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Soil-Water Potential and Soil-Water Content Concepts and Measurement Methods

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Soil-water status is a critical and rapidly changing variable that determines and impacts numerous important factors in production fields such as crop emergence and growth, water management, water and crop yield productivity relationships, and within-field hydrologic balances. Thus, its accurate determination dictates and impacts the success of water management and related agricultural operations. This, in turn, affects the attainment of potential yield, as well as the reduction of water losses and chemical leaching. Maintaining optimum soil moisture in the crop root zone also strongly influences optimum nitrogen (N) uptake by plants, which helps to reduce N leaching. Numerous soil moisture measurement technologies are available. None of the methods, however, are perfectly suited to all operational conditions as each has drawbacks and advantages, depending on the application conditions.

In this publication, some of the basic principles of soil-water status [soil-water content (SWC) and soil-matric potential (SMP)] are presented. Basic principles and operational aspects of each method are discussed. Also, some of the advantages and disadvantages of each method is presented. Several commonly available and used soil moisture technologies are also presented. Other effective methods that are less commonly known and/or used such as carbide method, thermal conductance (heat dissipation), soil psychrometers and hygrometers, gamma ray attenuation, filter paper technique, and freezing point depression are not included in the publication. Also not included is the widely used Watermark® granular matrix sensor as detailed information about technical and operational principles of this sensor is provided in Irmak et al. (2016) and Irmak and Haman (2001).

Accurate determination of soil-water status (SWC or soil-water potential) is a fundamental element of irrigation management. In addition, it is important for studying soil-water movement, chemical transport, crop water stress, evapotranspiration, hydrologic and crop modeling, soil physics, water resources management, climate change impacts on agricultural water management and crop productivity, meteorological studies, yield forecasting, water run-off and run-on, infiltration studies, field traffic and within-field work ability and soil-compaction studies, aridity indices, and other agricultural and ecosystem functions and practices. Effective irrigation management requires the knowledge of "when" and "how much" water to apply to optimize crop production. Some of the most effective irrigation management decisions also include "how" to apply the irrigation water for most effective productivity under different climate, soil, crop, and management practices to reduce unbeneficial water losses and increase water application and use efficiency. Water application rates higher than necessary and/or too frequently may cause anaerobic soil conditions, which may promote undesirable chemical and biological reactions in the soil, cause chemical leaching to surface and/or groundwater resources, and result in the waste of water and energy resources. Too light or infrequent irrigation applications may cause water stress conditions; in turn, this may reduce crop yields and yield quality. These issues may be more pronounced under water-limiting, arid and semi-arid environments such as those in some parts of Nebraska and surrounding midwestern regions and western and southwestern USA.

A number of methods have been developed and are currently in use to determine soil-water status directly or indirectly; however, none are entirely ideal. Decision-making on "which technique should be used" depends highly on the sensor cost, ease of use, durability, purpose of the practice, soil and crop conditions, desired accuracy, financial resourc-

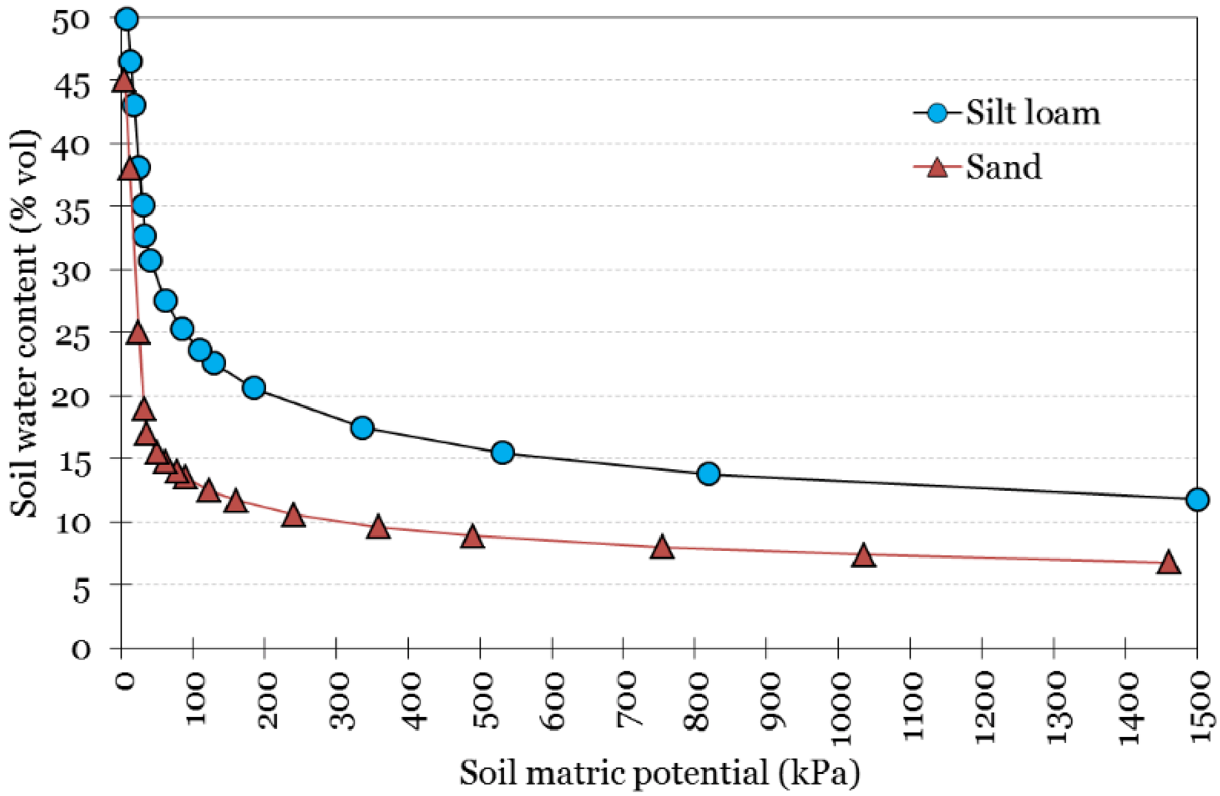

Figure 1. Relationship between SMP and SWC (soil-water retention curves) for two different soil types.

es, and other factors. In the indirect methods, calibrations are required, and calibrations are not always dependent solely on the moisture content of the soil. With a well-installed sensor, some of the factors that may influence calibrations, and in turn sensor performance, are soil texture (especially clay content), soil temperature, time of reading, electrical contact resistance, and salt concentration. Salt concentration influences readings when fertilizer is added to soil and when salt concentration in the soil changes as a result of soil-water evaporation. Time of reading causes some problems in methods in which a period of time (aka response time) is required for the soil moisture detector to reach equilibrium with the surrounding water. Thus, sensors with a fast response time have advantages over those with slow response time in terms of better tracking and responding to changes in soil-water status as a function of precipitation, irrigation, plant water uptake, evaporation, and deep percolation.

Soil-water status can be expressed primarily in two basic ways: (i) soil-water content (SWC) and (ii) soil-matric potential (SMP). In basic terms, SWC is defined as the amount of water held in a certain mass or volume of soil. SWC indicates the quantity of water in the soil; however, it does not indicate the availability of this water to plants. SMP provides the relative availability of soil-water to plants, but does not indicate directly how much irrigation water should be applied. Soil-water characteristic curves provide a graphical representation of the relationship between SWC and SMP. This relationship is critical for various applications in terms of determining soil-water-plant-atmosphere relationships and can be used to convert SMP to SWC, or vice versa. The relationship between SWC and SMP is not unique; it is affected by the direction and rate of change of soil-water status and is sensitive to changes in soil volume and structure. Therefore, individual characteristic curves should be determined for a given soil type. An example of soil-water characteristic curves for a silt-loam soil and a sandy soil is presented in Figure 1. SMP is a reverse scale, with the highest value of SMP at zero, which indicates very wet soil conditions (near saturation, but not saturated), whereas greater SMP values (larger negative values) indicate drier soil conditions. In both soils, there is a sharp decrease in SWC in the SMP range of approximately 0–70 kilopascal (1 kPa = ~0.15 psi). The amount of water held in both soils decreases as SMP increases. At any given SMP value, the SWC is greater in a silt-loam soil than in a sandy soil due to the greater soil-water holding capacity of a silt-loam soil. The sol-water holding capacity concept was studied and introduced by Widtsoe and McLaughlin in 1902 and 1903 for different soil types and their findings were published in 1912. Israelsen and West (1922) further developed the concept.

