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Perspectives and Considerations for Soil Moisture Sensing Technologies and Soil Water Content- and Soil Matric Potential-Based Irrigation Trigger Values

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Soil-water status (soil moisture) plays a critical role in determining yield potential of crops. Soil-water in the plant root-zone must be maintained in a balance so that plants can optimize their transpiration (biomass/yield production process) as well as water, nutrient, and micronutrient uptake. Accurate determination of soil-water status (either matric potential or water content) is not only very important for irrigation and water resources management, it is also a fundamental element of soil-water movement, chemical (fate) transport, crop water stress, evapotranspiration, hydrologic and crop modeling, climate change, and other important disciplines. Irrigation management requires the knowledge of "when" and "how much" water to apply to optimize crop production and increase and maintain a high level of water use efficiency. Insufficient irrigation applications can impose water stress on crops, which and can also cause irreversible damage to plants and this may lead to reductions in crop yield and yield quality. Overirrigation cause anaerobic soil conditions, promote undesirable chemical and biological reactions in the soil, which can cause yield reductions and be wasteful of water and energy resources. For example, from a multi-year research at the UNL South Central Agricultural Laboratory near Clay Center, Irmak (2014) reported that even only 25% more water than needed in the maize root-zone reduced grain yields as much as 15 bu/ac, which is a substantial portion of attainable maize yield in south central Nebraska. Reduced oxygen concentrations in soil due to wet soil or flooding conditions can cause stomatal closure of plants, which causes plant stress, because plants cannot transpire water vapor at an optimal/potential rate although water is available. Some researchers have reported that the soil oxygen deficiency can cause stomata closure as well even when plants do not experience water deficit stress. As a result, stomata closure reduces the transpiration rate and yield, because transpiration and yield are strongly and linearly correlated (Irmak, 2016).

Given its vital importance on numerous processes, plant physiological functions, and soil-water-atmosphere relationships, soil moisture determinations and irrigation management decisions must be made based on technology rather than non-technological approaches (i.e., hand-feel method, calendar day approach, based on neighbors' schedule, visual observations of soil and/or crop status) to optimize crop production efficiency. Furthermore, unlike some of the weather variables, soil moisture *is not a transferrable variable* between the locations or fields and it is a field-specific variable and hence must be measured for each field. Side by side fields and even different locations within a field can have substantially different soil-water status due to various factors and the interactions of these factors. Assuming that the same well-calibrated technology is used to monitor soil moisture, the factors that contribute to differences in soil-water status between the two side by side fields include, but not limited to, differences in the following variables between the fields:

- Soil physical and textural properties
- Organic matter content
- Field slope
- Crop type
- Planting date

- Crop emergence
- Plant growth and development rates and maturity date
- Irrigation management (method, timing, amount)
- Fertilizer management (method, timing, amount)
- Variability in precipitation (timing, amount)
- Soil and crop management practices between the fields (especially tillage)
- Crop water use (evapotranspiration) rates
- Residue cover type, percentage, and amount
- Pesticides application method, amount, and timing
- Field wetting history
- Crop exposure to water, heat, and wind stress (timing, duration, and magnitude)
- Crop exposure to fertilizer stress (timing duration, and magnitude)
- Disease pressure
- Other variables/factors

All these differences will result in substantial differences in soil moisture and different irrigation management requirements between the fields. The potential of using soil moisture data/information from another field/location to make effective irrigation management decisions is almost impossible. Thus, accurate soil moisture measurement for a given production field is necessary for various applications and is much more important than it is usually thought or perceived.

