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A Guideline for Selecting the Best Soil Moisture Sensors

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Introduction

Although only 8.2% of farms in Kentucky have been equipped with *soil moisture sensors* (SMS), this amount is higher than in 27 other states in the US (Kukal et al., 2020). On most Kentucky farms (more than 90%), *irrigation* scheduling has been applied based on empirical methods including condition of crop, soil type, personal calendar schedule, and when neighbors begin (United States Department of Agriculture (USDA), 2018). Most SMS are easy to use and affordable for monitoring soil moisture and *irrigation* scheduling. SMS can help farmers to enhance *water use efficiency* (WUE) and increase profits while substantially reducing use of water and energy. In addition, using SMS decreases *erosion* and *leaching* of chemicals such as pesticides, fertilizers, and soil nutrients. The other advantage of SMS is helping farmers apply water at optimum rates and only where needed. Blonquist Jr. et al. (2006) evaluated the performance of SMS under Kentucky Turf Grass in a silt loam *soil*. Relative to *evapotranspiration* (ET) based *irrigation* recommendations, the SMS helped to save 16% less *irrigation* water. Also, relative to a fixed *irrigation* rate of 2 inches per week, the SMS helped to apply 53% less water. In a newer study, Viloria and Dunwell (2017) demonstrated that SMS can help reduce *irrigation* water applications by 40 - 70% of *irrigation* without using SMS. It is worth mentioning that an average 50% reduction in *irrigation* can save over 43 million gallons of water and $6,500 in pumping cost annually in Kentucky (Viloria and Dunwell, 2017). Using SMS in fields can increase average net income by almost 20% and, for some crops like soybean, by 64% (Payero, 2021). Now the question is which SMS is best for Kentucky conditions. The objective of this fact sheet is to present a guideline for Kentucky farmers to select the best SMS for their farms with respect to various factors, including cost, *soil texture*, soil salinity, ease of operation, *calibration*, and performance accuracy.

Plant available water (PAW)

SMS usually measure soil *volumetric* water content. PAW is the water available to support plant growth. PAW as a function of soil *volumetric* water content. PAW capacity equals the difference between field capacity (FC) and the permanent wilting point (PWP). FC is the maximum amount of water that a soil can hold. The PWP is the point when there is no water available to the plant. Table 1 shows FC, PWP, and PAW capacity for different types of *soil texture*. For example, a silt loam soil (which is the predominant *soil texture* in Kentucky) has a PAW capacity of 0.21. For a plant with a root depth of 19 inches, the total amount of PAW capacity is 0.21 x 19 = 3.99, or about 4 inches. If more than 4 inches of water is applied to the soil, either by precipitation or by *irrigation*, some of it will be lost to *runoff* or *leaching* below the root zone. According to Table 1, loam and silt loam soils are the best for agriculture because they have the highest PAW capacity compared to the other types of *soil texture.* In fact, loam and silt loam soils drain excess water quickly and are not prone to drought conditions (Easton and Bock, 2016). Table 1. FC, PWP, and PAW based on *soil texture* (adapted from Easton and Bock, 2016).

Top 10 SMS

The top 10 SMS that are highly used for *irrigation* purposes are tensiometers, granular matrix sensors (GMS), heat dissipating sensors (HDS), capacitance, time domain reflectometers (TDR), frequency domain reflector (FDR), amplitude domain reflector (ADR), time domain transmission (TDT), neutron probe, and wireless sensors. Tables 2 and 3 show a short description, photos, pros, cons, and an estimated price of each SMS. It should be taken into account that “the best” SMS is not the same for all farmers based on their different point of views and limitations. For example, a farmer with a budget limitation has to opt for a sensor that is economical and cost efficient even if it is not as accurate as the other SMS. Another example is a farmer whose priority is to deal with saline and/or heavy soils, leading to paying more to have reliable and functional SMS.