Soil-Water Content (SWC)

Soil-water content (SWC) is the percentage of water held by the soil, and it can be expressed in terms of either percentage by dry weight or volume basis. Water content of a soil sample on a dry weight basis (SWC_{dw}) is defined as the num-

Figure 2. Taking soil bulk density samples in a weighing lysimeter using an undisturbed soil core sampler. (100 cm^3 = 6 in^3)

ber of grams (gr) of water per gr of oven-dried soil, usually expressed as a percent, and can be calculated as:

$$SWC_{dw} = [(WW - DW) / (DW)] \times 100 \quad (1)$$

WW = wet weight of the soil sample (gr)
DW = dry weight of the soil sample (gr)

It is often beneficial and convenient to express SWC on a volume basis (θ_v), i.e., the ratio of the soil-water volume to the bulk soil volume. This is a more suitable expression than water content expressed on a dry weight basis for irrigation and drainage applications and for theoretical considerations of water retention and flow in a porous soil medium. This is because additions to, and losses of water from the soil are often measured in inches or millimeters, which on an area basis become the volume (Kramer, 1983). The water content on a volume basis can be calculated as:

$$\theta_v = \theta_{dw} \text{ x } (\rho_b / \gamma_w) \quad (2)$$

ρ_b = bulk density of soil (gr/cm^3 or mg/m^3) (cm = centimeter; mg = milligram; m = meter)
γ_w = density of water (usually 1.0 gr/cm^3)

The soil bulk density is calculated using weight of dry soil (gr) and volume of the soil (cm^3) as:

$$\rho_b = \frac{\text{Weight of dry soil}}{\text{Volume of soil}} \quad (3)$$

After water content is determined on a volume basis, then it can be expressed in relevant units for irrigators such as inches per foot or centimeters per meter of soil depth. For example, a soil with a water content of 15% by volume contains (15%) × (12 in/ft) = 1.8 inches of water per foot of soil depth. The accuracy of the volume-basis water content calculations depends on the accuracy of the soil bulk density value used as well as the accuracy of the determination of dry weight water content value. The soil bulk density (ρ_b) is defined as the oven dry mass of soil—at 105°Celsius (°C) [221°Fahrenheit (°F)] until the soil sample reaches a constant weight—in a given volume. It can be measured by drying and weighing a known volume of soil. The mass of dry soil divided by the total volume (solids plus voids) will give the bulk density value. In practice, bulk density is usually determined by collecting a 100 cm^3 (~6 in^3) volume of soil using a brass cylinder to take an undisturbed soil core sample (Figure 2). For non-swelling soils (e.g., sand) the bulk density of soil does not change much with water content, and the calculation of ρ_b is relatively easy. For swelling soils (e.g., clay), however, bulk density values must be determined at different water content ranges due to changes in volume as water content increases. Considering the heterogeneity of soil, enough soil samples should be taken and then averaged to determine both bulk density and SWC in a given field to increase the accuracy of measurements, which can result in increasing the effectiveness of operational decision-making.

Soil-Water Potential (Ψ)

According to Cassel and Nielson (1986), "total" soil-water potential is defined as "the amount of work that must be done per unit quantity of pure water to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil-water (at a specified point)." Soil-water is subject to a number of possible forces (e.g., cohesive and adhesive forces), and each force contributes some change to the total soil-water potential. Therefore, the total potential of soil-water can be written as the sum of those individual contributions of these forces as:

$$\Psi_t = \Psi_g + \Psi_m + \Psi_o + \ldots \quad (4)$$

where, Ψ_t is the total potential, Ψ_g the gravitational potential, Ψ_m the soil matric potential (SMP) (matric suction or capillary potential) produced by capillary and surface forces, and Ψ_o the osmotic potential produced by solutes (e.g., dissolved salts) in the soil-water. The ellipsis indicates that additional potentials are theoretically possible.

The gravitational potential of soil at a given point is determined by measuring the vertical distance between this point and some arbitrary reference level. For convenience, it is customary to set the reference level at the elevation of a pertinent point within the soil or below the soil profile being considered so that the gravitational potential can always be taken as positive or zero. In practice, osmotic potential can be ignored, because the soil solution (soil-water substrate) is usually assumed to be diluted enough that it does not contribute to the total potential of the soil. However, if the soil solution is not diluted enough (saline soil solution), the osmotic potential must be considered in determining total water potential.

Soil-matric potential (Ψ_m or SMP) is one of the components of the total water potential that characterizes the tenacity with which water is held by the soil matrix. In another way, SMP indicates the force that must be applied by plants to extract water from the soil particles. In soil-water studies, the terms *soil-water potential*, *matric potential*, *matric suction*, *capillary potential*, and *tension (*or *soil-water suction*) are used interchangeably. Soil-water potentials are negative numbers. However, because it is implicit, sometimes, the negative sign is omitted, or the term "tension" is used. In this publication, the negative sign is omitted, and the term *soil matric potential* is used. Since the values of the soil-water potential may vary over several orders of magnitude, sometimes it would be convenient to use a logarithmic scale for soil-water potential (suction). In soil-water-plant relationships, irrigation management and related applications, SMP is the most commonly used variable among soil potential components.

In general, it is assumed that soil-water is available to plants at water potentials from 33 kPa (4.8 psi) to as high as 1,500 kPa (217.6 psi). The availability of soil-water to plants is a plant- and soil-specific process and can change considerably between plant species and soil textural and hydraulic properties. For example, while many agronomic crops can extract water between these two potential values (33 and 1,500 kPa), other plant species such as cactus, shrubs, and sunflower can extract water beyond 1,500 kPa. Cactus plant, for example, can extract water from soil particles up to 5,000 kPa (725 psi), giving these plants a strong resiliency in survival capability/ability in harsh environments such as deserts. The water potential of 33 kPa shows the upper limit of available water for plants and is called "field capacity" (FC), whereas the 1,500 kPa shows the lower limit of available water and is called "permanent wilting point" (PWP). In general terms, plant available water is the difference between these two limits. However, accurate determination of plant available water is an extremely difficult task and it varies substantially between the crop species, soil characteristics, and other factors. One of the earliest studies that introduced FC concept was conducted by Veihmeyer and Hendrickson (1927, 1949) and they defined FC as "the amount of water held in the soil after the excess of gravitational water has drained away and after the rate of downward movement of water has materially decreased." Later, Cassel and Nielsen (1986) defined the FC as as "the amount of water remaining in a soil two or three days after having been wetted (by rain or irrigation) and after free drainage is negligible." In general, 10 kPa for coarse-textured soils and 33 kPa for medium- and fine-textured soils, respectively, are used to indicate the field capacities of soils (Cassel and Nielsen, 1986).

Permanent wilting point (PWP) concept was introduced by Briggs and Shantz in 1912 and they defined it as the amount of water per unit weight or per unit soil bulk volume in the soil, expressed in percent, that is held so tightly by the soil matrix that roots cannot absorb this water and a plant will wilt. Later, Cassel and Nielsen (1986) defined the PWP as "the water content of a soil when indicator plants growing in that soil wilt and fail to recover (due to irreversible damage) when placed in a humid chamber." Sunflower (*Helianthus annuus* L.) was used as an indicator plant to determine the PWP of a soil. Richards and Weaver (1943) showed that the soil-water potential at PWP for sunflowers was approximately 1,500 kPa. Richards and Wadleigh (1952) found that the soil-water potential at wilting ranged from 1,000 to 2,000 kPa, with the average at about 1,500 kPa, which is generally used as an approximation of soil-water at permanent wilting for most soils. Sykes and Loomis (1967) showed that the lower limit of plant available water varies with the plant species.

Field capacity, permanent wilting point, and as a result, plant available water for a given plant species are not unique values. They are dynamic. There are a range of values at which the rate of water supply to a plant is not sufficient to prevent wilting, depending on the soil profile (soil texture, compaction, stratification); the amounts of water in the soil at different depths, which affect root distribution; the transpiration rate of a plant; and the temperature (Briggs and Shant, 1912). While FC, PWP and soil-water holding capacity concepts (as well as most of the associated values) were developed over a century ago, today the same concepts and (and values) are being used to manage modern irrigation-crop production systems.