Soil Water Content vs. Soil Matric Potential to Express Soil-Water Status

Soil-water status in the soil profile can be expressed in two very different ways:

1. Soil water content (θ) and
2. Matric potential (Ψ).

Soil water content (SWC) indicates the quantity of water in the soil, but does not directly indicate the availability of this water to plants. Soil matric potential (SMP) represents the relative availability of the amount of water held in the soil profile for plant uptake/use and the quantity of soil-water from SMP is determined through soil-water characteristics curves developed for specific soil types. In more practical terms, SMP is a direct indication of how much energy must be exerted (application of pressure) by plants to extract the water molecules from soil particles. As the soil gets drier, the plants must exert increasingly more energy to extract water molecules because water molecules are extracted from the large soil pores first and water is held more tightly in the smaller pores and the bond between water molecules and soil pores becomes even stronger as soil gets drier. Plants extract most readily available water molecules first and gradually extract more strongly held water molecules and that is the reason for SMP gradually increasing as soil gets drier (the maximum value of SMP is zero, which indicates very wet soil conditions). As soil gets drier, SMP increases negatively (more negative tension), but in practical applications, the negative sign in SMP is usually ignored. SMP is usually expressed in units of energy such as erg/gr (1 bar = 1 x 10^6 erg/gr), or in joule/kg (1 bar = 100 joule/kg). Commonly used subunits are megapascal (MPa), kilopascal (kPa), centibars (cb) or millibars (mb) (1 bar = 0.1 MPa = 100 kPa = 100 cb = 1000 mb). SMP can also be presented in units of pressure such as atmosphere (1 bar = 1 atm = 14.7 psi), or in units of water head of an equivalent water column in centimeters (1 bar = 1022 cm H_2O at sea level) or equivalent mercury (Hg) column [1 bar = 76 cm (29.92 inch) Hg at sea level]. Additional information about SMP is provided in Irmak and Haman (2001) and Irmak et al. (2016).

Numerous methods have been used to determine soil-water status directly or indirectly. However, none of these methods is perfect. Decision-making on "which technique should be used" to monitor soil moisture highly depends on the purpose of the application, soil conditions, crop type, management practices, desired accuracy, durability, complexity, financial conditions, and other factors. While in practice SWC-based technologies are more widely used, scientifically SMP is a more powerful and robust method to determine soil-water deficit or soil-water availability for plant uptake. However, the application of SMP in practice is a little more complicated (i.e., development of soil-water release curves). Thus, SWC-based applications are used probably more widely than SMP-based technologies. However, if the soil-water release curves are developed and SMP values are converted to SWC or if irrigation management is practiced directly based on certain threshold or SMP trigger points, this would be a more robust and representative irrigation management strategy as it has been researched, taught, demonstrated, and practiced in the Nebraska Agricultural Water Management Network (NAWMN; https://water.unl.edu/category/nawmn) functions. In sensitive research and many other scientific applications, the use of SMP rather than SWC is preferred. Two of the most fundamental parameters in the entire soil water status, agriculture, hydrology, crop production and crop physiology, and other related disciplines are the field capacity and permanent wilting point and these two fundamental soil properties that drive almost all soil-water-atmosphere relationships were developed based on SMP rather than SWC.

In practice, quantification of SMP is a more difficult process than quantifying SWC. Also, measurement of soil-water retention curve for individual soil types to quantify soil water availability from SMP measurements is a sensitive and difficult task. Any instrument that is able to detect the change in some of the soil properties as a function of SWC can be used to monitor SWC. Such soil properties include dielectric constant and electrical resistivity. However, this process is much more prone to errors than measuring SMP, because relating the chance in any of the soil properties to SWC is an indirect process, it changes substantially from one soil type to another, and there is not any one soil property that is a direct and sole function of SWC. In other words, none of the soil properties can fully and solely explain the changes in SWC. Thus, the accuracy and performance of any soil water content sensors is a direct function of how well they are calibrated for a given soil type. If the calibration is done properly and based on developed standards, the SWC can also provide good indication of soil water status. Thus, the performance and accuracy of the SWC sensor is as good as the quality of the calibration process.