Table 1. FC, PWP, and PAW based on *soil texture* (adapted from Easton and Bock, 2016)

Soil texture	FC (inch of water/inch of soil)	PWP (inch of water/inch of soil)	PAW capacity (inch of water/inch of soil)
Sand	0.05	0.12	0.07
Sandy loam	0.09	0.21	0.12
Loam	0.16	0.36	0.20
Silt loam	0.18	0.39	0.21
Clay loam	0.24	0.39	0.15
Silty clay	0.26	0.39	0.13
Clay	0.27	0.39	0.12

Table 2. A short description and photos of highly used SMS for *irrigation* (adapted from Kelleners et al., 2004; Ling, 2004; Sample et al., 2016; Labodia Prima, 2019; SwitchDoc, 2019; Edaphic, 2021; Robinson, 2021; Trellise 2021)

SMS	Short description	Photo
Tensiometer	Soil particles hold water through either tension or *adhesion*. Tensiometers are SMS that measure the tension between soil particles and water molecules. In order for plants to access this water, they must overcome the tension to draw water molecules away from the soil particles and into their roots. The soil *matric potential* or *soil moisture* tension reading tells how hard the plant must work to extract water. A tensiometer is a vertical, water-filled tube with a porous tip that is inserted into the soil at recommended depths; the soil draws water out of the porous tip of the sealed tube, creating a vacuum. Drier soils create a stronger vacuum since water molecules are harder to pull off soil particles.	

SMS	Short description	Photo
GMS	GMS consist of *electrodes* contained in a granular matrix that is enclosed within a gypsum solution, a membrane, and a metal case. Gypsum buffers salinity effects. A small charge is placed on the *electrodes*, and *electrical resistance* through GMS is measured. As water is used by plants or as the *soil moisture* decreases, water is drawn from GMS and resistance increases. Conversely, as *soil moisture* increases, resistance decreases.	
HDS	In HDS, the air temperature in a porous block is measured before and after a small heat pulse is applied to it. The amount of heat flow from the pulse-heated point is mostly proportional to the amount of water contained within the porous material. That means a wet material will heat up slower than a dry one. This rise in air temperature (or the cooling) is measured with an accurate air temperature sensor located at the sensor tip.	
Capacitance	A capacitive does not measure moisture directly (pure water does not conduct electricity well); instead, it measures the *ions* that are dissolved in the moisture. These *ions* and their concentration can be affected by a number of factors; for example, adding fertilizer will decrease the resistance of the soil.	
TDR	TDR consists of parallel rods, acting as transmission lines, where a *voltage* is launched along the rods and reflected back to TDR for analysis. The velocity of the *voltage* pulse along the rod is related to the *dielectric permittivity* of the soil. The velocity of the pulse for wet soils is slower than that of drier soils.	
FDR	FDR uses an *oscillator* to propagate an *electromagnetic signal* through either a metal tine or other wave guide. The difference between the output wave and the return wave frequency is measured to determine *soil moisture*.	

SMS	Short description	Photo
ADR	ADR uses an *oscillator* to generate an *electromagnetic signal* at a consistent frequency, which is transmitted through a central signal rod, using outer rods as an electrical shield. The *electromagnetic signal* is partially reflected by areas of the medium with different water content, producing a measurable *voltage* standing wave.	
TDT	TDT measures the transmission of a pulse along a looped, or closed circuit, rod. TDT measures the time taken for an *electromagnetic signal* to travel along a given length of a transmission line in the soil. With TDT, a step pulse with a fast rise time is transmitted into a transmission line. The step pulse travels down the transmission line, and a *voltage* is detected at the other end of the transmission line. A pulse measured via TDT will be slower in wetter soils rather than drier soils.	
Neutron probe	Neutron probe consists of a neutron source, detector, and an electronic counting scale. Measurements at desired depths are made by lowering the probe into an access tube installed vertically in the soil. This radioactive probe emits high-energy neutrons in all directions into the soil. When these neutrons collide with hydrogen atoms in the soil, the velocity of the neutron is attenuated or slowed down. The rate of attenuation is dependent on the amount of water present.	
Wireless sensors	Wireless sensors are buried under the soil at the start of the growing season with the logo facing towards the sky. The sensors are located in the silver bands surrounding the device. Throughout the growing season, it sends data back to a phone application over a low power cellular data that can operate at significant distances from cellphone towers.	

