Soil water sensing:
Implications of sensor capabilities for variable rate irrigation management

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. *Irrigation scheduling using soil water sensors aims at maintaining the soil water content in the crop root zone 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 or that the crop quality is impaired. To be useful for managing water to prevent over filling the soil or allowing it to dry so much that crop yield is compromised, soil water sensors must be accurate to the order of 0.02 to 0.04 inch/inch. Issues of sensor performance, numbers of sensors required for effective variable rate irrigation (VRI) management, and other factors complicating sensor application to VRI management all hamper adoption of soil water sensing systems for VRI. An alternative to soil water sensing that may be helpful is soil bulk electrical conductivity mapping, which can delineate field zones of different soil textures if salinity is not a factor. Another alternative, soil canopy temperature sensing, has been shown to accurately reflect plant water status and thus soil water status in semi-arid and arid irrigation regions; and this method is approaching commercial availability. A combination of crop canopy temperature sensing, which effectively uses the crop as many thousands of biological soil water sensors, and a few accurate soil profile water content sensors may prove to be the most practical approach to variable rate irrigation management in many regions.*

Keywords. Soil water sensor, variable rate irrigation, accuracy, management allowed depletion, bulk electrical conductivity, canopy temperature, crop water stress index

Soil Water Criteria for Irrigation Scheduling

Soil water sensing has been used to guide irrigation management since the advent of commercially successful neutron probes in the 1960s. The neutron probe (NP) became widely used in the 1970s and has remained an important tool for consultants and some large farming operations, particularly with high value crops. More onerous regulation, including licensing, use, storage and training requirements, has increasingly limited the use of the NP. In addition, the advent of commercially available capacitance systems for soil water sensing in the early 1990s has caused some users to adopt these admittedly less accurate sensors due to the absence of regulations concerning their purchase and use. The more accurate time domain reflectometry (TDR) method also became commercially available for soil water sensing in the early 1990s, but was not widely adopted for irrigation scheduling because of its expense and complicated methods of application. In the late 1990s, the International Atomic Energy Agency (IAEA) and Food and Agriculture Organization (FAO) joint division on soil and water convened an expert panel to conduct a coordinated research project investigating whether the capacitance (frequency domain) and TDR systems would be capable of replacing the NP. The conclusion of that panel, based on five years of research on four continents, was that the capacitance sensors were not accurate enough to replace the NP, and that the conventional TDR systems, although accurate enough, were not presently able to be installed deeply enough or inexpensively enough for wide spread irrigation scheduling (Evett et al., 2008).

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 (Fig. 1), 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 (Table 1), which is better than many commercial soil water sensors are able to provide. 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. 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 understand 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.

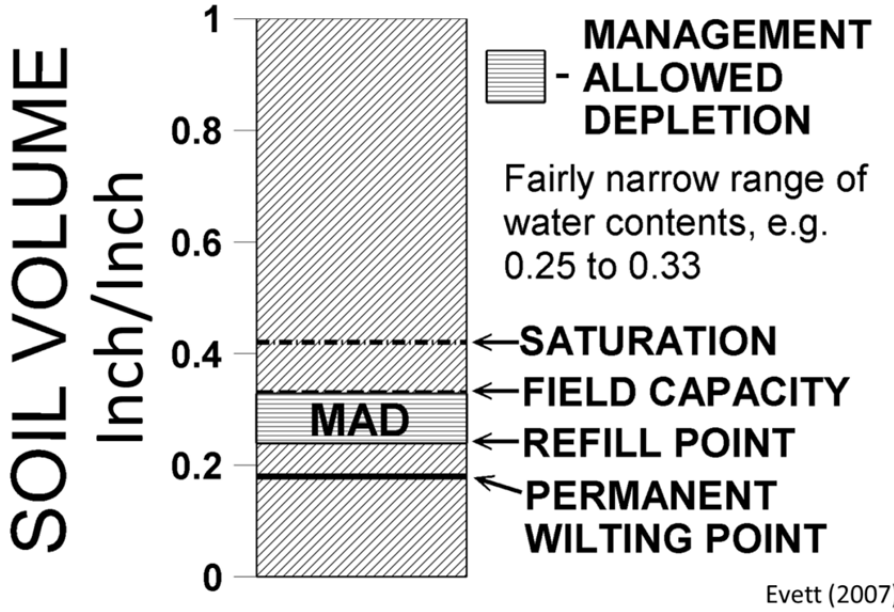

Figure 1. Sketch defining the key crop root zone water content values. In the clay loam soil depicted here, the water content at saturation is about 0.42 inch/inch and equal to the soil porosity. The soil cannot hold more water than saturation, and a saturated soil layer will drain to drier soil layers beneath until the soil reaches field capacity, about 0.33 inch/inch for this soil. If the soil dries to the permanent wilting point, about 0.18 inch/inch in this soil, the crop will be permanently damaged. The refill point is the water content below which the crop will be water stressed and yield may be reduced. It is about 0.25 inch/inch for a corn crop in this soil. The difference between the field capacity and the refill point is the management allowed depletion, about 0.08 inch/inch in this soil for a corn crop.

Table 1. Example calculation† of management allowed depletion (MAD, $m^3\ m^{-3}$) in three soils with widely different textures. 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
	----------- $m^3\ m^{-3}$ ---------				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 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 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.