Proper Introduction of Soil Moisture Monitoring Devices to Agriculture and Irrigation Community

Whether it is SMP-based or SWC-based, the successful introduction as well as adoption of any soil moisture sensor/device is strongly dependent on the quality of the research that determines the performance under various soil conditions. If the necessary groundwork is done and the necessary performance characteristics are determined through good quality research, the potential probability of implementation and adoption of the soil moisture sensors should increase. When establishing the NAWMN about 15 years ago, the presence of soil moisture sensing companies in Nebraska was minimal. The NAWMN demonstrated significant economic and environmental and production-related benefits and values of technology implementation in agriculture and monitoring soil-water status, crop growth stages, and crop water use for effective irrigation management since 2005. The Network has established a culture and behavioral change, and as a result, helped to change how irrigation is managed. The Network had significant impacts on technology implementation in agricultural water management and set examples to other states. While Nebraska had lower ranking in terms of technology implementation in water management before the NAWMN, today the state leads the nation in terms of using technology for making water management decisions, in which NAWMN has played an important role and made significant contributions to this substantial positive change in ranking. Before establishment of NAWMN, the presence of soil moisture sensor companies in Nebraska was extremely limited or did not exist. Due to extensive demonstrations, educational programs, and documented large scale impacts of NAWMN, in the last several years, a number of soil moisture sensor companies started to be present/visible and market various soil moisture sensors in Nebraska, which is a good and positive step towards further promoting the technology use in agricultural water management. However, *unfortunately*, many of the SWC sensors that is available in the market today, including:

- Pseudo transit time-based sensors
- Time-domain reflectometry-based sensors
- Frequency-domain reflectometry-based sensors
- Capacitance-type sensors
- Neutron attenuation
- Gamma ray attenuation
- Remote sensing approach

and other types of SWC monitoring sensors are introduced to farmers, crop consultants, and other irrigation and agriculture community *without proper research and calibration for local soil conditions*. While all these methods and others continue to be developed, none of these methods would provide satisfactory performance in measuring soil-water status without proper calibration for various soil types using carefully designed and executed experiments based on scientifically valid methodologies. While the author has been heavily engaged in determining the performance of some of these additional soil moisture measurement devices, this is a time consuming, costly, and labor-intensive process and also the results, analyses, and interpretation have to go through a peer-review process and reviewed by other experts scientist in the field before the research is published and implemented as a scientifically valid practice. It is an extremely difficult task to research and calibrate each of the soil moisture monitoring devices available in the market due to enormous amount of time and resources and effort required. Thus, private companies that are introducing any kind of soil moisture sensor into the irrigation and agricultural water management community should conduct research and develop calibration parameters for dominant soil types in a given state (preferably in close partnership and collaboration with university scientists) and should provide the scientific/research evidence of the soil moisture sensor performance in various soil moisture ranges before a given soil moisture sensor is introduced. If proper research and calibration procedures are not followed, the sensors will either over- or underestimate soil water status and can even provide inconsistent (poor repeatability) and this will result in either crop stress as a result of insufficient water application or detrimental effects due to over-irrigation. In both cases, effective irrigation management will fail and this will result in reduction in grain yield, wasting water and energy resources, which will cause reduction in farm net return. Thus, it is important for users to ask for calibration information of the soil moisture sensor device that they desire to use in their management practices.

In the selection of proper soil moisture sensor technology, the following criteria should be considered:

- Cost
- Performance, accuracy, reliability, repeatability (for major soil types)
- Soil (what critical operational aspects need to be considered in various soil types)
- Crop (are the sensors suitable for majority of the row crops produced in the area?)
- Response time (is the response time of the sensor adequate for assessing the effectiveness of the irrigation and/or precipitation for making irrigation management decisions?)
- Complexity (preparation, installation, removal, service, use, maintenance)
- Ease of data interpretation
- Durability
- Life span of the sensor
- Power requirement for operation
- Ease of incorporation of sensor data into decision-making
- Safety
- Unattended and continuous monitoring
- Performance vs. soil and water salinity (i.e., fertilizer) relationships. Is the sensor impacted by soil and/or water salinity due to fertilizer application and other potential source(s) of salinity?
- Performance vs. soil temperature relationships. Is the sensor impacted by soil temperature fluctuations? If so by how much and how this can be accounted for?
- When applicable, is the sensor sensitive to installation orientation?

Researching all these aspects is critical for a successful introduction/implementation of any soil moisture sensor technology in agricultural water management and crop production. The technologies that are used in the NAWMN have been researched extensively for these components before they were introduced into the NAWMN functions. Thus, the soil moisture sensor companies should research these important aspects for various soil textures and provide research data and information to the users before the technologies are introduced. This approach would contribute to the acceptance and success of the adoption of a given technology.