Table 3. Pros, cons, and an estimated price of SMS highly used for *irrigation* (adapted from Ling, 2004; Munoz-Carpena, 2004; Maughan et al., 2015; Sample et al., 2016; Labodia Prima, 2019; Sharma, 2019; Singh et al., 2019; Risinger, 2021; Robinson, 2021)

SMS	Pros	Cons	Price
Tensiometer	Capable of high frequency sampling Salinity buffering Large sensing area (8 - inch diameter) Direct water potential reading for *irrigation* scheduling Continuous measurements at same location Not affected by salinity Comes in different lengths	Maintenance to replace water in tube could be necessary Might have to be reset frequently in coarse or swelling soils Less intuitive due to negative relationship between *volumetric* water content and tensiometer reading Requiring periodic service Not useful in drier soil conditions Not suitable for fine *soil texture* Slow response time to soil water changes Do not withstand cold soil temperatures Manual readings and data collection Should be read daily when crop water use is high to detect false readings due to air bubbles entering the tube Soil temperatures below freezing can also seriously damage the tensiometer. It must be removed from the ground and stored before soil temperatures drop to freezing	$75 - $125 per sensor $140 - $155 for transducer

SMS	Pros	Cons	Price
GMS	Can measure a large area (8 - inch diameter) Can be used in moderately saline soils Can be used to sense wet or dry *soil moisture* readings for *irrigation* If soil does not dry out, little maintenance is required Good accuracy in medium to fine soils Data can be logged and retrieved remotely Applicable for large soil tension range Continuous measurement at same location Can be permanently installed (through winter) in soil No water refilling needed	Relatively inaccurate Performs poorly in sandy soils due to slow reaction time (water moves fast in sandy soils) Performs poorly in soils that shrink/swell Susceptible to drying; must be dug out and solution reset when this occurs Relatively slow response time to soil water changes Sensitive to soil temperature and high salinity *Calibration* in needed for each soil type Slow reaction time Does not work well in sandy soils	$40 - $70 per sensor $250 for handheld meter $500 -$600 for data logger
HDS	Sensor output is independent to *electrical conductivity* (EC) value. Measurements not affected by salts in the soil Small size Very accurate Soil/site *calibration* usually not required Remote access of data available Measures a wide range of *matric potential* Long lasting, with no maintenance required	HDS have a larger power requirement compared to other sensor types for frequent observations Very small area of influence Slow reaction time Does not work well in sandy soils	$280 - $380 per sensor $300 - $440 for excitation module $2,000 - $2,500 for data logger

SMS	Pros	Cons	Price
Capacitance	Not only avoids corrosion of the probe but also gives a better reading of the moisture content of the soil as opposed to using resistive SMS Since the contacts (the plus plate and the minus plate of the capacitor) are not exposed to the soil, there is no corrosion of the sensor itself Response time is very fast Remote access available Very accurate after *calibration* Can be used in moderate saline soils	Small sensing area Affected by soil conditions - high salinity, clay content, and soil temperature Site/soil specific *calibration* preferred	\$10 - \$350 per sensor \$500 -\$2,500 for data logger
TDR	Can be used without *calibration* to specific soils; however, it reduces accuracy Not easily influenced by moderate saline soil conditions until the signal disappears Can remain in soil through winter. Continuous measurements can be collected with data logger Accurate with soil-specific *calibration* (2 - 3% error) Easily expanded by multiplexing Wide variety of probe configurations Minimal soil disturbance	Need for good contact between sensor and soil Small sensing area (2.4-inch diameter) Might have limited applicability in highly saline or heavy clay soils *Calibration* is needed for soils with tightly held water Takes time to install because you must dig a trench rather than a hole Uses a lot of power (large rechargeable batteries) Soil-specific *calibration* required for soils having large amounts of bound water (i.e., those with high organic matter content)	\$250 - \$350 per sensor \$1,000 - \$3,500 for data logger