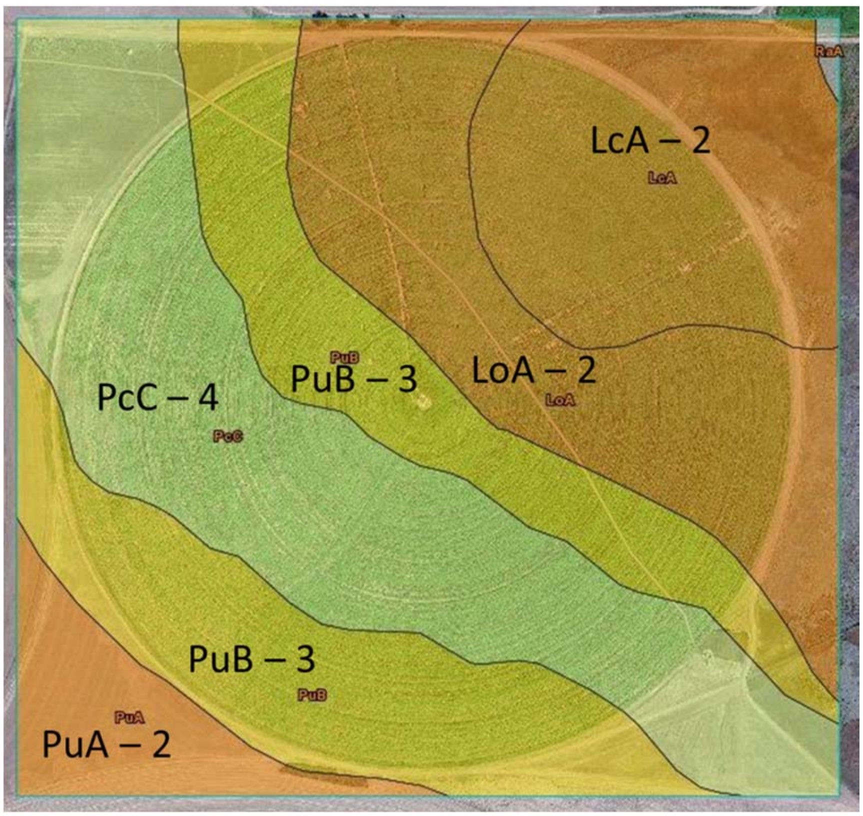

Figure 2. Soil and irrigation capability classification map from the NRCS soil survey web site for a center pivot in the Texas Panhandle. Letter codes indicate soil type; numbers indicate irrigation capability class. See Table 2 for details.

The soils illustrated in Figure 2 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.**

Soil Water Sensing – Relationship to VRI

Factors that Influence Spatial Variability of Crops

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. 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).

Number of Measurement Locations and Depths Required

As a first approximation, the needed number of soil water measurement locations will vary according to the spatial variability of soil types and the interactions between soil type, slope and aspect. Perhaps the most tractable and easily understood approach to this problem is to begin with defining management zones. The number of management zones that can be separately delineated by a VRI irrigation system depends on whether the system's VRI capabilities are limited to sector-only variations in application rate determined by varying lateral rotation speed (Fig. 3A), or whether it can vary both lateral rotation speed and application rate in zones radially (Fig 3B). Angular size of sectors can vary, not being limited to the regular angular sizes of 18 degrees shown in Figure 3. And, radial sector sizes are not restricted to those shown in Figure 3, although radial dimensions typically are defined by the linear dimensions of banks of nozzles that can be controlled together, e.g., six nozzles per bank with nozzle spacing of 5 feet would give a 30-ft radial zone width.

If management zones can be defined in both angular (speed control) and radial (nozzle bank control) dimensions, then management zones can be more adequately tailored to field differences (soils, slopes, etc.) that impact water infiltration and runoff (Fig. 4B). If only speed control is possible such that only sector-wide zones can be defined, then management zones may not adequately respond to field soil variations, especially if the long axis of an area of variation is oriented perpendicular to the pivot lateral (Fig. 4A).

Assuming that the four management zones defined in Figure 4B are to be managed on the basis of soil water sensing, then at least one soil water sensing system is needed for each zone, for a total of four sensing systems, each composed of at least two sensors, one in the shallow root zone and one nearer the bottom of the root zone, for a total of eight sensors. This total assumes, however, that each system is capable of adequately representing the soil water content of a zone. There are two major factors affecting this assumption; the accuracy and spatial representivity of the sensor, and the field variation in microrelief, which will affect the surface and subsurface redistribution of water. Little can be done about field variation in production fields, except to recognize it where possible, but soil water sensors can be chosen that are more accurate and spatially representative.

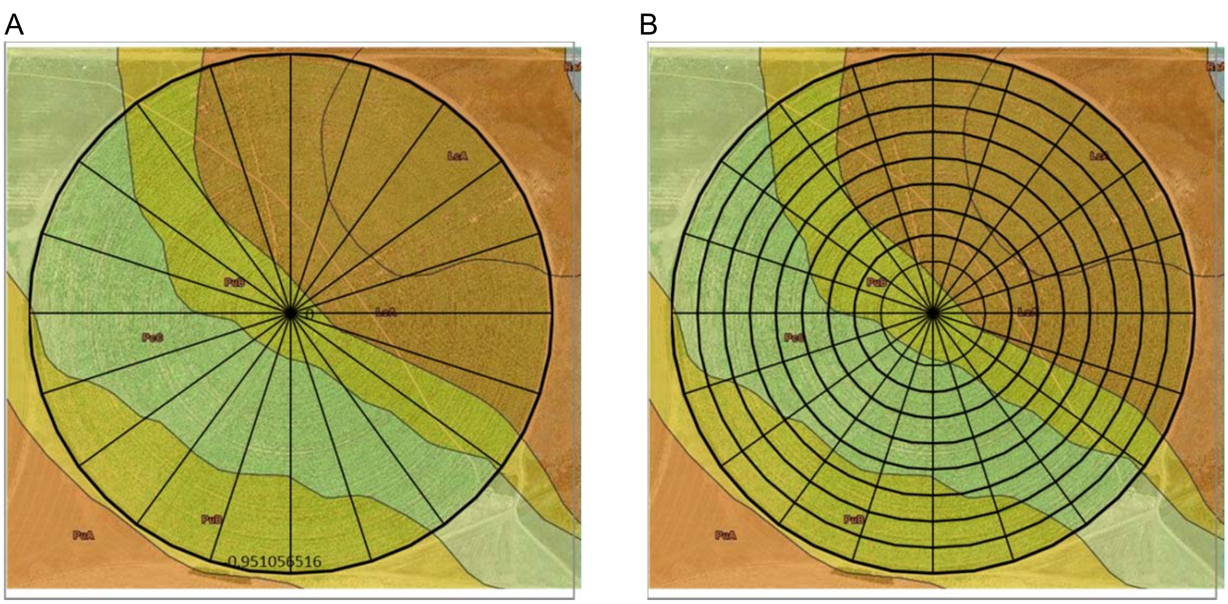

Figure 3. Examples of management zones. (A) Sector-only management zones are all that can be defined by varying lateral rotation speed alone. (B) If nozzle banks can be controlled along the length of the lateral, then radial sector dimensions can be defined as well, giving much more spatial control of irrigation application.