Irrigation Trigger Points (Thresholds) when Using Soil Water Content (SWC)-Based and Soil Matric Potential (SMP)-Based Sensors

While the author developed some of the first guidelines for irrigation management/irrigation trigger points for different soil types using SMP values for Watermark and other SMP-based sensors, the guidelines for irrigation management/trigger points using SWC-based sensors did not exist. This is the first publication that developed research-based irrigation trigger points for different soil types using SWC-based measurements. In Table 1, soil textural characteristics, soil-water holding capacity, and suggested range of SWC-based irrigation trigger points (%vol) are presented. These SWC-based trigger points were calculated with the assumption of no sensor malfunction. The trigger points are applicable to any SWC-based sensor. The trigger points were calculated based on approximately 35–40% depletion of the total soil-water per foot of soil layer. The sensor readings and the trigger points should be verified/checked against the crop appearance in the actual field conditions during the season (at least during the first season when this approach is implemented). For irrigation management, irrigation trigger point should be the average of first 2 feet of SWC sensors (average of top 1st and 2nd ft sensor readings, when sensors are installed with 12 inch increments) prior to crop reproductive stages (for example, before R3 stage for soybean; tassel stage for corn) and first 3 feet (average of top 1st, 2nd, and 3rd sensor readings) once crop reaches the reproductive stage. However, for the sandy soils, the average of top 2 sensor readings should be used as a trigger point at all times during the season to trigger irrigations due to very low water holding capacity. It should be noted that some of the soil characteristics are also provided in Table 1 because trigger points are a function of these soil-water characteristics. For the same soil series, the trigger points may vary due to differences in these characteristics. For example, even though two soils can be classified as Hastings silt loam soil, their particle size distribution (i.e., percent sand, silt, and clay), field capacity (FC), permanent wilting point (PWP), bulk density (BD), saturated hydraulic conductivity (K_{sat}), and other characteristics can be different and they would have different irrigation trigger

Table 1. Soil textural properties, soil-water holding capacity, and research-based irrigation trigger points for major soil types. FC: field capacity; PWP: permanent wilting point; K_{sat}: saturated hydraulic conductivity; BD: bulk density.

	Soil textural properties, water holding capacity, and irrigation trigger points for various soil types when using soil water content sensors					
Soil textural and hydraulic characteristics	SILTY CLAY LOAM TOPSOIL, SILTY CLAY SUBSOI (SHARPSBURG)	CLAY LOAM	UPLAND SILT LOAM TOPSOIL, SILTY CLAY LOAM SUBSOIL (HASTINGS, CRETE, HOLDREGE)	SANDY LOAM	LOAMY SAND (O'NEILL)	SAND (VALENTINE)
% Sand	10	33	20	65	82	92
% Clay	34	34	20	10	6	5
% Silt	56	33	60	25	12	3
FC (% vol)	37.9	35	32.2	17.9	12	9.4
PWP (% vol)	21.0	21.3	17.3	8.1	5.7	5
Saturation (% vol)	51.0	47.20	48.2	45.0	45.70	46
K_{sat} (in/hr)	0.23	0.18	0.48	1.98	3.59	4.5
BD (lbs/ft^3)	81.06	87.39	85.67	91.10	89.78	88.9
BD (gr/cm^3)	1.30	1.40	1.37	1.5	1.44	1.42
Water holding capacity (in/ft)	**1.80–2.0**	**1.60–1.80**	**2.20–2.30**	**1.20–1.80**	**0.75–1.10**	**0.50–0.60**
Suggested range of irrigation trigger point when using SWC sensors (% vol)	**(25–27)**	**(23–25)**	**(23–24)**	**(12–14)**	**(8–10)**	**(6–8)**

points. Since it is an extremely difficult task to present the trigger points for every soil series, soils are grouped under five different classifications in Table 1.