SMS	Pros	Cons	Price
FDR	Accurate with soil-specific *calibration* (1% error) Can be used in saline soils High resolution signal Can be connected to conventional loggers Flexibility in probe design	*Calibration* is necessary Sensitive to soil temperature Small sensing area (3.2-inch diameter) Need for good contact between FDR and soil Sensitive to air gaps Sensitive to clay soils	$60 - $300 per sensor $500 - $3,500 for data logger $2,000 - $3,000 for access tube installation kit
ADR	Accurate with soil-specific *calibration* (1% error) and without soil-specific *calibration* (5% error) Can be used in high saline soils Minimal soil disturbance Soil temperature does not interfere with signal	*Calibration* to a specific soil is recommended Volume of measurement is relatively small (≈0.3 in3) Sensitive to air gaps, stones, or water traveling through channels separate from soil matrix	$200 - $350 per sensor $1,000 - $3,500 for data logger
TDT	Accurate (2% error) Large sensing volume (≈30 in3) Low power consumption	Sensitive to soil compaction Soil disturbance during installation Reduced precision because the generated pulse is distorted during transmission Needs to be permanently installed in the field	$220 - $300 per sensor $1,000 - $3,500 for data logger

SMS	Pros	Cons	Price
Neutron probe	Samples a relatively large area One sensor for all sites and depths Unaffected by salinity and air gaps around access tube Robust and the most accurate SMS (0.5% error) Large soil sensing volume (sphere of influence with 32 – inch diameter, depending on moisture content) Stable soil - specific *calibration*	Soil/site specific *calibration* usually required Contains radioactive material (safety hazard). Licensing and certified personnel is required. Even at 16-inch depth, radiation losses through soil surface have been detected Manual reading and recording (≈3 minutes per access tube) Not good at shallow depths (less than 6 inches). Readings close to the soil surface are difficult and not accurate Heavy, cumbersome instrument The sphere of influence may vary according to the following reasons: a) It increases as the soil dries because the hydrogen concentration reduces, so that the probability of collision is smaller and thereby fast neutrons can travel further from the source. b) It is smaller in fine texture soils because they can hold more water, thus the probability of collision is higher. c) If there are layers with large differences in water content due to changes in soil physical properties, the sphere of influence can have a distorted shape	\$10,000 - \$15,000 per sensor \$25 - \$30 for access tubes

SMS	Pros	Cons	Price
Wireless sensors	Environmental and business benefits across the crop life cycle: growth, harvest, transportation and storage Wireless sensors deliver real-time, actionable information to help agriculture professionals increase yields and crop quality whilst reducing inputs Reduce trips to the field No need to data logger	Some farmers either do not have access to smartphones or do not want to use them for *soil moisture* monitoring	$400 - $450 per sensor $80 - $100 for data services

SMS installation

We should install stationary SMS either horizontally (by digging a hole) or vertically (by using an *auger*) between crops within a crop row at their certain depths. It is recommended to install SMS at different depths and locations in the farm. The best layout is to place SMS in pairs at 1/3 and 2/3 the root depth and at least at two extra locations in the field (Sharma, 2019). Table 4 represents the maximum root depth for different plants.