Methods of Soil-Water Content (θ) Measurement

Currently, one direct method is available to measure soil-water content (SWC) and SMP; however, there is no universally standardized method of indirect measurement. And of the numerous indirect methods available, none is completely satisfactory for all operational conditions. The methods continue to be further developed and improved. Indirect SWC and SMP measurement methods include:

i. Gravimetric
ii. Neutron attenuation (scattering)
iii. Time-domain reflectometry (TDR)
iv. Frequency-domain reflectometry (FDR)
v. Capacitance
vi. Tensiometry
vii. Remote sensing/satellite

(i) Gravimetric Method

Practically, the gravimetric method is the most accurate method and is used as a reference to measure SWC as well as to calibrate and compare the accuracy of indirect methods. Augers, soil probes, and shovels can be used to collect soil samples from the field. Water content measurement by this method involves collecting soil samples from the field. Each sample is weighed and then oven-dried at 105°C (221°F) until reaching a constant weight. After the sample is dried, it should be cooled in a desiccator before reweighing since the soil sample heat might create convection currents, which may affect sensitive balances. Cooling in the moist atmosphere, however, may allow the hot soil to absorb moisture. Thus, the dry sample should be cooled in the dry atmosphere of a desiccator. After cooling, the soil sample is weighed again to determine the dry weight of the sample. The wet and dry weight differences are considered to be the amount of water removed from the soil sample. Then, the water contents can be calculated on a dry weight basis using equation (1) or on a volume basis from equation (2), if the bulk density of the soil is known (Gardner and Kirkham, 1952).

In the gravimetric method, a standard dryness of the sample must be reached. Even though some water (hygroscopic or residual) is held by some soils (clay) even after drying the sample at 105°C (221°F) for several days (Nutting, 1943), drying at 105°C until a constant weight is obtained is the commonly accepted definition of oven dry and is the standard used for soil moisture determinations. On the other hand, temperature control in the oven is a critical issue in this method, and unless the temperature of an oven is maintained at 105°C (221°F) during the drying period, it would not be appropriate to assume that drying of the sample in the specified 105°C temperature is achieved in ordinary laboratory ovens. Gardner (1986) suggested that the temperature measurements can be made within the soil sample rather than in the oven atmosphere, as is done with the conventional oven thermometers, if high accuracy is necessary. Other methods can be used in place of oven drying to produce more rapid results. Such methods include the use of microwave ovens and/or desiccants to drive off the moisture.

Since the gravimetric method requires sampling, transporting the soil samples, and repeated weighing procedures, it is subject to errors and some precautions should be taken. The soil sample must not be allowed to lose water between collection and weighing. Thus, use of air-tight sample collection cans and weighing the sample as soon as possible after collection is important. While it has always been assumed that it is safe to dry the soil samples at 105°C (221°F), limited information is actually available regarding the effect of the temperature (105°C) on the weight changes due to oxidation and decomposition of the organic matter in mineral soils. Hillel (1998) points out that some organic matter may oxidize and decompose at this temperature, so the weight loss may not be due only to the evaporation of water. Gardner (1986) observed weight changes in silt-loam samples during drying over periods as long as 15 days; however, whether this change represents water loss or oxidation and decomposition is not clear.

Advantages and Disadvantages: One of the disadvantages of this method is the small volume of soil sampled. Since soil is heterogeneous, water content can differ by several units from one location to another in the same field, even in a small area. Because of this, a considerable number (≥ 20) of samples should be taken for a representative estimation of water content. This challenge, however, is not unique to this method as it applies to other methods, as well. The error can be reduced by increasing the volume and the number of samples. But if the sampling area is not large enough (especially in laboratories, greenhouses, growth chambers, etc.), repeated sampling in the same area can be an invasive and destructive procedure. The method is time consuming, and results cannot be obtained quickly or in a timely manner. Also, it does not allow continuous measurements of SWC. On the plus side, this method ensures accurate measurements if the above-mentioned precautions are taken. It is not dependent on salinity, temperature, and soil type or any other soil properties, and SWC calculations are easy.

Figure 3. Taking standard counts using a Troxler 4300 neutron probe (Troxler Electronic Laboratories Inc., Research Triangle Park, North Carolina) that is attached to an aluminum access tube in approximately 50% clay soil.

The method is destructive; multiple sampling cannot be made at the same location. It is also laborious and inapplicable to automatic irrigation control. Due to the aforementioned challenges with this method, in most cases researchers and irrigators prefer indirect methods of SWC measurements. Most indirect methods allow frequent or continuous measurements to be made at the same location. In addition, once the sensor or equipment is installed and calibrated, measurements can be made with much less time and labor and, in some cases, with telemetry. Some of the errors in gravimetric SWC determination may be caused by the type of device used to obtain the sample, container in which the sample is placed, time before the wet weight is determined, temperature and time of drying, size of the sample, and by methods used for weighing and recording the sample's wet and dry weights. It should not be overlooked that since volumetric SWC is determined by multiplying SWC on a weight basis with soil bulk density, any errors associated with determining soil bulk density would also translate to the errors in determining volumetric SWC using this method.

(ii) Neutron Scattering (Attenuation) Method

The neutron scattering (neutron probe) method is the most accurate method for SWC measurements after gravimetric sampling and has been used as the standard/reference to calibrate other SWC-based sensors. It is known that hydrogen nuclei are very effective in reducing the energy and velocity of high-energy neutrons to velocities of motion comparable to thermal energies. Most of these nuclei in the soil occur in water. Thus, it is possible to correlate the scattering of thermal neutrons in the soil in a way that would be independent of soil temperature, texture, structure, and salt concentration. Since the effective volume on which the neutrons are scattered is considerable—approximately 12 inches (~30 cm) in diameter, depending on the soil-water status—the error of field sampling for soil-water status using this method might be reduced. This same factor, however, makes it impossible to determine the moisture content at any precise depth with small increments (Taylor, 1955).

In the neutron scattering method, in applications when the radiation source is lowered in the access tube and the probe is turned on, the secondary gamma radiation is emitted and returning neutrons are measured by means of the ionization chamber. The nuclear source in the probe can yield about 17,000 neutrons per second. The measurements yield information concerning the lithological characteristics of the surrounding material. Two aspects are key for operation: (1) hydrogen (H) slows fast neutrons more effectively than any other common element; and (2) all H in most soils is present, practically, in the form of water. Thus, a fast neutron source, an adjacent slow neutron detector, and a timer in the probe are essentially the basic items in the neutron method of soil moisture determination. The number of slowed up neutrons detected per unit time would be a measure of the soil moisture content (Gardner and Kirkham, 1952).

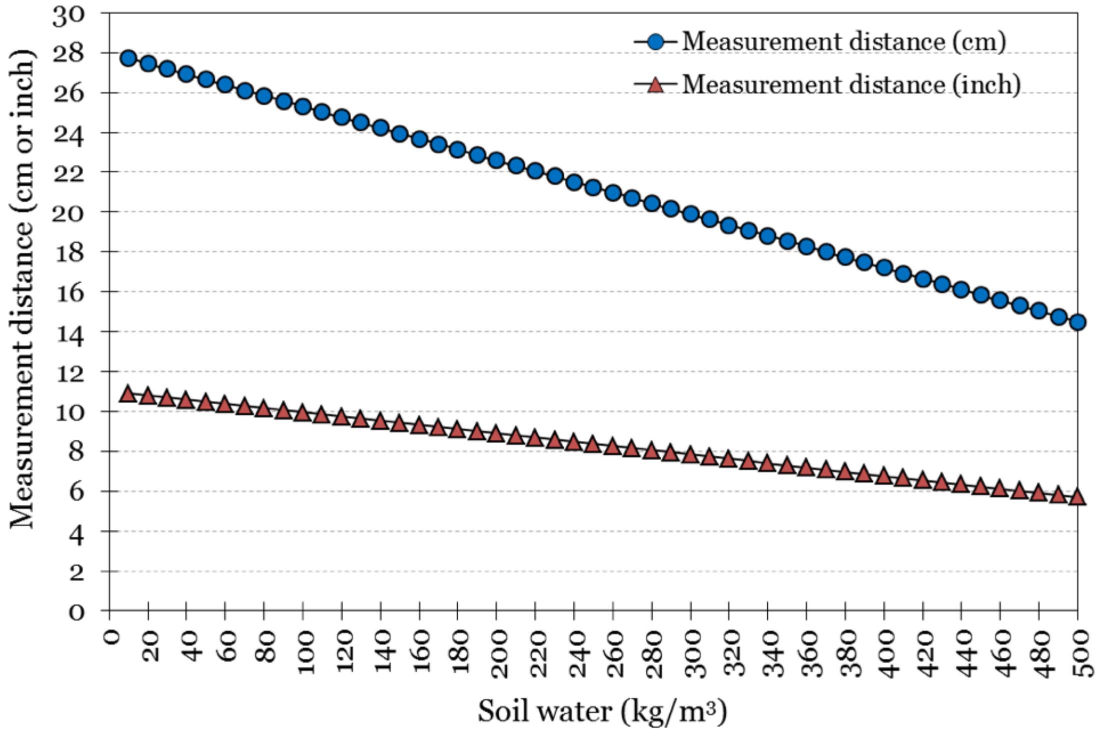

Figure 4. Relationship between the measurement distance (radius or area of influence) of the neutron probe measurements as a function of soil-water (500 kg/m^3 = 0.02 lb/in^3).

