction of PASW. A feasible model could incorporate cokriging of fractional PASW and CWSI combined with TSEB modeling of ET to determine the rate at which fractional PASW is changing, thus providing for determining and forecasting needed water application depths. Such a map could be uploaded as an instructive visual aid and used to develop a VRI prescription for whole-field irrigation management that provides water in precise amounts to precise locations, mitigating the limitations of the all-or-nothing prescription mapping described by Peters and Evett (2003) and others.

In previous research, cotton CWSI values were well correlated with soil profile water content within the root zone (Fig. 4), at least relatively later in the irrigation season (Evett et al., 2014b). Other research has shown that the crop temperature data can be used in energy and water balance models of crop water use (ET), which can be used to estimate changes in soil water content over time (Colaizzi et al., 2003), thus closing the circle between soil water sensing and crop water stress sensing.

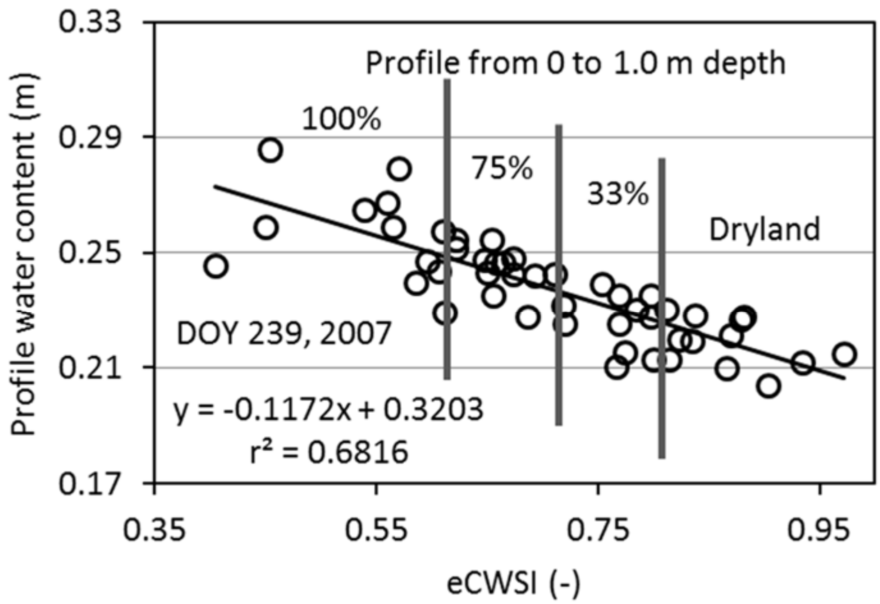

Figure 4. The soil profile water content within the crop root zone is correlated with the empirical crop water stress index (eCWSI). Different irrigation amount treatments produced groups of eCWSI values that did not overlap along the regression line, illustrating that eCWSI is a good surrogate for profile water content. Irrigation treatments were full (100%), 75% of full, 33% of full and dryland.

2016 Trials

The work of Jackson et al. (1981) was done using the neutron probe on a daily basis for a couple of irrigation cycles, but did not allow more thorough seasonal examination of the relationship between fPASW and CWSI. A variable rate irrigation study of corn response to varying irrigation levels provided a test bed for examining the relationship between fPASW and CWSI over a longer time scale at Bushland, Texas in 2016. Soil water sensors (Model TDR-315 true TDR sensors, Acclima, Inc., Meridian, ID) were installed at depths of 3.9, 7.9, 11.8, 17.7, 27.6, and 39.4 inches (10, 20, 30, 45, 70, and 100 cm) at each of three locations. The locations were irrigated weekly to replace either 30%, 50% or 80% of the weekly crop water use as determined using a field-calibrated neutron probe. At each location, infrared thermometers (model SAPIP-IRT, Dynamax, Inc., Houston, TX) were positioned to view the corn canopy above the soil water sensing profile from opposite oblique angles in order to reduce sun angle effects on the mean temperature. The daily integrated CWSI was calculated according to methods of O'Shaughnessy et al. (2016). From these values, a daily fractional iCWSI was computed as the ratio of iCWSI for a day to the value 370, which was slightly more than the maximal daily iCWSI determined for the season. Fractional soil water depletion (1 – fPASW) was calculated based on field capacity water content of 0.35 inch/inch and permanent wilting point water content of 0.19 inch/inch.

For the entire growing season, fractional soil water depletion was more significantly related to fractional iCWSI for the most heavily irrigated treatment (80%) and the importance of the relationship declined as deficit irrigation became more severe (Table 3). The implication of this is that the likelihood of developing a useful map of soil water depletion declines as irrigation deficit increases.

Table 3. Linear regression relationships between fractional soil water depletion (0-1, dimensionless) to fractional integrated crop water stress index (0-1, dimensionless) for corn over the entire growing season at Bushland, Texas in 2016. SE is the standard error

Irrigation Level	Slope (P value)	Intercept (P value)	r^2	SE	N
80%	0.276 (<0.01)	0.14 (<0.01)	0.45	0.06	55
50%	0.227 (<0.01)	0.43 (<0.01)	0.10	0.12	60
30%	0.181 (0.064)	0.34 (<0.01)	0.05	0.12	55

If data from only the latter part of the irrigation season were used (day of year 244 to 275, well after canopy closure), then the linear relationships between fractional soil water depletion and fractional iCWSI was much less strong for all three irrigation levels, with r^2 values of 0.21 for 80% irrigation, 0.05 for 50% irrigation, and 0.07 for 30% irrigation. However, polynomial relationships between fractional soil water depletion and iCWSI (not fractional) were strong for this latter part of the season (r^2 = 0.83, 0.69 and 0.55 for irrigation levels of 80%, 50% and 30%), and became more nonlinear for the more severely deficit irrigation levels, indicating a problem with a simple fractional soil water depletion metric for developing this relationship. As soil dries the relationship between soil water potential and water content becomes quite nonlinear, so it is likely that conversion of fractional PASW to a fractional soil water potential metric is necessary to develop a stronger relationship.

Summary

The first year of research to develop a relationship between fractional plant available soil water (or fractional soil water depletion) and a crop water stress index was exploratory but provided useful data for analysis. Further analysis will focus on using the relationship between soil water potential and soil water content to develop a fractional plant available soil water potential index that can reasonably be expected to relate to crop water stress. It appears that the effective soil water potential over the root zone will have to be computed in order to develop a stronger relationship with CWSI. This may require a computer modeling approach similar to that employed in the ENWATBAL model (Evett and Lascano, 1993) in which root length density changes with depth and over time are modeled and then used to scale effective soil water potential.

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