It is also recommended to flag the SMS in order to help operators/labors see where they are. It can help them to prevent damage to SMS. Some farms contain more than one *soil texture*. In those farms, it is recommended that each *soil texture* be equipped with SMS and managed separately for *irrigation*. The best way to accurately identify soil properties is to have several soil samples and test them in soil laboratories. Nevertheless, some farmers are not interested in spending money for soil sampling. Another option is using Web Soil Survey produced by USDA (https://websoilsurvey.sc.egov.usda.gov/).

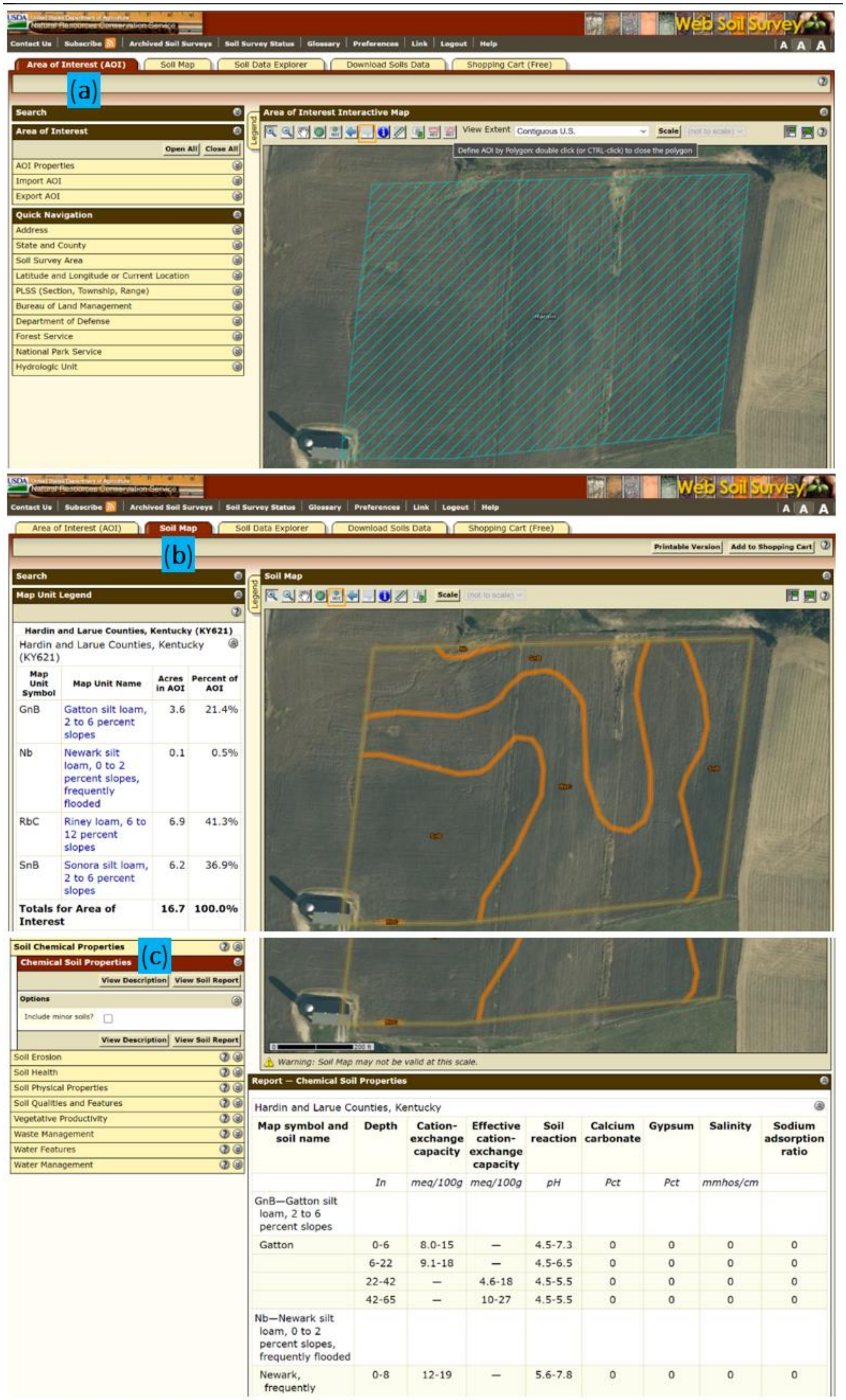
Figure 1 illustrates an example of using Web Soil Survey to identify soil properties for a field located in Hardin and Larue Counties in Kentucky. The first step is to define the area of interest (AOI) using a polygon icon (Figure 1a). After separating the field, the next step is using Soil Map to identify *soil texture* (Figure 1b). As can be seen, *soil texture* for 41.3% of the area is loam and the rest is three different types of silt loam (i.e., Gatton, Newark, and Sonora). As we discussed in this fact sheet, loam and silt loam are the best soils for agriculture with respect to their highest PAW compared to the other types of *soil texture*. Finally, in Figure 1c we can check soil salinity by using Soil Chemical Properties, which show no salinity for the selected field.