The neutron soil moisture gauge (Figure 3) consists of a probe containing a fast neutron source, a detector to count slowed down neutrons, a pulse counter, a cable connecting the two units, and a transport shield. In the operation of the probe, the radioactive source emits fast moving neutrons. These fast neutrons are either slowed down through repeated collisions with the nuclei of atoms in the soil (scattering) or are absorbed by those nuclei. A small fraction of the neutrons are deflected back to the detector, and an even smaller fraction is slowed down to thermal energy levels and is detected. The radius of the measurement is the distance through which 98% of the counted thermalized neutrons pass before reaching the detector. The most common atoms in soil (aluminum [Al]), silicon [Si], and oxygen [O]) scatter neutrons with little energy loss, because they have much greater mass than a neutron. When a neutron hits an H atom, however, its energy is reduced on average to about half, because the mass of the H nucleus is the same as that of the neutron. On average, 19 collisions with H are required to thermalize a neutron. Carbon (C), nitrogen (N), and O are also relatively efficient as neutron thermalizers (about 120, 140, and 150 collisions, respectively); however, the concentration of thermal neutrons changes mainly with the H content of the surrounding material. Changes in H content occur mainly due to changes in SWC. Therefore, the concentration of thermal neutrons surrounding a neutron source placed in the soil can be precisely related to the volumetric SWC. Because H and C are both effective neutron thermalizers, the organic matter content of soil affects the calibration. Organic matter and clay contain considerable amounts of H that may not be in the form of water and may not be driven off by heating to 105°C (221°F). This H will also affect calibration. Atoms that absorb neutrons include boron (B), cadmium (Cd), chloride (Cl), fluoride (F), iron (Fe), lithium (Li), and potassium (K). Although these elements usually comprise a small fraction of soil material, soils or soil horizons that contain large or fluctuating amounts of such elements will require separate calibrations or adjustments in data interpretation (Hignett and Evett, 2002).

When compared with other electrical sensors, the sampling volume of a neutron probe is more easily influenced by the SWC. The radius of the sphere of influence (measurement volume) is larger at low water content, whereas the radius gets smaller with an increase in water content. Also, if measurements are going to be taken at a depth above 30 cm (~12 in), then a separate calibration needs to be developed for the neutron probe due to the loss of neutrons to the air (Hignett and Evett, 2002; Evett et al., 2003). Based on the numerical equation presented by Rogowski (1990), the measurement radius can be calculated as a function of SWC as:

$$\text{Measurement distance (mm)} = 280 - 0.27SWC \quad (5)$$

Measurement distance (from the center of the radiation source) is the radius of the measurement area (area of influence), and SWC is expressed in kg/m^3 or [(m^3/m^3) × 10]. Figure 4 presents the relationship between the radius (cm and inch) of the neutron probe measurements and SWC. There is a strong and linear decrease in measurement radius with an increase in SWC. Near saturation, the measurement radius is roughly 16.6 cm (6.5 in). In very dry soil, the measurement radius is approximately 28 cm (~11 in), emphasizing the importance of calibrating the neutron probe (Rawls and Asmussen, 1973) for SWC measurements in the topsoil layer [~top 2 in (5 cm)]. When the neutron probe is used to measure SWC close to the top layer, some of the emitted neutrons will escape the soil, especially in dry soil, and will be emitted into the air, and this may cause erroneous measurements. While measurement distance is reduced to as low as 14 cm (~5.5 in) in dry soil, this area of influence is still greater than the area of influence of all other sensors/instruments that measure SWC.

While the neutron probe is the most accurate and reference method to measure SWC, its use is mostly limited to research platforms due to the method being radiation-based. Its use requires training, permits, certifications, and several other carefully controlled and monitored applications, including transportation, storage, etc. The radioactive source in the neutron probe can produce four kinds of radiation: alpha particles, beta particles, gamma rays, and neutrons. The alpha and beta particles can be stopped by the sources' stainless steel capsule. Only gamma and neutron radiation contribute to occupational radiation exposure. The current limit for occupational radiation exposure in the United States and many other countries is 5,000 millirem (mrem) per year. According to the radiation profile given by the manufacturer for Troxler model 4300 and 4302 neutron probes, the radiation emittance of the surface of the neutron probe in the front, back, left side, right side, top, and bottom are 0.25, 0.60, 0.73, 0.40, 0.15, and 0.75 mrem/hour, respectively. The bottom of the probes has the largest amount of radiation, so when operating this probe, the user should be careful not to have direct contact with the bottom of the probes. The intensity of radiation follows the "inverse square law," which means when the distance from radiation source is doubled, the intensity will be decreased to one-fourth of its original value (Troxler Electronic Laboratories, 2006). It is mandatory to have a dosimeter (badge) worn by the user of the neutron probe to measure their exposure to radiation. The badge is sent to an Environmental Health and Safety Office (mostly resides in university campuses) on a regular basis to measure the amount of radiation the user is exposed to. The absorbed radiation is usually very low when the probe is operated based on established protocols.

Advantages and disadvantages: The neutron probe has several important advantages. The method is nondestructive (after the access tubes are installed), enables soil profile SWC measurements, can measure water in any phase, and provides measurements that are directly and strongly related to SWC. Readings can be linearly calibrated with high precision. In addition to sandy, clay, silt-loam, and other soil types, the method works well in gravel soils and cracking clays in which other methods may not work effectively. Due to the large measurement distance (area of influence), fewer replications of SWC measurements may be required as compared with other methods to produce a given level of precision (Hignett and Evett, 2002). The probe readings are not affected by soil temperature or soil chemical properties, and the probe has a fast (instantaneous) response time that can be important to monitor soil-water movement in the soil profile accurately.

The method's disadvantages include cost, and the probe readings must be calibrated for different soil types as is the case for all other SWC-based methods. The access tubes must be installed early in the growing season and removed toward the end season; the probe cannot measure soil-water near the soil surface with great accuracy (depending on the SWC of the topsoil), and may pose health problems if not used properly. The use of a neutron probe requires special certification and training and is subject to strict regulations. The weight of the probe (approximately 22 pounds [~10 kilogram]) also makes it challenging to measure SWC in very large fields where a number of readings will be taken as transporting the probe between the measurement locations is necessary.

(iii) Time-domain reflectometry (TDR)

Time-domain reflectometry (TDR) is an electronic instrument used to determine the characteristics of a conducting medium (including soil and water) by measuring reflected waveforms. The TDR method allows multiplexed, automated, and in-situ measurement of volumetric SWC. Its basic principle involves measurement of the dielectric constant in the time-domain by measuring the propagation velocity of a voltage pulse emitted by the TDR sensor. This concept and application was first introduced by Fellner-Feldegg (1969). Davis and Chudobiak (1975) applied a wide-band time-domain reflectometry with a balanced parallel transmission line in the laboratory and field measurements and found that there was correlation between dielectric permittivity and SWC. Topp et al. (1980) demonstrated that TDR can measure water content with an accuracy of better than 2%, and suggested that a single calibration equation could be applied to nearly all soils and developed equations that relate dielectric constant to SWC. Consequent research, however, showed that a universal calibration is not applicable for all soils to measure SWC using the TDR method with great accuracy in all soils. Dalton et al. (1984) proposed the simultaneous measurement of both SWC and salinity for water and salt management using TDR. The relative dielectric constant of soil is primarily related to its water content (Dasberg and Dalton, 1985; Baker and Allmaras, 1990).

In principle, TDR determines the dielectric constant of the soil by measuring the transit time of an electromagnetic pulse launched along a pair of parallel metallic rods of known length imbedded in the soil. Because of the unique relationship between dielectric constant and water content, the soil's

Figure 5. An example of time-domain reflectometry (TDR)-based sensor (Model CS616 water-content reflectometer, Campbell Scientific Inc.) with 12 in (30 cm) parallel rods installed in a silt-loam soil horizontally to measure vertical soil-water movement dynamics at the University of Nebraska–Lincoln, South Central Agricultural Laboratory, near Clay Center, Nebraska (left). The picture on the right shows installation of CS616 sensors in a riparian zone with a gravel-dominant soil on an island in the Platte River near Central City, Nebraska, to monitor SWC and water level fluctuations on a real-time basis.

water content can be calculated (Dalton et al., 1984; Drungil et al., 1989). A pulse of radio frequency energy is applied into a transmission line, and its propagation velocity is measured by detecting the reflected pulse from the end of the line and measuring delay time between transmitted and reflected pulses. The velocity depends on the dielectric constant and loss of the transmission line dielectric as well as on the frequency (Stafford, 1988).