Since, every SWC-based soil moisture sensor measures SWC with some degree of error, to accommodate at least some of the measurements errors (related to resolution/sensitivity and precision) in SWC-based sensors, some safety factors were also included in the trigger values presented in Table 1. It is very important to note that the irrigation trigger points presented in Table 1 assumes that the SWC sensor that is used to measure these trigger points are well-calibrated for the soil conditions in which the sensor is deployed. If the soil moisture sensors are not well-calibrated, the trigger points as well as the soil moisture sensor readings themselves will not be useful and both will result in erroneous trigger points and irrigation applications, resulting in non-optimal crop production and waste of energy, time, labor, water, and financial resources and this would compromise yield quality and quantity.

Similarly, Table 2 presents the soil-water depletion per SMP readings in kPa (cbar) and the range of irrigation trigger points for eight major soil types. *These trigger points and depletion levels are not unique to only Watermark sensors and can be used for any other soil moisture sensors that measure SMP*. As was the case in Table 1, safety factors were built into the SMP-based trigger point calculations to account for uncertainties in SMP measurements. These SMP-based trigger points have been successfully used in the NAWMN functions and are still valid and represent the latest information and data on SMP-based irrigation management practices. Between Tables 1 and 2, practitioners can manage irrigations using any kind of well-calibrated SWC-based or SMP-based soil moisture sensors for up to eight major soil types. The trigger point-based irrigation management is a unique, robust, and research-based approach that does not need measurement of precipitation or tracking soil water status for water balance (budget) calculations to determine irrigation trigger. The SWC or SMP sensors would measure the change in SWC or SMP in the soil profile and will respond to any precipitation events by measuring the change in SWC or SMP and the values will fluctuate until the irrigation trigger point is reached for a given soil type.

In cases where soil matric potential sensors are used to monitor soil water status, SMP values can be converted to volumetric soil water content. For this purpose, the author has developed numerous soil-water retention release curves for different soil types. Examples of the soil-water retention curve equations developed for the conversion for six major soil types are listed below.

$$VWC\ (\%) = 92.19\ SMP^{-0.285} \quad R^2 = 0.99 \quad for\ silt\ loam\ soil \tag{1}$$
$$VWC\ (\%) = 77.356\ SMP^{-0.181} \quad R^2 = 0.97 \quad for\ silty\ clay\ loam\ soil \tag{2}$$
$$VWC\ (\%) = 77.816\ SMP^{-0.212} \quad R^2 = 0.97 \quad for\ clay\ loam\ soil \tag{3}$$
$$VWC\ (\%) = 80.823\ SMP^{-0.266} \quad R^2 = 0.98 \quad for\ loam\ soil \tag{4}$$
$$VWC\ (\%) = 62.828\ SMP^{-0.186} \quad R^2 = 0.95 \quad for\ sandy\ clay\ loam\ soil \tag{5}$$
$$VWC\ (\%) = 73.308\ SMP^{-0.274} \quad R^2 = 0.98 \quad for\ sandy\ loam\ soil \tag{6}$$
$$VWC\ (\%) = 63.13\ SMP^{-286} \quad R^2 = 0.97 \quad for\ loamy\ sand\ soil \tag{7}$$
$$VWC\ (\%) = 64.621\ SMP^{-0.326} \quad R^2 = 0.94 \quad for\ sand\ soil \tag{8}$$

where, VWC (%) is volumetric water content (%) and SMP is soil matric potential in kPa.

Examples of SWC values measured using a neutron probe in a center pivot-irrigated corn field at the UNL-South

Table 2. **Depletion (in/ft) in available soil-water versus soil matric potential (SMP) and suggested range of irrigation trigger point for different soil types. These SMP-based trigger points and depletion levels are not unique to only Watermark sensors and can be used for any other soil moisture sensors that measure SMP.**