In Figure 1, since neither soil salinity nor heavy *soil texture* is a limitation, all SMS (Table 2) will work accurately in the selected field. If our soil was saline and/or we had a heavy *soil texture* (i.e., clay loam, silty clay, and clay based on Table 1), we would not use those SMS that are sensitive to salinity and/or heavy *soil texture* (Table 3). For more information about how to use Soil Web Survey, this link will be helpful, particularly for beginners who have less experience working with datasets: https://websoilsurvey.nrcs.usda.gov/app/Help/WSS_HomePage_HowTo_3_0.pdf

Table 4. Maximum rooting depth for different plants (adapted from Allen et al., 1998)

Plant	Root depth (in)	Plant	Root depth (in)	Plant	Root depth (in)
Small vegetables					
Broccoli and Brussel Sprouts	16 - 24	Cabbage	20 - 30	Carrots	20 - 40
Cauliflower	16 - 28	Celery, Garlic, Spinach, Radishes, and Lettuce	12 - 20	Onions	12 - 24
Big vegetables					
Egg Plant and Cucumber	28 - 47	Sweet Peppers	20 - 40	Tomato	28 - 60
Sweet Melons and Watermelon	35 - 60	Cantaloupe, Pumpkin and Winter Squash	39 - 60	Squash and Zucchini	24 -40
Perennial vegetables					
Artichokes and Asparagus	24 - 70	Mint	16 - 30	Strawberries	8 - 12
Forages					
Alfalfa	40 - 118	Bermuda	40 - 60	Clover	24 - 35
Rye grass	24 - 40	Grazing Pasture	20 - 60	Turf Grass	20 - 40
Roots and Tubers					
Cassava	28 - 40	Turnip	20 - 40	Potato	16 - 24
Sweet Potato	40 - 60	Sugar Beet	28 - 47	Parsnip	24 - 40
Legumes					
Beans	20 - 47	Peas	24 - 40	Peanut	20 - 40
Lentil	24 - 30	Soybeans	24 - 50	Green Gram	20 - 43
Fiber Crops					
Cotton	40 - 67	Flax	40 - 60	Sisal	20 - 40
Oil crops					
Ricinus and safflower	40 - 80	Rapeseed, Canola, and Sesame	20 - 40	Sunflower	30 - 60
Cereals					
Barley, Oates, Spring Wheat	40 - 60	Winter Wheat	60 - 70	Millet and Sorghum	40 - 80
Field Maize	40 - 67	Sweet Maize	30 - 47	Rice	20 - 40
Fruit trees					
Almonds, Apples, Cherries, Pears, Apricots, and Peaches	40 - 118	Avocado	20 - 40	Conifer Trees and Pistachio	35 - 60
Kiwi	28 -50	Olives	47 - 67	Walnut	67- 94
Grapes	40 - 60	Berries	24 - 47	Pawpaw	120 - 240
Citrus (20% *canopy*)	30 - 43	Citrus (50% *canopy*)	43 - 60	Citrus (70% *canopy*)	47 - 60