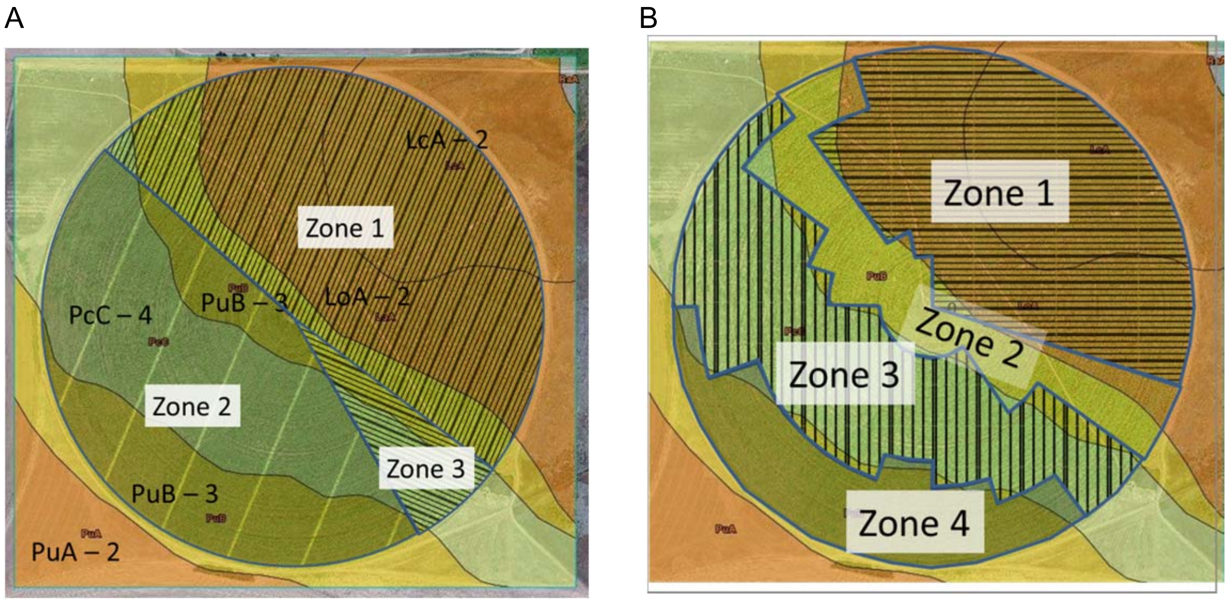

Figure 4. Examples of management zones for the soils and center pivot shown in Figure 1. (A) Sector-only management zones prescribed to cover the low lying and shallow slope soils in the NE half of the circle (Zone 1), some of the sloping soils (Zone 2), and the rest of the sloping soils and upper elevation Pullman soils (Zone 3). (B) Management zones prescribed according to both angular and radial dimensions, for the low lying and low slope Lazbuddie clay and Loften clay loam soils (Zone 1), the sloping Pullman soils (Zone 2), the sloping Pep soils (Zone 3) and the higher lying, less sloping Pullman soils (Zone 4).

Selecting Soil Water Sensors & Systems

Due to the numbers of sensors involved, labor associated with soil water sensing for VRI must be minimized. To be useful in VRI scheduling, soil water sensors must be accurate, relatively inexpensive, and require little labor. The latter criterion means that these sensor systems must be capable of being left in the field with little or no maintenance throughout the growing season, not require moving them when machine operations (mostly spraying) are needed, and be capable of wireless data transmission to either the farm office or directly to the irrigation controller.

Soil water sensors vary widely in their accuracy and spatial representivity (CPIA Proceedings: Chávez and Evett, 2012; Evett et al., 2007; Evett et al., 2012). In general, sensors can be classed as those that respond to the electromagnetic (EM) properties of soils as influenced by water content (and also by salinity and temperature), resistance blocks (e.g., gypsum blocks, granular matrix sensors and the like), tensiometers and the neutron probe. Tensiometers and the resistance blocks respond to soil water potential rather than water content, but these sensors can be useful since plants respond directly to soil water potential. Tensiometers are too difficult to maintain in the field to be useful for VRI scheduling. The several kinds of resistance blocks can, however, be easily installed and left for a season, connected to a datalogger and radio transmitter. With flexible antennae, field installations can allow tractor movement. The main disadvantage of resistance sensors is their limited range. They operate best near field capacity, but may lose contact with the soil before it dries to the management allowed depletion, a particular problem if deficit irrigation is being managed to improve water use efficiency and reduce pumping costs. A VRI scheduling system using a wireless soil water sensing system based on granular matrix resistance sensors with a “high density of nodes” is being demonstrated by Velledis et al. (2013a,b), but so far the emphasis is on developing and testing the wireless data transmission capabilities, not the aspects related to accuracy of soil water sensing and effectiveness of VRI management. Recently, an underground wireless communication system was tested with soil water sensors at the University of Nebraska (Tooker et al., 2012). The granular matrix sensors were buried at 16-inch depth to be clear of tillage operations. An antenna suspended from a center pivot lateral picked up the wireless signal as the lateral moved over the location of each sensor. This system is still in the development stage. Soil type, water content and amount of vegetation affect the wireless signal strength, and optimal radio frequency and antenna size and design are still being studied (Dong and Vuran, 2013; Dong et al., 2013).

The neutron probe is an excellent research tool, but expensive and labor intensive since it cannot be left in the field. Part of the expense is the regulatory requirement for licensing and safety training due to the radioactive source involved in this method. It is not suitable for production agriculture VRI.