	Soil type, depletion in inches per foot associated with a given soil matric potential value measured by the Watermark and other soil matric potential sensors, and available water holding capacity for different soil types							
Soil matric potential (kPa)	SILTY CLAY LOAM TOPSOIL, SILTY CLAY SUBSOIL (SHARPSBURG)	SILT-LOAM TOPSOIL, CLAY LOAM SUBSOIL	UPLAND SILT LOAM TOPSOIL, SILTY CLAY LOAM SUBSOIL (HASTINGS, CRETE, HOLDREGE)	BOTTOM LAND SILT-LOAM (WABASH, HALL)	FINE SANDY LOAM	SANDY LOAM	LOAMY SAND (O'NEILL)	FINE SAND (VALENTINE)
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.20	0.30	0.30	0.30
33	0.20	0.14	0.00	0.00	0.55	0.50	0.45	0.55
50	0.45	0.36	0.32	0.30	0.80	0.70	0.60	0.70
60	0.50	0.40	0.47	0.44	1.00	0.80	0.70	0.70
70	0.60	0.50	0.59	0.50	1.10	0.80	0.80	0.80
80	0.65	0.55	0.70	0.60	1.20	1.00	0.93	1.00
90	0.70	0.60	0.78	0.70	1.40	1.20	1.04	N/A
100	0.80	0.68	0.85	0.80	1.60	1.40	1.10	N/A
110	0.82	0.72	0.89	0.88	N/A	N/A	N/A	N/A
120	0.85	0.77	0.91	0.94	N/A	N/A	N/A	N/A
130	0.86	0.82	0.94	1.00	N/A	N/A	N/A	N/A
140	0.88	0.85	0.97	1.10	N/A	N/A	N/A	N/A
150	0.90	0.86	1.08	1.20	N/A	N/A	N/A	N/A
200	1.00	0.95	1.20	1.30	N/A	N/A	N/A	N/A
Water holding capacity (in/ft)	**1.8–2.0**	**1.8–2.0**	**2.20**	**2.00**	**1.80**	**1.40**	**1.10**	**1.00**
Suggested range of irrigation trigger point (kPa)	**75–80**	**80–90**	**90–100**	**75–80**	**45–55**	**30–33**	**25–30**	**20–25**

Central Agricultural Laboratory are presented in Figure 1. The SWC was measured with 1 foot increments down to 6 ft soil depth on a weekly or every other week basis in a fully-irrigated (a) and rainfed (b) treatments. Field capacity (FC) and permanent wilting point (PWP) values (34 and 14% vol, respectively) are marked on the graphs for reference. For irrigation purposes, soil-water in the crop root-zone should be managed between FC and PWP as this is the amount of water available for plant uptake. SWC should not be allowed to get close to PWP as this can cause severe stress and/or irreversible damage to plants. Thus, the use technology to monitor soil-water status to make effective decisions is important to maintain optimum soil-water in the crop root zone, which otherwise cannot be determined using visual or hand-feel or other qualitative methods.

In Figure 1a and b, SWC fluctuates as a function rainfall and/or irrigation and soil evaporation and transpiration (evapotranspiration). SWC increases with irrigation and/or rainfall and decreases as soil-water is taken up by plants. When irrigation is applied, soil-water should be replenished up to about 90% of FC so that some storage remains in the profile to store any potential rainfall. In both figures, it is clear that the driest layer is the top 1 ft and SWC in this layer fluctuates with the largest magnitude as this layer is subject