Figure 1. Application of Web Soil Survey, (a) using AOI to define area of interest, (b) using Soil Map to identify *soil texture*, (c) using Soil Chemical Properties to identify soil salinity



Final remarks before selecting SMS

Before selecting the suitable SMS for our farm, we should always pay attention to our budget (capital and annual costs), soil properties, application (i.e., *irrigation* scheduling, monitoring, research), plant type and root depth, accuracy and moisture range required, quality of *irrigation/fertigation* water, and skill level needed for operation and maintenance of SMS. Here are some key notes:

In general, higher frequency measurements result in higher quality data, but also higher SMS cost. Indeed, true value in SMS comes from the optimization of the balance between performance accuracy and price.

Variations of salinity in the soil will often result in perplexing SMS readings and frustration for farmers. For salinity conditions, TDR, FDR, and capacitance are better choices but still need careful consideration, as not all of them are created equally.

It is recommended to apply data loggers to store and log the soil data. This will help in data interpretation and quick decision making. However, if the labor cost is more affordable than the data logger cost, manual recording of SMS could be an option too.

The highest performance will be achieved if we use SMS with *irrigation* scheduling, apps, weather stations and other *best management practices* (BMPs).

We should read SMS daily if we use data loggers and every two to three days if we record the data manually.

Reading catalogues and manuals of SMS helps for a precise *calibration* and installation.

It is recommended for *irrigation* to replenish the *soil moisture* to less than FC. Then there will be some room for potential precipitation, especially for the days when *irrigation* is necessary but there is a moderate to high chance of precipitation.

Glossary

Adhesion - A process in which soils hold water molecules rigidly at their soil-water interfaces.

Auger - A spiral-shaped tool to drill holes into the ground.

Best management practices - Ways to manage our land and activities to mitigate pollution of surface and groundwater near us.

Calibration - Process of configuring a device to provide a result for a sample within an acceptable range.

Canopy - Aboveground portion of a plant, formed by the collection of individual plant crowns.

Dielectric permittivity - Ability of a substance to hold an electrical charge.

Electrical conductivity - A measure of the resistance of a particular material to an electric current.

Electrical resistance - A measure of opposition to the flow of electric current.

Electrodes - Conductors that are used to make contact with a nonmetallic part of a circuit.

Electromagnetic signal - One of the waves that is propagated by simultaneous periodic variations of electric and magnetic field intensity and that include radio waves, infrared, visible light, ultraviolet, X-rays, and gamma rays.

Erosion - Geological process in which earthen materials are worn away and transported by natural forces, especially by water.

Evapotranspiration - A process by which water is transferred from the land to the atmosphere, by water leaving the soil (evaporation) and water lost through plant leaves and stems (transpiration).
Fertigation – A process of using the existing *irrigation* system in a field to inject plants with the required fertilizers.

Ions - Group of atoms that bears one or more positive or negative electrical charges.

Irrigation - A controlled agricultural process during which water is applied to soil to assist in the production of crops, also known as watering.

Leaching - Infiltrated water moving down through the soil profile before it can be used by crops.

Matric potential - A negative pressure or suction head that is read by SMS and reflects the ability of soil to either retain or move water as a result of suction exerted by soil pores.

Oscillator - A device that converts direct current (DC) from a power supply to an alternating current (AC) signal.

Runoff - Water that originates from landscapes during precipitation/*irrigation* events that does not infiltrate into the soil.

Soil moisture sensors - Devices that are used to measure water content of a soil by various techniques.

Soil texture - Composition of soil based on its particle sizes.

Voltage - Difference of potential energy between two points on a circuit.

Volumetric - A unit of measurement in which the water in a soil is described by the percent volume of the space that the water is occupying.

Water use efficiency - Percentage of applied water used by the intended plant.

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