Most relatively inexpensive and commonly available soil water sensors are of the EM type, of which there are two major kinds, the capacitance sensors and the travel time sensors. There are important differences between the two main kinds of EM sensors (Evett et al., 2012). The capacitance sensors radiate an EM field into the soil, thus involving the soil as part of the dielectric of a capacitor in an oscillating electric field. The frequency of oscillation decreases as water content increases, but the frequency is also affected by soil bulk electrical conductivity and bound water content. All soils are somewhat conductive, but conductivity increases with water content, temperature, content of high CEC clays and salinity. Thus the capacitance sensors are also temperature, conductivity and clay content sensors. Bound water is water that is bound by attraction to the surface charge of clay particles, and there are important amounts of bound water in high surface area clays (smectites, montmorillonites, etc.). The degree to which water is bound to clay is also temperature sensitive, which causes a secondary effect on the frequency of oscillation of capacitance sensor. Although soil-specific calibration may improve the accuracy of capacitance sensors, at least in laboratory studies, there will still be effects of varying temperature and salinity in the field.

An equally important disadvantage of the capacitance technique is related to the EM field that is radiated into the soil. This so-called fringing field does not uniformly penetrate the soil, but is instead attracted to more conductive parts of the soil. Because soil structure and water content vary a great deal on the small scale in field soils, there is a large random variation in the EM field shape and frequency response depending on the exact location of a capacitance sensor. The random response makes the capacitance sensors relatively non-representative of soil water content on the scale of plant root systems. In field studies in California and Texas of the major capacitance sensors used in access tubes, Evett et al. (2009) and Mazahrih et al. (2008) found that these sensors reported field variability of soil water content that did not in fact exist when measured directly by soil coring or by the neutron probe. The neutron probe has a much larger measurement volume and is insensitive to conductivity and temperature effects. The false variation was so large that these sensors were incapable of providing data accurate enough to schedule irrigations using the MAD paradigm.

The variability of sensed soil water content is described by the standard deviation (SD) of water content. Even in a quite uniform soil, there is a certain irreducible variability of soil water content that dictates the number of sensors or access tubes needed to determine the water content to within a given precision criterion. Based on data from Evett et al. (2009), Evett and Steiner (1994) and Mazahrih et al. (2008), Table 3 gives the number of access tubes needed in order to determine profile water content to precisions of 0.4 and 0.8 inch (1 and 2 cm in a 100 cm profile) for several different soil water sensors and for gravimetric core sampling using a push tube. Statistically speaking, only the gravimetric sampling and the neutron probe can deliver a precise profile water content with only one access tube per uniform management zone. The capacitance sensors (first four listed in Table 3) all require several access tubes to determine a mean water content with sufficient precision. In addition, the studies cited indicate that this precise water content will likely still be inaccurate. Note that in drier soils all sensing and measurement methods become more imprecise due to the increased random variation in soil water content as soils dry. As discussed previously, this random variation has larger effects on the capacitance sensors than on the neutron probe or gravimetric sampling.

Table 3. Number of access tubes (*n*) needed to find mean volumetric water content (VWC) to a precision *d* (unitless) at P=95% for a given field-measured standard deviation (*s*, -) of volumetric water content. For 40-inch deep soil profile, a VWC precision of 0.01 is equivalent to 0.4 inches of water, and a precision of 0.02 is equivalent to 0.8 inches of water.

		s	*n*	
Method	**Soil condition**	**Volumetric (unitless)**	***d* = 0.01**	***d* = 0.02**
Diviner 2000	**Wetter**	**0.0131**	**7**	**2**
	Drier	**0.0242**	**23**	**6**
EnviroSCAN	**Wetter**	**0.0152**	**9**	**2**
	Drier	**0.0266**	**27**	**7**
Delta-T PR1/6, PR2/6	**Wetter**	**0.0272**	**28**	**7**
	Drier	**0.1216**	**568**	**142**
Sentry 200AP	**Overall**	**0.0378**	**55**	**14**
Trime T3	**Wetter**	**0.0075**	**2.2**	**1**
	Drier	**0.0238**	**22**	**5**
Gravimetric by push tube	**Wetter**	**0.0045**	**1**	**1**
	Drier	**0.0070**	**2**	**1**
Neutron probe	**Wetter**	**0.0015**	**1**	**1**
	Drier	**0.0027**	**1**	**1**

In contrast with capacitance methods, the travel time sensors work by sending an electric pulse (step pulse) along an electrode that is buried in the soil and measuring the time it takes the pulse to move along the electrode. Travel times are associated nearly linearly with water content. The travel time sensors employ different physical laws than do the capacitance sensors (Evett et al., 2012) and so are relatively immune to the effects of soil electrical conductivity, temperature and salinity, unless conductivity is so large that these sensors cannot determine the travel time. Early travel time sensing systems depended on expensive, research quality pulse time domain reflectometry instruments, expensive coaxial multiplexers for connecting more than one soil probe to the instrument and a computer system to control the instrument and switching of the multiplexer(s). These systems required many cables and were not useful in production agriculture although, like the neutron probe, they became a standard for research efforts. Within the last ten years, however, the adoption of miniaturized high frequency electronic components of the type used in cell phones has allowed the creation of time domain measurement circuits that are inexpensive, low power and small enough to be contained in the plastic head of a soil water sensor. These tend to be superior to the capacitance sensors and typically report accurate water contents, soil bulk electrical conductivity (useful for monitoring salinity in soils prone to it) and temperature (useful for timing of planting operations). Three examples are the CS655 (Campbell Scientific, Inc., Logan, Utah) and the ACC-TDT and TDR-315 sensors (Acclima, Inc., Meridian, Idaho). All can be used in solar-powered field systems with wireless connectivity that can be left unattended in the field for months. Until recently, time domain sensors were only useful in the upper root zone where they could be installed easily. However, a deep profiling soil water sensor has now been patented (Evett et al., 2014) that would allow for wireless, automatic sensing of soil water content to 48 inch depth in 8-inch increments. The sensor can also sense soil bulk electrical conductivity and so is useful for salinity management as well. The tube-type sensors can be connected together to access deeper root zones (up to 96 and 144 inches). Data such as those in Table 3 have not yet been collected for this sensing system, which is not yet commercially available.

The present state of the art does not provide a complete soil water sensing solution for variable rate irrigation management. Limitations include the costs of deploying sufficient densities of sensors to detect within-field variations, sensor inaccuracy (except for the time domain sensors) and calibration effort needed, often insufficient sensor depth range and limitations of wireless communications in dense vegetation. All of these limitations are being addressed by state, federal and commercial research and development efforts.