In the TDR method, the following equation (Topp et al. 1980; Dalton, 1992) is used to calculate dielectric constant of the medium:

$$\epsilon = \left(\frac{c\ x\ t}{2\ x\ L}\right)^2 \qquad (6)$$

where, ϵ (unitless) is dielectric constant of the medium, t (sec) is the transit time over the length of the probe, L (m) is the length of the soil moisture probe and c is the light velocity in the vacuum [3×10^8 meters/second (m/s)].

Topp et al. (1980) showed that the real part of the complex dielectric constant (equals to apparent dielectric constant if there is low electrical loss) is not strongly frequency-dependent, but is highly sensitive to volumetric water content and weakly sensitive to soil type and density. Topp et al. (1980) established dependence of the real part of the complex dielectric constant on volumetric water content in the laboratory condition over the frequency range from 1 megahertz (MHz) to 1 gigahertz (GHz) for four mineral soils with a wide range of textures, ranging from sandy loam to clay and with varying organic matter contents (1 MHz = one million cycles per second). The equation has a standard error of estimate of about 1.3% vol. The regression equation (equation 6) relates bulk dielectric constant to volumetric water content for general application for mineral soils. This equation works well in coarse- and fine-textured soils and provides water content differences within ± 10% of those measured with weighting lysimeters (Zegelin et al., 1992; White, et al., 1994). For peat/organic and heavy clay soils, however, the "universal" relationship does not work very well (Roth et al., 1990; Dirksen and Dasberg, 1993; White et al., 1994):

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}\epsilon - 5.5 \times 10^{-4}\epsilon^2 + 4.3 \times 10^{-6}\epsilon^3 \qquad (7)$$

where, ϵ is bulk dielectric constant can be calculated using equation (5) and θ_v is volumetric water content of the medium.

The TDR method is one of the most robust and accurate methods to measure volumetric SWC, especially in soils with low clay content. Currently, numerous TDR-based soil moisture sensors are available. While the basic principles of most TDR-based instruments are similar, they differ in design and operational aspects. Most of the TDR-based sensors (e.g., Model CS616 30-cm water content reflectometer from Campbell® Scientific Inc., Logan, Utah) allow automated and continuous measurements in the same location. Other TDR sensors are operated manually (e.g., FieldScout™ TDR 300 from Spectrum® Technologies Inc., Aurora, Illinois; and TDR Model CS620 from Campbell Scientific), but allow taking measurements from different locations in a given field. TDR

Figure 6. TDR 300 (FieldScout soil moisture meter, Spectrum Technologies) that measures volumetric SWC.

sensors also differ in terms of the soil depth in which they measure SWC. An example of TDR-based sensors used to measure volumetric SWC is presented in Figure 5.

Another example of a portable TDR-based instrument (TDR 300) is presented in Figure 6. This instrument is manual and does not allow continuous/automated measurements; however, it provides a moveable way to measure SWC rapidly from many locations in a given field. Its shaft-mounted probe can allow the user to easily and rapidly take many measurements. There are two modes for the probe: (i) standard mode, which is valid for a wide range of mineral soils, and (ii) high clay mode, which is designed for soils with high clay contents (i.e., > 27%). The built-in data logger can free the user from recording the readings manually, and it can average all the readings taken after the meter is turned on. There is also a period mode that provides the raw readings. Different lengths of rods (1.5, 3.0, 4.8, and 8.0 in [3.8, 7.6, 12.2, and 20.3 cm]) are available for the probe, which can then be used to measure SWC at precise depths. Instrument measurements are confined primarily in the topsoil, whereas profile (multi-depth) SWC measurements are not possible.

Advantages and disadvantages: The TDR method offers several unique and important advantages. Topp et al. (1982a, b) confirmed that the TDR method is a practical and useful technique for measuring SWC over depth even when steep gradients or wetting fronts are present. Also, they found that TDR was also a reliable technique to detect the depth of wetting fronts and measuring the amount of water behind the wetting front. Dalton et al. (1984) found that TDR can be used to measure electrical conductivity as well as recording the voltage attenuation through two parallel metallic rods. Most TDR sensors allow fast and continuous measurements with fast response time and are suited for automated measurements and irrigation control. The TDR system is reliable, yielding measurements throughout winter and through rainfall events with only minor challenges.

There are several disadvantages, however. Most of the automated TDR sensors are relatively costly, and the readings are affected by soil texture (notably clay content) and salinity. The method's electronics, programming, and maintenance can be complex and challenging for some users. As is the case with most other methods and sensors, the accuracy of the method is a strong function of proper installation of the rods. And during installation, the rods must be inserted perfectly parallel to each other, which can present challenges in some installations, especially when the sensors are installed in deeper soil layers. In some cases, electrical noise may interfere with the low voltage TDR signal, which can also affect SWC readings. In general, TDR-based sensors are more sensitive to soil temperature than FDR-based sensors. A 1°C (1.8°F) increase in soil temperature for the TDR-type sensor can increase the volumetric SWC by 0.1918% vol (Zhu et al., 2019).

(iv) Frequency-domain reflectometry (FDR)

Frequency domain reflectometry (FDR) is an electronic instrument/method consisting of an oscillating circuit and sensing electrodes, the latter of which are embedded in the soil to measure volumetric SWC. The operating frequency depends on the soil's dielectric constant. Soil surrounds the electrodes as part of the capacitor, in which the permanent dipoles of water in the soil-water-air dielectric medium

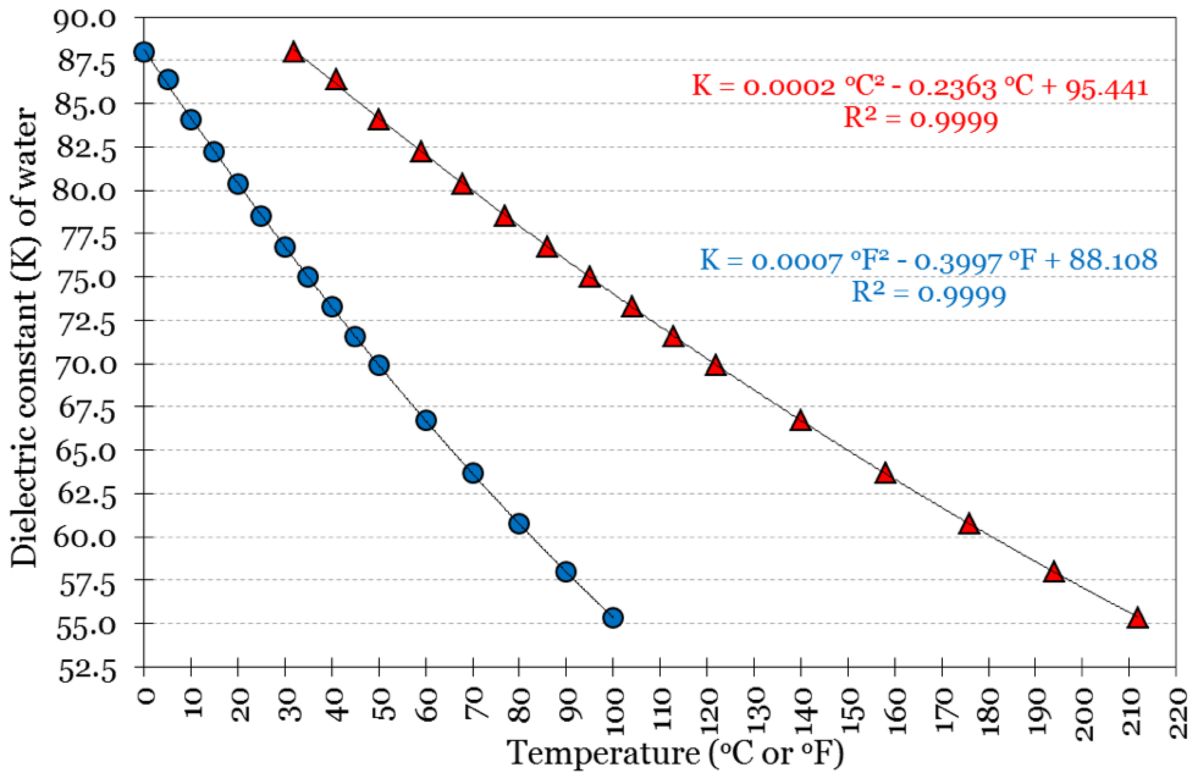

Figure 7. Relationship between temperature and dielectric constant of water.

become polarized in response to the frequency of an imposed electrical field. The independence of the dipoles to respond is determined by the molecular binding forces so that the overall response is a function of molecular inertia, the binding forces, and the frequency of the electric field (Dean et al., 1987; Paltineanu and Starr, 1997).