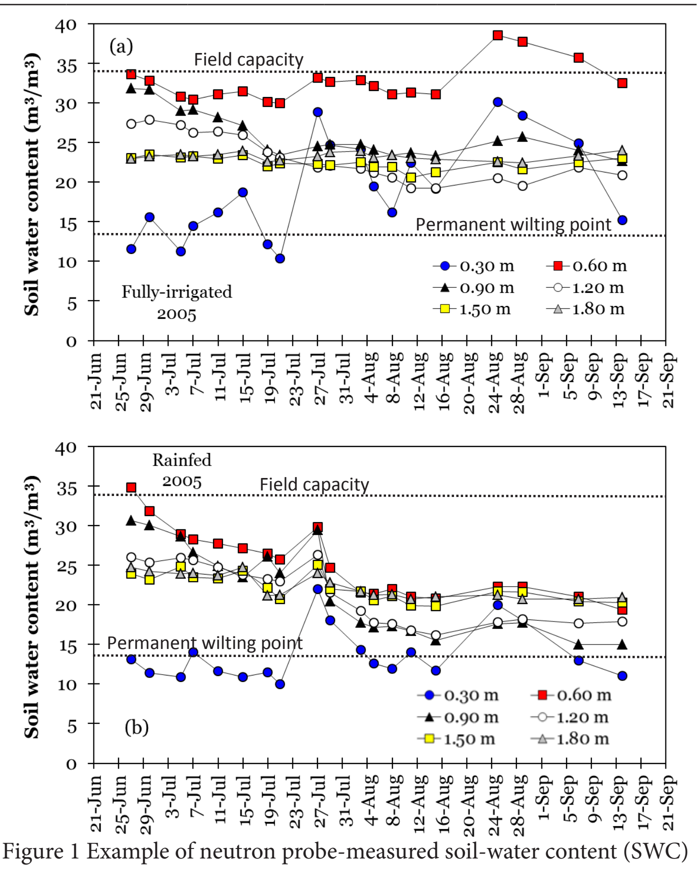

Figure 1 Example of neutron probe-measured soil-water content (SWC) for fully-irrigated (a) and rainfed (b) corn plots in a silt loam soil [adopted from Irmak (2015a and b)].