Alternatives to Soil Water Sensing

Conductivity Mapping

The availability of soil bulk electrical conductivity (BEC) mapping using equipment pulled by tractors or other vehicles (e.g., Veris Technologies, www.veris.com; EM38, Geonics Limited, www.geonics.com; GEM-2, Geophex, www.geophex.com) has resulted in easy availability of field BEC mapping. As explained previously, soil BEC is influenced by many factors, including temperature, salt content (including fertilizers), water content, soil texture and buried metal (e.g., wiring and piping). If soil salinity is the predominant influence on BEC, it may also have an effect on yield (Fig. 5). In a given field, more clayey soils are often more conductive both because they can hold more water than sandier soils and because the clay itself is more conductive when wet than is sand at an equivalent water content. Thus soil BEC may be related to the water holding capacity of soils, and BEC maps may be correlated with soil texture, which can provide a basis for prescriptive irrigation scheduling. Grisso et al. (2009) stated that soil EC values change over time due to wetting and drying of a field, but that mapping of relative water holding capacity remained stable over time, and can be related to yield (Fig 6). They also stated that soil BEC maps more accurately identified the locations of transitions between soil types and small areas of different soil texture than did Order 2 NRCS soil surveys, which were not designed to identify areas smaller than 2.5 acres and were not as accurately georeferenced (Fig. 7).

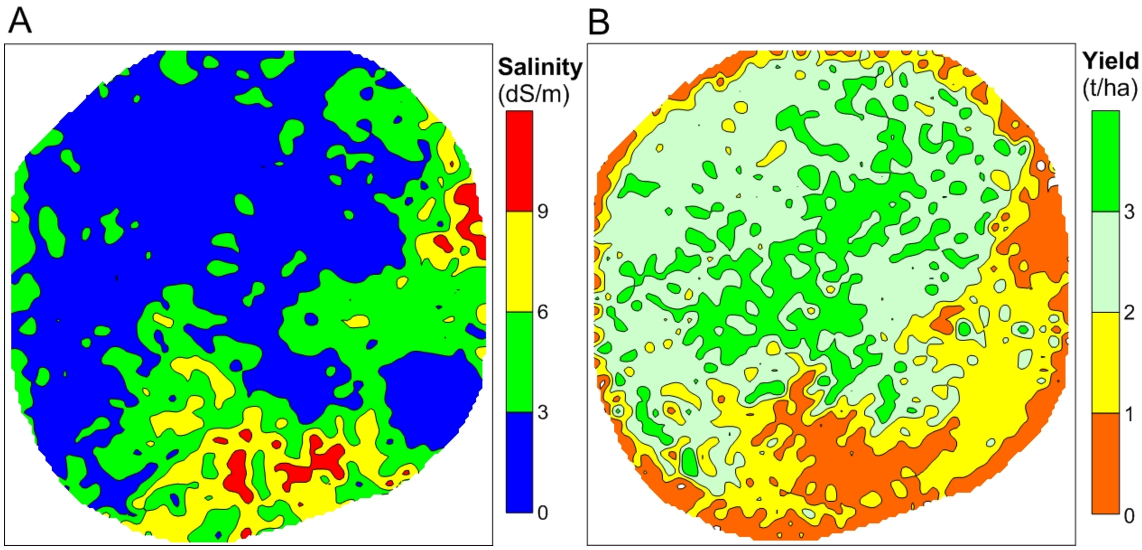

Figure 5. Georeferenced soil bulk electrical conductivity data can be transformed into maps of soil salinity using georeferenced soil salinity samples for calibration of the transform. As shown here, there can be a strong relationship between salinity and yield, especially for salt-sensitive crops such as dry beans. Illustration courtesy of Woods (2013).

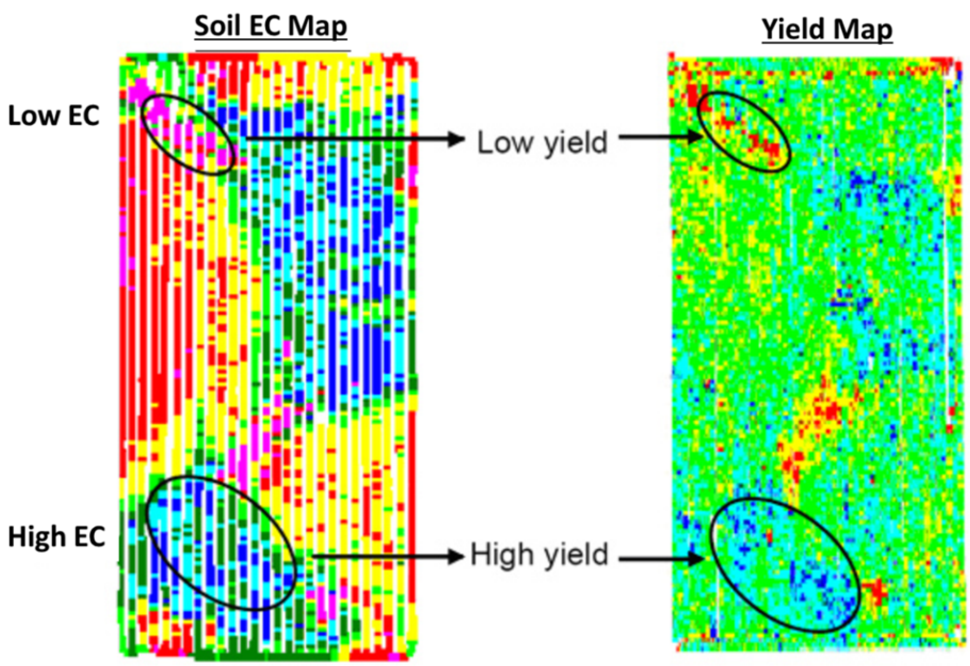

Figure 6. Example of a soil EC map that mostly represents soil texture differences. The lower EC areas were more sandy and had smaller water holding capacity, which resulted in less yield. The larger EC areas were more clayey and had larger water holding capacity, which resulted in more yield. Illustration courtesy of Grisso et al. (2011).