Both TDR and FDR methods are based on the measurement of the soil-water dielectric constant to derive SWC. At radio frequencies, the dielectric constant of pure water at 20°C (68°F) and atmospheric pressure is 80.4, while that of moist soil ranges from 3 to 7 and that of air is 1 (Topp et al., 1980; Paltineanu and Starr, 1997). Dry soil has a dielectric constant of 2.7. The dielectric constants of water in the soil can be influenced by the frequency of imposed electromagnetic field, temperature, salinity, water content, and the ratio of the content of bound water to free water in the soil, which are also related to the soil surface area per unit volume. It can also be influenced by the soil bulk density, shape of soil particles, and shape of water inclusions (Paltineanu and Starr, 1997). Because so many factors can influence the dielectric constant of water, there is no simple relation between SWC and the soil mixture dielectric constant (and the capacitance); therefore, calibration equations for different types of soil and sensors are necessary to achieve accurate soil-water status measurements (Robinson and Dean, 1993) for effective irrigation management and other purposes. Furthermore, the dielectric constant of water (and moisture in the soil medium) is affected by temperature, which makes it very challenging to develop a single relationship to completely explain or derive SWC from soil-water dielectric constant. A relationship between temperature and dielectric constant of water is presented in °C and °F in Figure 7. There is a strong relationship between the two, and as the soil temperature increases, dielectric constant of soil-water decreases. Based on the relationship presented in Figure 7, a 1°F increase in temperature results in a decrease of dielectric constant of soil-water by 0.4 (unitless). Thus, when measuring SWC using methods that rely on dielectric properties, it is important to account for temperature effect on dielectric constant and, in turn, on SWC.

FDR can measure the oscillation frequency of the electrode-soil capacitor, and the oscillation frequency is related to capacitance and total inductance of the circuit as (Paltineanu and Starr, 1997; Starr and Paltineanu, 2002; Fares and Polyakov, 2006):

$$F = (2 \, x \, \pi \sqrt{L \, x \, C})^{-1} \tag{8}$$

where, F is oscillation frequency, π = 3.14159; L is the total inductance of the circuit, which is constant (set by the electronic circuitry), and C is the capacitance, which is calculated as:

$$C = g \, x \, \varepsilon_{ra} \tag{9}$$

where, g is a geometrical constant based on electrode configuration (size, shape, and distance between electrodes); ε_{ra} is the bulk dielectric constant of the soil. The frequency is then related to volumetric SWC as:

$$F = f(\theta_v) \tag{10}$$

Figure 8. The 5TE frequency-domain reflectometry (FDR)-based soil moisture sensor from Decagon Devices Inc. (now METER Group Inc., USA), Pullman, Washington. The device measures volumetric SWC.

Typically, the operational frequency varies from about 38 to 150 MHz. Soil conductivity is inversely proportional to frequency, so the interference from acidity and salinity can be minimized by operating the sensors at frequencies ranging from 100 to 150 MHz. FDR sensors are based on electrometric techniques to measure the dielectric constant and electrical resistance of the soil, which is dominated by the amount of water in the soil. Calibration equations are used to convert these data to soil moisture content.

An example of a FDR-type sensor (5TE water content, temperature, and electrical conductivity sensor from METER Group Inc., USA) is presented in Figure 8. The 5TE sensor has three short (2 in [5 cm]) prongs, and it continuously measures soil temperature, volumetric SWC, and soil conductivity. There is an oscillator inside the 5TE sensor, which runs at 70 MHz to measure the dielectric permittivity of soil and a thermistor in thermal contact with prongs to provide soil temperature measurement.

Advantages and disadvantages: The method is effective and robust for measuring SWC accurately with soil-specific calibration. The method is stable, has fast response times, has good accuracy with good soil-probe contact, it is safe to use, and is available in several sensor configurations (parallel rods, cylindrical metal rings, and combination of a cylindrical ring and rod) (Starr and Paltineanu, 2002). There are several advantages of the parallel rod design. Probes are well suited for surface measurement, highly portable, and simple in design, thus inexpensive (Starr and Paltineanu, 2002). In general, FDR-type sensors are less sensitive to soil temperature changes than TDR-type sensors when measuring volumetric SWC. A 1°C (1.8°F) increase in soil temperature for the FDR-type sensor can decrease volumetric SWC by 0.0273% vol (Zhu et al., 2019). They can also be used to determine the depth of wetting fronts. Most FDR sensors allow fast and continuous measurements and can be suited for automated measurements and irrigation control.

The method's electronics, programming, and maintenance can be complex for some users. The accuracy of the method is a strong function of proper installation of the sensors, thus during the installation, the rods must be inserted perfectly parallel to each other, which can present difficulties in some installations, especially when the sensors are installed in deeper soil layers. Some sensors are designed to measure SWC in multiple soil depths, and some sensors (e.g., 5TE) are designed to measure SWC in individual depths so multiple sensors are required for profile SWC measurements.

(v) Capacitance

FDR and capacitance-type sensors have very similar operational principles. Dielectric constant of soil can also be measured by making the soil the dielectric in a capacitor (Atkins et al., 1998). In the capacitance method, essentially a positive and ground electrode (capacitor) are charged and discharged rapidly in the soil, generating an electromagnetic field whose charge time t is related to the capacitance (C) of the soil using the following equation:)

$$t = R \, x \, C \, ln\left[\frac{V - V_f}{V_i - V_f}\right] \quad (11)$$

where, R is the series resistance (Ω), V is voltage at time t, V_i is the starting voltage, and V_f is the applied or supply voltage.

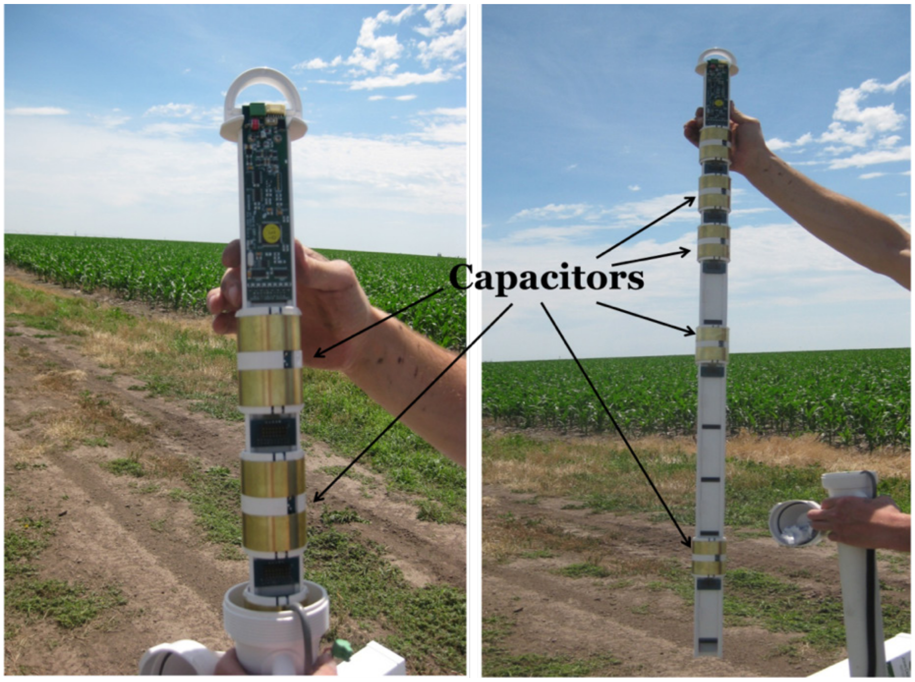

Figure 9. An example of a John Deere Field Connect™ capacitance-based soil moisture sensor used by the Irmak Research Laboratory at UNL's South Central Agricultural Laboratory. These sensors allow remote (telemetry) programming, measurements, and data downloading.


Figure 10. Example of John Deere Field Connect™ capacitance-based soil moisture sensors that are deployed grid-wise in a center-pivot irrigated maize field for research to investigate the spatial and temporal variability in soil moisture in the Irmak Research Laboratory at the South Central Agricultural Laboratory.