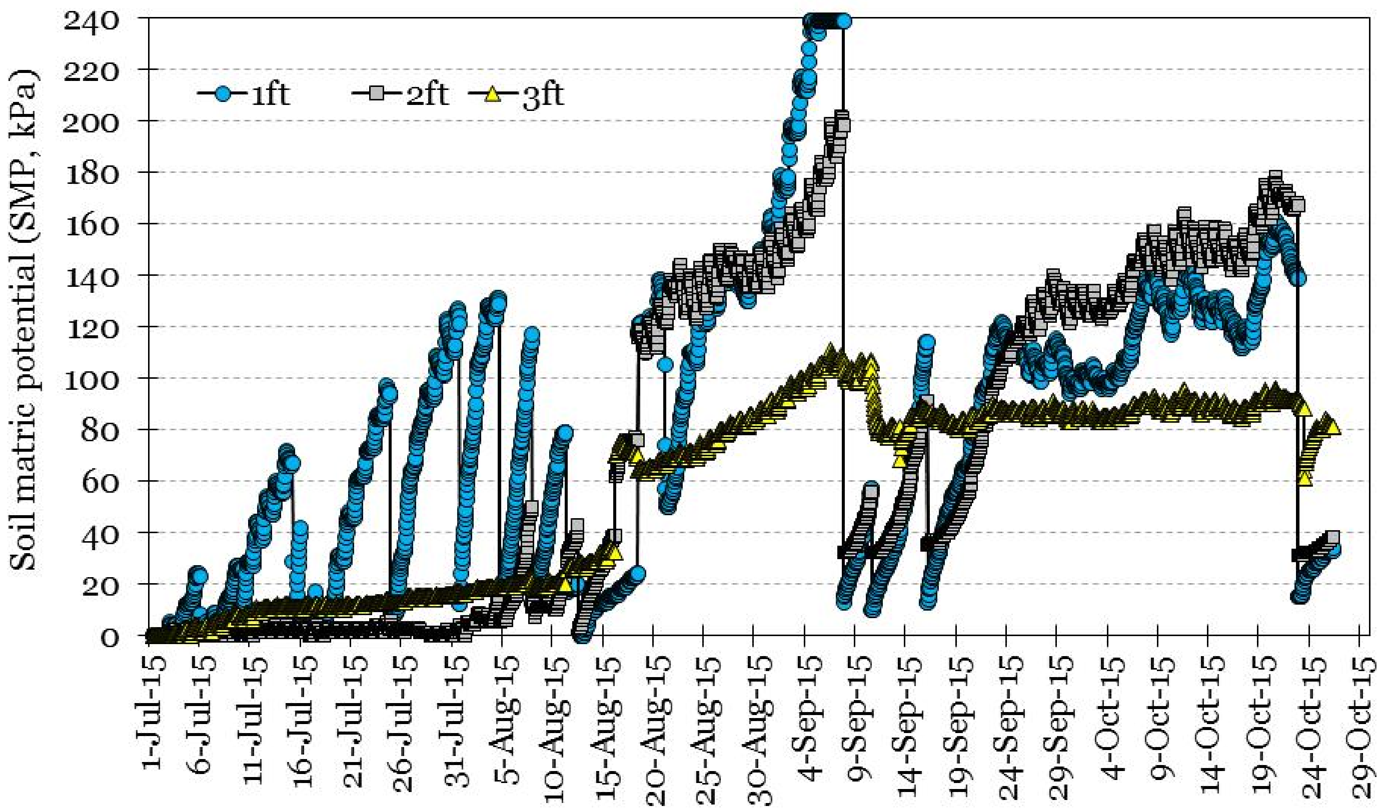

Figure 2. Example of seasonal progression of measured soil matric potential (SMP) values in a variable rate irrigation and variable rate fertigation corn research field at the UNL South Central Agricultural Laboratory near Clay Center.

to direct radiation, soil evaporation and plant water uptake as most of the plant roots are in the first foot layer. In the fully-irrigated treatment (Figure 1a), the SWC in most of the layers is managed between FC and PWP and there is no clear decreasing trend as irrigations maintained SWC adequate for plant growth, development, and meeting the evapotranspiration demand. Since there is no irrigation in the rainfed treatment (Figure 1b), the SWC in almost all soil layers has a decreasing trend due to insufficient rainfall to meet crop water demand, which is typical for rainfed cropping systems.

An example of measured SMP in three soil depths in a variable rate-irrigated and variable rate- fertigated corn field at the UNL South Central Agricultural Laboratory in one of the Irmak Research Laboratory fields with silt loam soil for the portion of the growing season is presented in Figure 2. Similarly to SWC, the SMP fluctuated the most in the top soil layer (1 ft) as a function of greater evaporative losses and this layer being subject to most radiation, wind speed, crop water uptake, evaporation, etc. The second soil layer (2 ft) fluctuated to a lesser extent than the first layer and more than the third layer. During the season, the SMP reached irrigation trigger point several times (when the top two layers' average SMP value reaches 90–100 kPa before tassel and when the average of top three sensors' SMP value is 90–100 kPa after tassel) which can provide an effective irrigation management information.

References

Irmak, S. and D.Z. Haman. 2001. Performance of the Watermark granular matrix sensor in sandy soils. *Applied Engineering in Agriculture* 17(6):787–795.

Irmak, S. 2014. Plant growth and yield as affected by wet soil conditions due to flooding or over-irrigation. *UNL Extension NebGuide G1904*. http://extensionpubs.unl.edu/publication/9000016366481/plant-growth-and-yield-as-affected-by-wet-soil-conditions-due-to-flooding-or-over-irrigation/.

Irmak, S. 2015a. Inter-annual variation in long-term center pivot-irrigated maize evapotranspiration (ET) and various water productivity response indices: Part I. Grain yield, actual and basal ET, irrigation-yield production functions, ET-yield production functions, and yield response factors. *J. Irrigation and Drainage Engineering, ASCE* 141(5):1–17. 04014068. doi:10.1061/(ASCE)IR.1943–4774.0000825.

Irmak, S. 2015b. Inter-annual variation in long-term center pivot-irrigated maize evapotranspiration (ET) and various water productivity response indices: Part II. Irrigation water use efficiency (IWUE), crop WUE, evapotranspiration WUE, irrigation-evapotranspiration use efficiency, and precipitation use efficiency. *J. Irrigation and Drainage Engineering, ASCE* 141(5):1–11. 04014069. doi: 10.1061/(ASCE)IR.1943–4774.0000826.

Irmak, S., J. Payero, B. VanDeWalle, J. Rees, G. Zoubek, D. Martin, W. Kranz, D. Eisenhauer and D. Leininger. 2016. Principles and operational characteristics of Watermark granular matrix sensor to measure soil water status and its practical applications for irrigation management in various soil textures. *UNL Extension Circular EC783*. 14 pp. http://extensionpubs.unl.edu/publication/9000016364584/principles-and-operational-characteristics-of-watermark-granular-matrix-sensor-to-measure-soil-water-status-and-its-practical-applications-for-irrigation-management-in-various-soil-textures/.

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