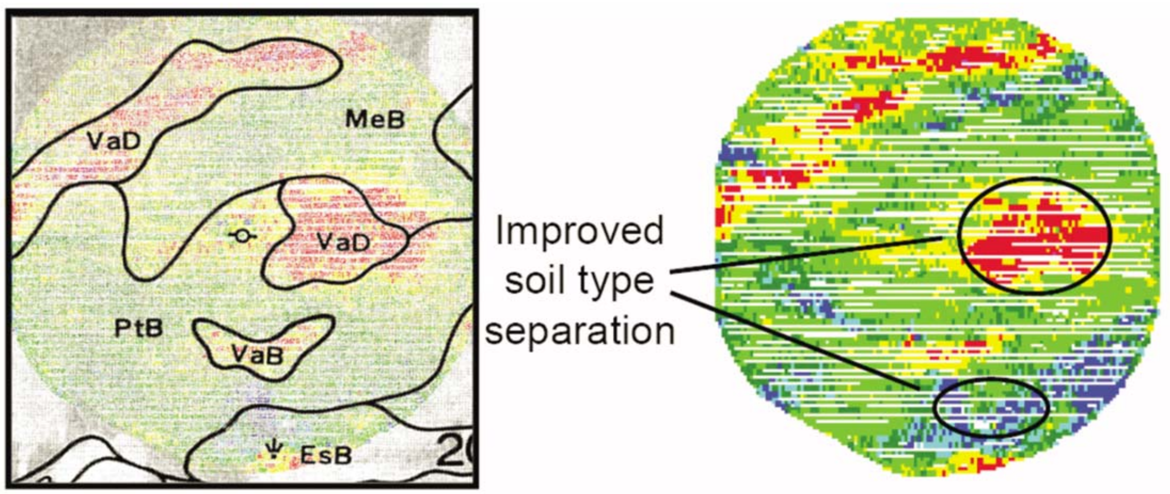

Figure 7. Example of soil EC map over which NRCS soil map boundaries have been overlaid (left), illustrating how the soil map could be corrected to more accurately represent the soil units. Illustration courtesy of Grisso et al. (2011).

Grisso et al. (2009) did, however, recommend using a soil BEC map in conjunction with an NRCS soil map because of the added information available from NRCS such as slope, crop suitability, etc. Factors such as large applications of manure or other fertilizer, variable irrigation in the past or very dry soils may result in misleading soil BEC maps. It should be remembered that soil BEC maps may indicate variations in soil water holding capacity, all other things being equal, but not necessarily crop water needs. Also, soil BEC sensing is typically done when there is no crop in the field, and it is relatively expensive, meaning that irrigation scheduling for VRI cannot be done using this technique.

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

In arid and semi-arid climates, greater crop canopy temperatures indicated greater crop water stress (Fig. 8) because crops with sufficient soil water availability are cooled by transpiration. Crop water stress irrigation scheduling 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 (Fig. 9). 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., 2014). 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 manufacturer who offers it for sale (model SapIP-IRT, Dynamax, Inc., Houston, Tex.).

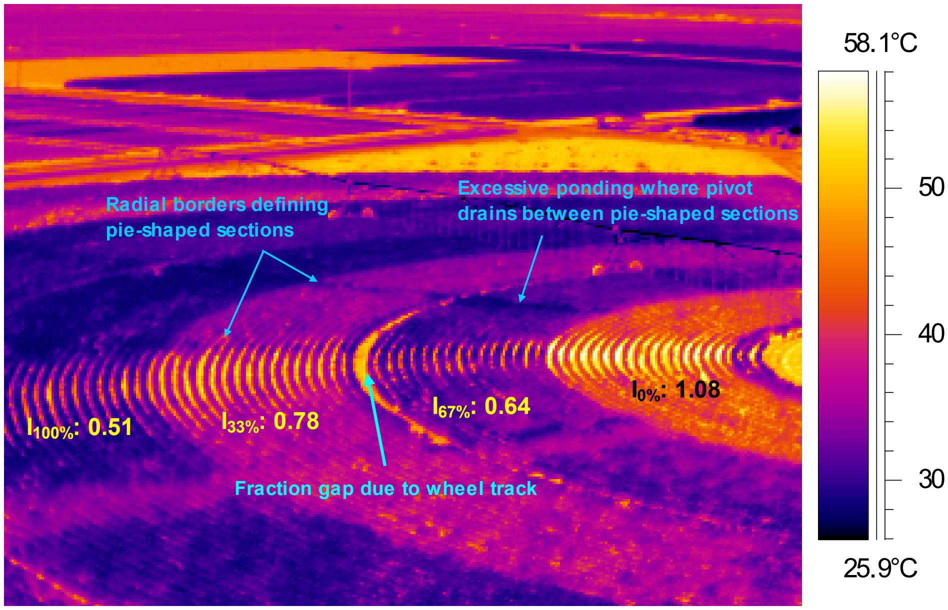

Figure 8. False color radiometric image of a center pivot irrigated field showing increasing canopy temperature as irrigation deficit increased from full irrigation ($I_{100\%}$) to 67% of full irrigation ($I_{67\%}$), to 33% of full irrigation ($I_{33\%}$) and to a non-irrigated (dryland) treatment ($I_{0\%}$). The values 0.51, 0.78, 0.64 and 1.08 are CWSI values. Also shown are cooler areas that received excess water when the pivot lateral was stopped to drain between treatments. The importance of infrared sensor aiming is also illustrated. View angles that look across rows see only plant canopy, whereas view angles that look down rows see both plant canopy and bare soil (brighter and warmer in this false color image).

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. The cotton CWSI values illustrated in Figure 9B were well correlated with soil profile water content within the root zone (Fig. 10), at least relatively later in the irrigation season. 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.