Then, using previously presented equations 4 and 5, the volumetric water content can be calculated.

Capacitance probes are a form of electromagnetic (EM) sensors that indirectly measure SWC based on the dielectric properties of the soil. As the water content of soil increases, the dielectric constant of the soil increases. As is the case with TDR-based sensors, this relationship is fundamental for determining volumetric SWC using capacitance-based sensors. In general, capacitance-type sensors contain a pair of metal rings that form a capacitor, which, in turn, emits an electromagnetic field approximately 4 in (~10 cm) around the probe. Corresponding frequencies are then measured using sensor circuits. The sensor outputs a DC voltage, which is then converted to volumetric SWC using the manufacturer's calibration equations, usually in the form of:

$$\sqrt{\varepsilon} = 0.88 + 4.24V + 65.6\,V^2 - 272.7\,V^3 + 402.9\,V^4 \quad (12)$$

$$\theta_v = \frac{\sqrt{\varepsilon} - a_0}{a_1} \quad (13)$$

where, V is sensor voltage output, ε is soil dielectric constant, a_0 and a_1 are calibration coefficients (default values are 1 and 7, respectively), and θ_v is volumetric SWC.

An example of a capacitance-based soil moisture sensor (John Deere Field Connect™) with a telemetry option is presented in Figures 9 and 10. The sensor has capacitors with certain intervals and takes volumetric SWC readings from

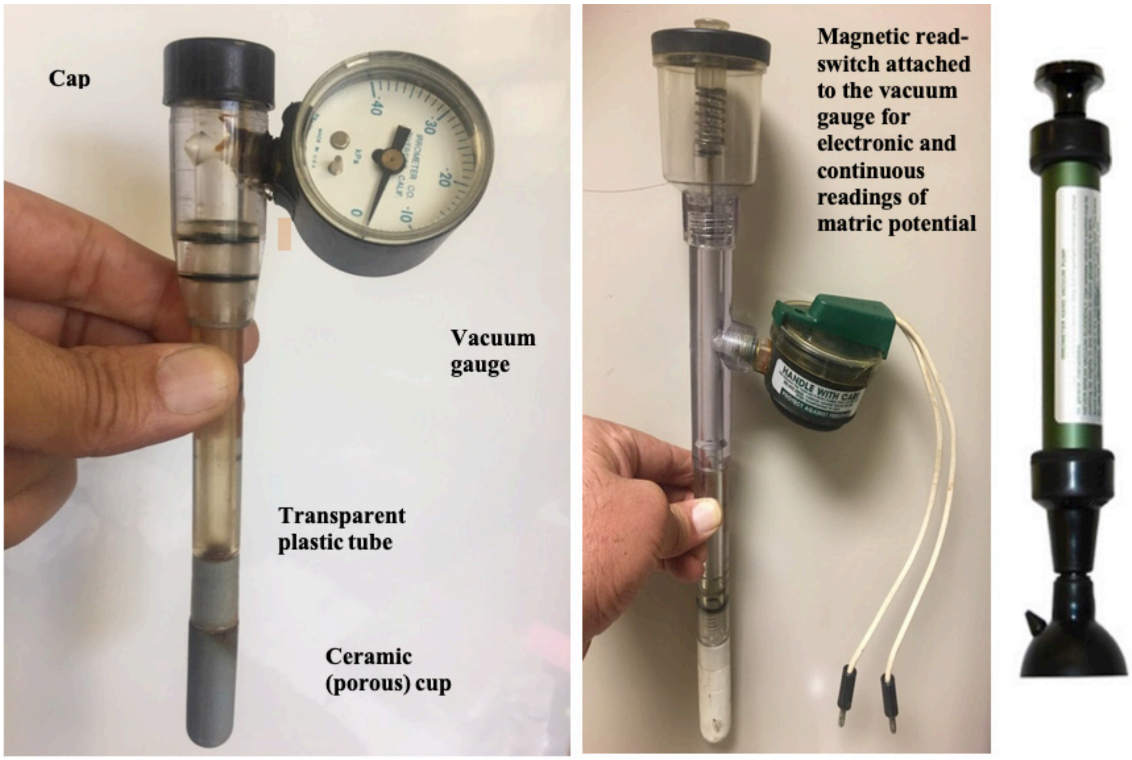

Figure 11. Tensiometer for soil-matric potential measurements and its basic components (left), tensiometer with a magnetic read-switch attached for automated control (middle), and a hand-held vacuum pump used to remove air bubbles from the tensiometer (right).

multiple depths (4, 8, 12, 20, and 40 in [~10, 20, 30, 51, and 102 cm]) simultaneously. John Deere Field Connect probes output a count proportional to the sensor circuit (resonant) frequency, which is used to calculate scaled frequency (SF), ranging between 0 and 1. The SF is then converted to volumetric SWC using the manufacturer's equation embedded into the sensor's electronics. The probe is encased in a plastic tube that is installed in the soil. The probe is equipped with an antenna that provides real time remote data access, and a solar panel that recharges the battery.

Advantages and disadvantages: Capacitance probes are usually resistant to environmental factors (e.g., temperature and humidity). They are reliable and have good long-term stability. They can be easily adapted to data loggers for continuous readout and automation. They are usually robust and stable, have fast response times, have good accuracy with good soil-probe interface/contact, and are easy and safe to use. The method can be somewhat challenging for programming, deployment, and data acquisition. As is the case with all other methods, capacitance-based methods also need soil-specific calibration for accurate SWC measurements.

(vi) Tensiometry

Tensiometer is an instrument that measures the energy status (matric potential) of soil-water and is based upon the attractive force of the soil for water. It consists of a porous cup that is connected to a closed tensiometer tube filled with deionized water. As the soil dries, water moves from the tensiometer through the ceramic cup into the surrounding soil. This creates a negative tension (soil-matric potential [SMP]) in the tensiometer, and this pressure can be read from the vacuum gauge either manually or electronically. Using irrigation trigger points developed for specific soil types, tensiometer-measured SMP readings can be effectively used for irrigation management.

An example of a tensiometer and its basic components are provided in Figure 11. The plastic tube of the tensiometer is normally transparent so the water level within the system can be observed. A Bourdon tube vacuum gauge is commonly used with tensiometers for pressure (potential) measurements, and the vacuum gauge can be retrofitted with a magnetic switch, which is then connected to a controller for automated irrigation based on SMP to trigger irrigations. Phene et al. (1981) demonstrated the use of SMP sensors to automate irrigations, which resulted in an increase in water use efficiency and grain yield.

The porous cup is usually ceramic due to its durability and for its ability and characteristics to enable water flow with similar velocity to the water that moves in the soil medium. The tensiometer is sensitive to soil moisture in only a relatively small volume of soil. When the moisture in the soil is in equilibrium with the water in the cup, the capillary or water potential of the soil would be equal to the tension in the tensiometer system. The maximum moisture tension that can be measured with the tensiometer is 90–100 kPa, with approximately 80 kPa being the practical maximum. When the tension exceeds this value, air enters into the cup and the instrument no longer functions properly. Although the tensiometer has a limited range, this range does include the tension holding the major portion of the soil-water available for plant growth in primarily coarse-textured soils.

Taylor (1955) reviewed tensiometer readings and stated that the greatest source of error in tensiometer use that he found arose from air getting into the system and causing erroneous readings. The plastic and rubber tubing that are usually used in tensiometer construction are somewhat permeable to the diffusion of some or all of the gaseous components of the atmosphere; if these materials are used in tensiometer construction, some amount of air entry is possible. After long periods of use, air will gradually enter even the best constructed tensiometers by solution in the soil-water. The air enters the instrument through the cup when the tension changes rapidly from high to low values. Where fluctuations in tension are not too rapid, however, some time may elapse before air bubbles will appear in the instrument. Whenever air bubbles are present in the system, the error in readings is greatly increased; consequently, the instrument should be serviced and air should be removed using a hand-held vacuum pump.

Tensiometers should be installed as early in the growing season as possible to allow plant roots to develop around the ceramic plate-soil interface so that accurate and representative measurements can be taken. The tensiometer should be installed in a representative location in the field in terms of soil properties, plant emergence, slope, etc. An excellent contact between the ceramic cup and soil must be established and maintained for accurate measurements. During the installation, the soil around the tensiometer should be tamped well at the surface to seal the instrument from air contact with the ceramic cup and to prevent rain or irrigation water from running down between the tube and soil. The use of a tightly fitting rubber ring around the tube can significantly help to prevent water from running down between the tube and the soil, which can cause erroneous readings. Tensiometers do not provide soil profile matric potential measurements using the same tensiometer. The soil-matric potential (SMP) of desired soil depths must be measured using individual tensiometers installed at multiple depths. Tensiometers are made with different lengths, ranging from a few inches to 4 ft or longer (~7 cm to 1 m or longer), which allow measurements in deeper soil layers.