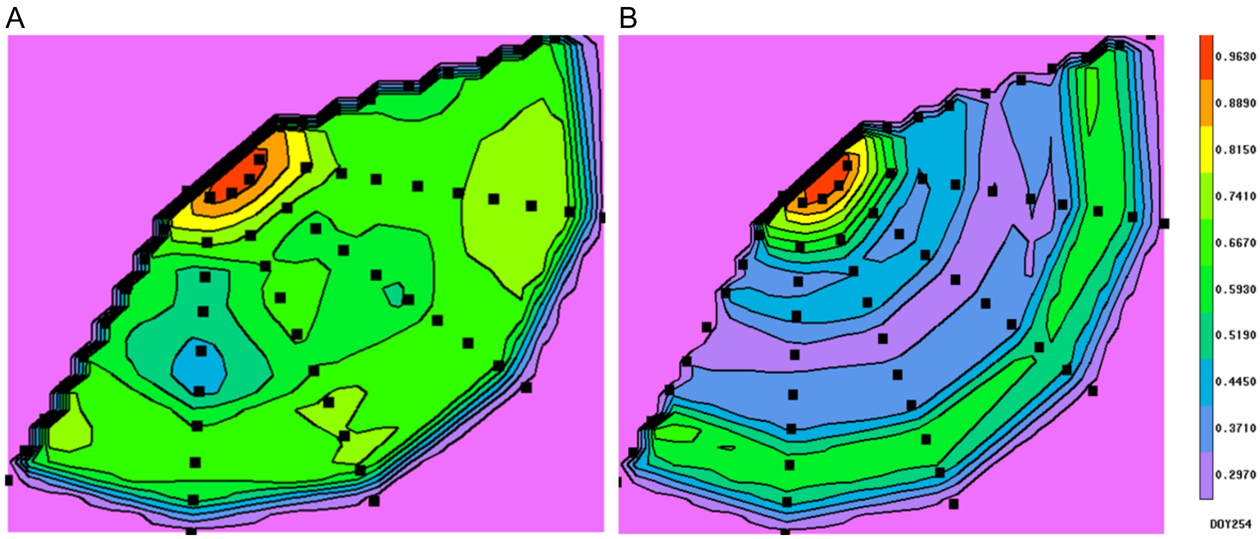

Figure 9. Empirical crop water stress index (eCWSI) calculated for a cotton field in which different deficit irrigation treatments were established. (A) Cotton early in irrigation season, DOY 204, 2007. (B) Cotton at end of irrigation season, DOY 254, 2007 (O'Shaughnessy et al., 2011). Early in the irrigation season, DOY 204, when a minimal number of differential irrigation treatments were applied, the stress index values do not vary substantially spatially. Only the unirrigated pivot center and the outer border rows showed appreciable differences. Near the end of the irrigation season, DOY 254, after imposing differential treatments for nearly 50 days, the variations in crop water stress were visible as a concentric pattern. The scale on the right varies from 0.297 to 0.963, which is the range of the data illustrated. The CWSI theoretically ranges from zero to unity,

Summary

Soil water sensing for variable rate irrigation scheduling is hampered by presently available accurate soil water sensors and wireless data transmission to the irrigation control center. Present challenges include field installation labor and timing to avoid machine operations that disturb the soil and may damage the sensors and antennas used. Depending on the spatial variation in field soil properties, installing an adequate number of sensors may be overly expensive. Wireless plant water stress sensors mounted on moving irrigation systems may be less expensive and offer proximal remote sensing that does not get in the way of field operations or require installing sensors in the soil. Nevertheless, soil water sensing will remain an important tool in irrigation scheduling, including as a check on VRI prescriptions generated using plant water stress sensors.

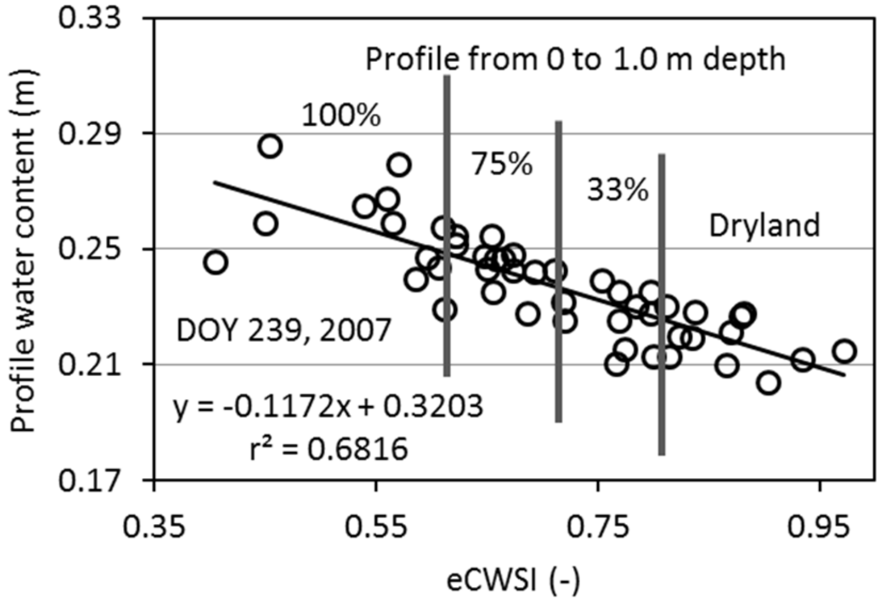

Figure 10. The soil profile water content within the crop root zone is correlated with the empirical crop water stress index (eCWSI). Different irrigation amount treatments produced groups of eCWSI values that did not overlap along the regression line, illustrating that eCWSI is a good surrogate for profile water content. Irrigation treatments were full (100%), 75% of full, 33% of full and dryland.

Acknowledgements

This research was supported in part by the Ogallala Aquifer Program, a consortium between USDA-Agricultural Research Service, Kansas State University, Texas AgriLife Research, Texas AgriLife Extension Service, Texas Tech University, and West Texas A&M University.

References

Chávez, J.L., and S.R. Evett 2012. Using soil water sensors to improve irrigation management. Pp. 187-202 *In* Proceedings of the 2012 Central Plains Irrigation Conference, February, 21-22, 2012, Colby Kansas. Manuscript in Adobe format (631 kb)

Colaizzi, Paul D.; Edward M. Barnes; Thomas R. Clarke; Christopher Y. Choi and Peter M. Waller. 2003. Estimating Soil Moisture under Low Frequency Surface Irrigation Using Crop Water Stress Index. J. Irrig. Drainage Eng., 129(1):27-35. Manuscript in Adobe format (157 kb)

Dong, X. and M.C. Vuran. 2013. Impacts of soil moisture on cognitive radio underground networks. Pp. 222-227 *In* International Black Sea Conference on Communications and Networking (BlackSeaCom), Batumi, Georgia. http://cpn.unl.edu/?q=system/files/ugcr-final.pdf

Dong, X., M. C. Vuran and S. Irmak. 2013. Autonomous precision agriculture through integration of wireless underground sensor networks with center pivot irrigation systems. Ad Hoc Networks J. 11(7):1975-1987. http://cpn.unl.edu/?q=system/files/CPS.pdf

Evett, S.R., T.A. Howell and J.A. Tolk. 2007. Comparison of soil water sensing methods for irrigation management and research. Pp. 1-27 *In* Proceedings of the 2007 Central Plains Irrigation, Kearney, Nebraska. Manuscript in Adobe format (736 KB)

Evett, S.R., R.T. Peters and T. A. Howell. 2006. Controlling water use efficiency with irrigation automation: Cases from drip and center pivot irrigation of corn and soybean. Proc. 28th Annual Southern Conservation Systems Conference, Amarillo TX, June 26-28, 2006. 57-66. Manuscript in Adobe format (980 KB)

Evett, S.R., L.K. Heng, P. Moutonnet and M.L. Nguyen (eds.). 2008. Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. IAEA-TCS-30. International Atomic Energy Agency, Vienna , Austria . ISSN 1018–5518. Manuscript in Adobe format (3 MB)

Evett, S.R., R.C. Scwhartz, J.A. Tolk, and T.A. Howell. 2009. Soil profile water content determination: Spatiotemporal variability of electromagnetic and neutron probe sensors in access tubes. Vadose Zone J. 8(4):926-941. Manuscript in Adobe format (2 MB)

Evett, S.R.**,** R.C. Schwartz, J.J. Casanova, and L.K. Heng. 2012. Soil water sensing for water balance, ET and WUE. Agric. Water Manage. 104:1-9. Manuscript in Adobe format (1,015 kb)

Evett, S.R., S.K. Anderson, J.J. Casanova and R.C. Schwartz. 2014. Patent application serial No. 13/404,491, Entitled "Soil Water and Conductivity Sensing System", filed 24 February 2012 with claims priority to Provisional Serial No. 61/515,381 – Filed August 5, 2011. Patent allowed on 7 October 2014.

Grisso, R., M. Alley, D. Holshouser and W. Thomason. 2009. Precision Farming Tools: Soil Electrical Conductivity. Publication 442-508, Virginia Cooperative Extension, Virginia Polytechnic Institute and State University. http://pubs.ext.vt.edu/442/442-508/442-508_pdf.pdf

Mazahrih, N.Th., N. Katbeh-Bader, S.R. Evett, J.E. Ayars, and T.J. Trout. 2008. Field calibration accuracy and utility of four down-hole water content sensors Vadose Zone J. 2008 7: 992-1000. Manuscript in Adobe format (1,027 kb)

O'Shaughnessy, S.A., S.R. Evett, P.D. Colaizzi and T.A. Howell. 2010. Automatic irrigation scheduling of grain sorghum using a CWSI and time threshold. Proc. 5th Decennial National Irrigation Proc., 5-8 December 2010, Phoenix, Arizona. Paper No. IRR10-9011. ASABE, St. Joseph, Mich. (CD-ROM). Manuscript in Adobe format (208 kb)

O'Shaughnessy, S.A., S.R. Evett, P.D. Colaizzi and T.A. Howell. 2011. Using radiation thermography and thermometry to evaluate crop water stress in soybean and cotton. Agric. Water Manage. 98(10):1523-1535.

O'Shaughnessy, S.A., S.R. Evett, P.D. Colaizzi and T.A. Howell. 2012a. Grain sorghum response to irrigation scheduling with the time-temperature threshold method and deficit irrigation levels. Trans. ASABE 55(2):451-461. Manuscript in Adobe format (1 MB)

O'Shaughnessy, S.A., S.R. Evett, P.D. Colaizzi and T.A. Howell. 2012b. Performance of a wireless sensor network for crop water monitoring and irrigation control. Paper # 12-1338246. 2012 ASABE Annual International Meeting, Jul 29 - Aug 1 2012, Dallas, Texas. St. Joseph, Mich.: ASABE. Manuscript in Adobe format (703 kb)

O'Shaughnessy, S.A., S.R. Evett, P.D. Colaizzi and T.A. Howell. 2013. Wireless sensor network effectively controls center pivot irrigation of sorghum. Appl. Engr. Agric. 29(6):853-864.

Peters, R.T. and S.R. Evett. 2008. Automation of a center pivot using the temperature-time-threshold method of irrigation scheduling. J. Irrig. Drain. Engr. 134(3):286-291. Manuscript in Adobe format (242 kb)

Tolk, J.A., S.R. Evett and R.C. Schwartz. 2014. Field-measured, hourly soil water evaporation stages in relation to reference evapotranspiration rate and soil to air temperature ratio. Submitted to Vadose Zone J.

Tooker, J., X. Dong, M.C. Vuran and S. Irmak. 2012. Connecting soil to cloud: A wireless underground sensor network testbed. 2012 9th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON). http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1203&context=cseconfwork

Vellidis, G., M.A. Tucker, C. Perry, H.E. Henry and R.W. Hill. 2013a. A soil moisture sensor-based variable rate irrigation scheduling system. 2013 Annual International Meeting of the ASA, CSSA and SSSA, Tampa, Florida. https://scisoc.confex.com/scisoc/2013am/webprogram/Paper81123.html

Vellidis, G., M. Tucker, C. Perry, D. Reckford, C. Butts, H. Henry, V. Liakos, R. W. Hill, W. Edwards. 2013b. A soil moisture sensor-based variable rate irrigation scheduling system. Pp. 713-720 in Precision agriculture ’13. Wageningen Academic Publishers. DOI: 10.3920/978-90-8686-778-3_88. Online ISBN: 978-90-8686-778-3.

Woods, S.A. 2013. Soil EC mapping technologies (EM38 and Veris) for identifying soil management zones. Agronomy Update, January 16, 2013. Alberta Agriculture and Rural Development, Lethbridge. http://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/all/crop14324/$FILE/au-2013-woods-effectiveness-of-em38-and-veris-soil-ec-technologies.pdf