Advantages and disadvantages: Irrigation management recommendations made based on tensiometer measurements are effective, as tensiometers are one of the most accurate SMP measurement devices. Tensiometers are inexpensive, work well in the range from near-saturation to very dry soil conditions in coarse-textured soils, are easy to install and maintain, operate for long periods if properly maintained, can be adapted to automatic measurement with pressure switches, can be operated in frozen soil with ethylene glycol, and can be used with a positive or negative gauge to read water table elevation and/or soil-water tension.

Tensiometers have a limited range of 0 to 85 kPa. This range is more than enough for most coarse-textured soils, but not enough for most fine-textured soils. Among the disadvantages, hysteresis can be an issue, regular (weekly or daily) maintenance is required, and response time to changes in SMP is slow. And, depending on the rate of change in soil-water status, tensiometers may need frequent refilling of water.

(vii) Remote sensing

Some of the physical properties of water such as thermal and dielectric, as well as reflectance properties (Lobell and Asner, 2002), can be estimated remotely. This allows soil moisture estimations using different remote/satellite technologies. Thus, remote sensing is an alternative method for estimating SWC and is essentially based on the physical models that explain the soil reflectance variations due to moisture change. Schmugge (1978) stated that observations of the diurnal surface temperature, the microwave brightness temperature (emissivity), and radar backscatter of the soil have shown strong correlation with soil moisture status in the topsoil. The term “remote sensing” usually indicates situations where the sensor is situated far away from the soil surface. The term “non-contact” usually indicates where the sensor is mounted on a field machine or other platforms to provide continuous and localized monitoring across a field. Remote and non-contact methods are usually based on the reflection/absorption of electro-magnetic radiation (from microwave frequencies to visible radiation) and generally relate to surface or near-surface moisture only (Stafford, 1988; Kano et al., 1985). This makes remote sensing methods challenging for application in practice, because in most cases soil moisture status in much deeper soil layers are needed for water management and other purposes.

Different types of remote sensing methods are available to measure SWC including gamma radiation flux (Gutwein et al., 1986), microwaves (Estes et al., 1977; Schmugge, 1980), infrared thermometry (Shih et al., 1986), and radar and satellite imaging (Carlson et al., 1984; Musick and Pelletier, 1986). Although all of these remote sensing methods are still in the research and improvement stage, thermal infrared temperature data can be measured quickly and accurately (Myhre and Shih, 1990). The advantage of the microwave technique is that it can still show sensitivity to moisture, and detect changes in surface soil moisture status, even in the presence of canopy cover.

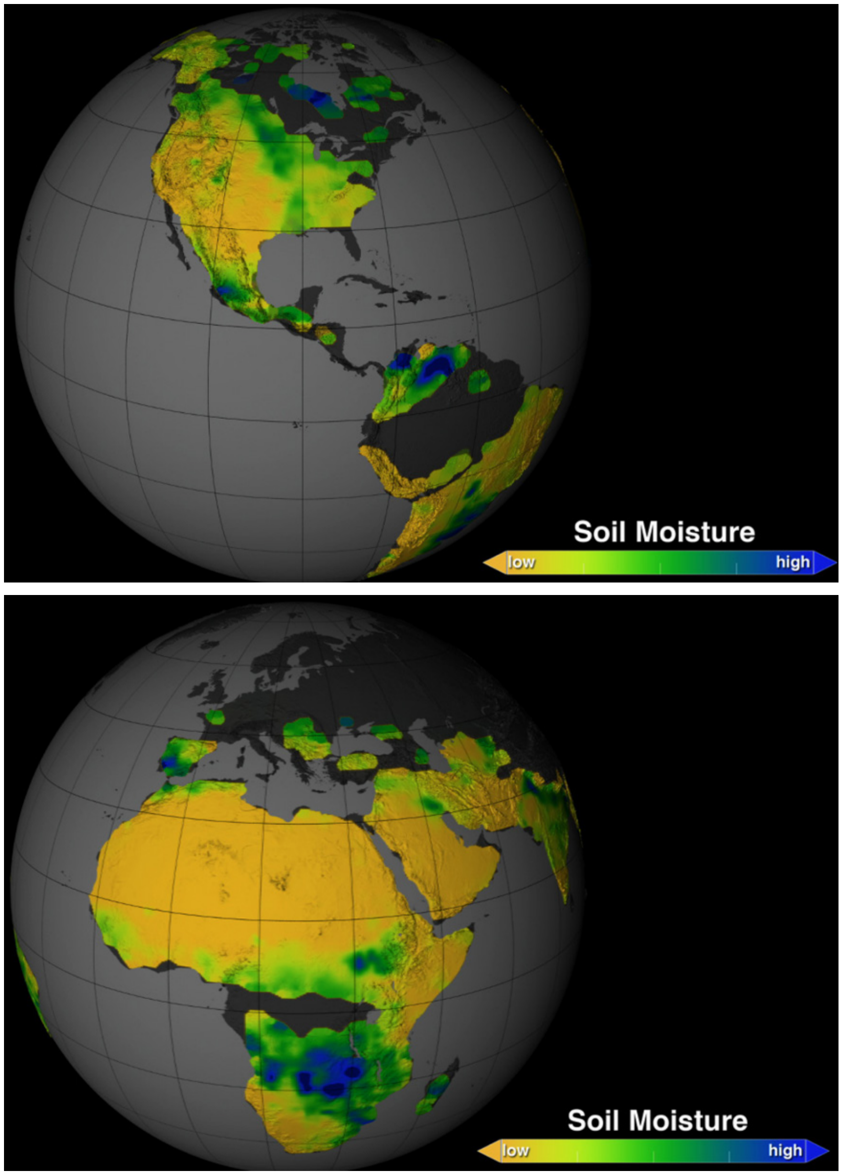

Figure 12a and 12b. Maps from Schindler et al. (2014). The top map shows surface soil moisture on August 2011, whereas the bottom map is for January 2013.

The remote sensing of soil moisture depends on the measurement of electromagnetic energy that has been either reflected or emitted from the soil surface. The intensity of this radiation with soil moisture may vary, depending on dielectric properties, soil temperature, or the combination of both. For active radar, the attenuation of microwave energy may be used to indicate the moisture content of porous media, because of the effect of moisture content on the dielectric constant or vice versa and thermal infrared wavelengths are commonly used for this measurement (Zazueta and Xin, 1994).

Examples of soil moisture maps created by using satellite data are presented in Figure 12. Data obtained by satellites orbiting earth at an altitude of approximately 400 miles (~640 kilometers), show an estimation of surface soil wetness by detecting microwave energy that is emitted from the top 2 in (5 cm) of the land surface (Schindler et al., 2014). As explained earlier, while remote sensing/satellite estimation of soil moisture may not have high frequency and resolution, the method allows powerful and important visualization of surface soil moisture on large scales, which can be used for approximate assessments of moisture distribution in the entire earth surface.

A significant drawback related to remote sensing of soil moisture is that these methods only provide data on the surface layer and not on the entire soil column. The thickness of the measurement layer can be increased by using longer-wavelength sensors; however, technological problems limit the use of wavelengths that might be able to sense the entire soil column (Jackson, 1980). Remote sensing soil moisture estimations can be valuable in terms of providing large scale mapping of surface soil moisture and for determining spatial and temporal variations, which can be beneficial for various purposes.

Advantages and disadvantages: This method allows remote measurements, which can save time, allow for spatio-temporal mapping of soil moisture, and provide large-scale assessments of soil moisture. The method, however, is complex and requires specifically trained personnel to create the maps and requires expertise in accurate interpretation of the soil moisture dynamics presented in the maps. It is also costly and is usually used for surface soil moisture estimations and does not provide profile moisture determinations, which significantly limits its applicability in practical situations, especially for irrigation/water management. Low frequency (estimation interval) and low resolution of the method in estimating soil moisture may also limit its applicability in some platforms. The method is not effective if a certain point area's soil moisture is concerned, as the maps are created using one of the interpolation methods that has certain assumptions built in the interpolation. Thus, maps are useful as general assessment tools of soil moisture, rather than specific/absolute values for a specific location. While the method offers considerable advantages, it still needs substantial calibration and validation with measured soil moisture for further development of its accuracy and applicability.

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