Soil Resource Guide

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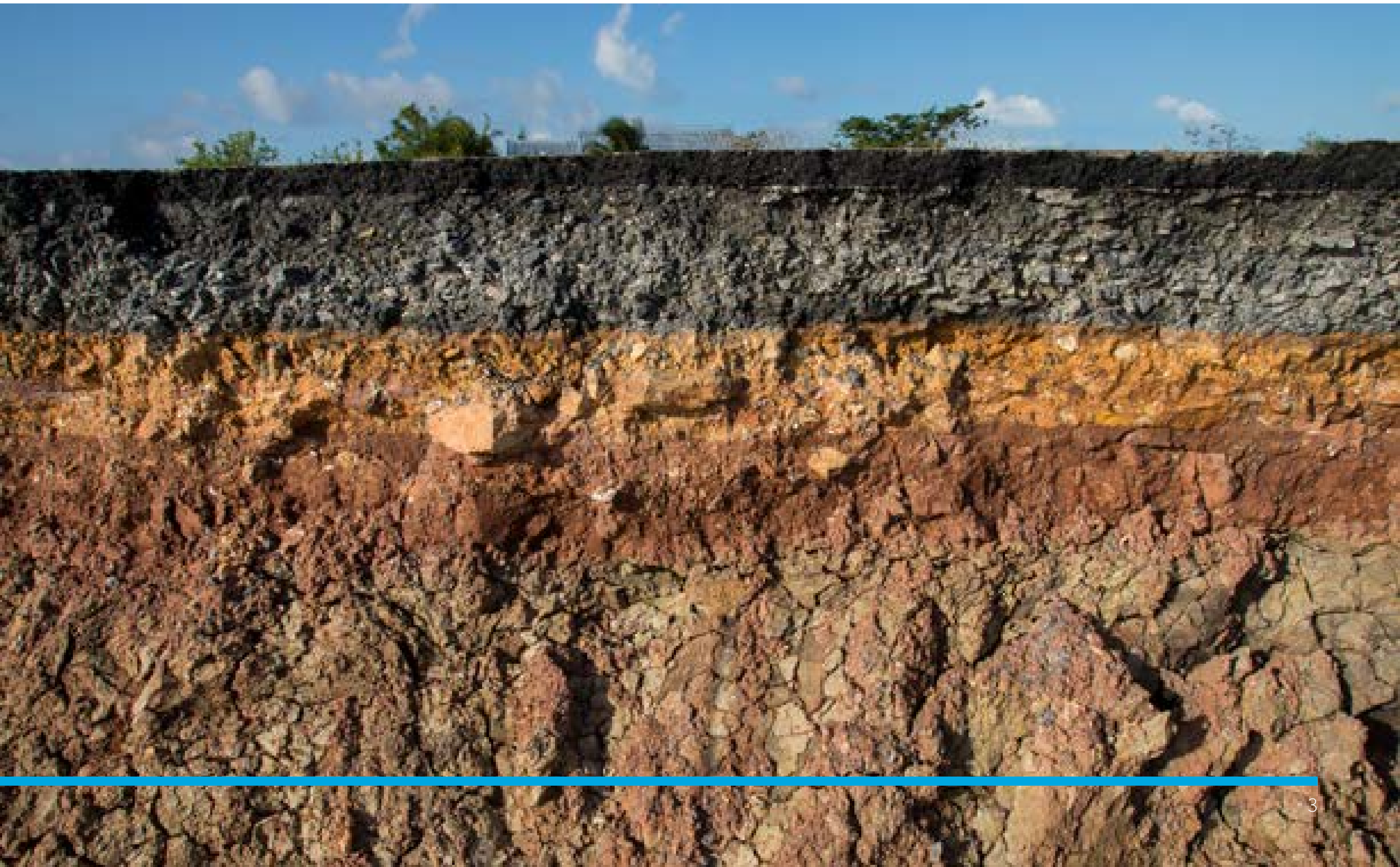
SOIL SENSORS



Why is Soil Monitoring So Important?

Soil is an important natural resource, just as the air and water that surround us are. Unfortunately it has been overlooked in the past and taken for granted with disastrous results, such as the North American dust bowl of the 1930s. Today, the role of soil health on our climate as a whole is taken more seriously, with researchers at organizations such as the USDA-ARS (US Department of Agriculture, Agricultural Research Service) looking into how exactly soil interacts with the rest of our environment.

Because of ongoing research and general interest in soil health and sustainability growing every year, monitoring soil in a more substantial and quantifiable way is becoming more important. Monitoring soil in the past meant going out and physically handling the soil, taking samples, and comparing what was found to existing knowledge banks of soil information.

While nothing will replace actually going out and handling the soil for basic information, today's technology makes it possible to remotely monitor soil and track parameters that simply can't be easily or quickly measured by hand. Soil probes are now extremely accurate and offer an unparalleled look at what is going on below the surface. They give instantaneous information on soil moisture content, salinity, temperature, and more. Soil sensors are an important tool for anyone involved with soil, from a small-town farmer trying to increase his crop yield to researchers looking at how soil retains and releases CO_2. More importantly, just as computers have increased in power and dropped in price due to economies of scale, advanced soil measurement systems can be found at prices that are affordable for everyone.

How Do Soil Sensors Work?

Soil moisture sensors (or "volumetric water content sensors") measure the water content in soil, and can be used to estimate the amount of stored water in a profile, or how much irrigation is required to reach a desired amount of saturation. These sensors can be portable and used for instant measurements or installed for long-term monitoring.

No commercially available soil moisture sensor measures water *directly*. Instead, they measure changes in some other soil property that is related to water content in a predictable way. The other soil property becomes a proxy for water content. Common soil properties that change in relation to water content and are easy to measure include dielectric permittivity and matric potential.

Sensors that measure dielectric permittivity are the most common type of soil moisture sensor. These sensors use different technologies to measure the permittivity of the surrounding soil.

Regardless of the technology used in a sensor, the same principle applies: the bulk dielectric permittivity of soil changes with volumetric water content.

A simple way to think of permittivity is as stored electrical energy. The sensor generates an electric field in the soil. Because water molecules are polar, unbound water molecules in the soil rotate to line up with the electric field lines.

The rotation of unbound water molecules requires energy—stored as potential energy in the aligned water molecules. More water in the soil stores more energy, and the higher the bulk permittivity of the soil will be.

In order for any soil probe to work, no matter the type, it must make contact with the soil. The greatest accuracy will be obtained when the soil probe is fully surrounded by the soil, with no gaps or air holes between the probe and the soil. The probe then sends electrical signals into the soil, measures the responses, and relays this information to a data logger (or directly to the cloud with an Internet-connected wireless network, like Stevens' Avo).

SOIL

Soils are one of Earth's essential natural resources, yet they are often taken for granted. Most people do not realize that soils are a living, breathing world supporting nearly all terrestrial life. Soils and the functions they play within an ecosystem vary greatly from one location to another as a result of many factors, including differences in climate, the animal and plant life living on them, the soil's parent material, the position of the soil on the landscape, and the age of the soil.

Soils are composed of four main components:

- Mineral particles of different sizes.
- Organic materials from the remains of dead plants and animals.
- Water that fills open pore spaces.
- Air that fills open pore spaces.

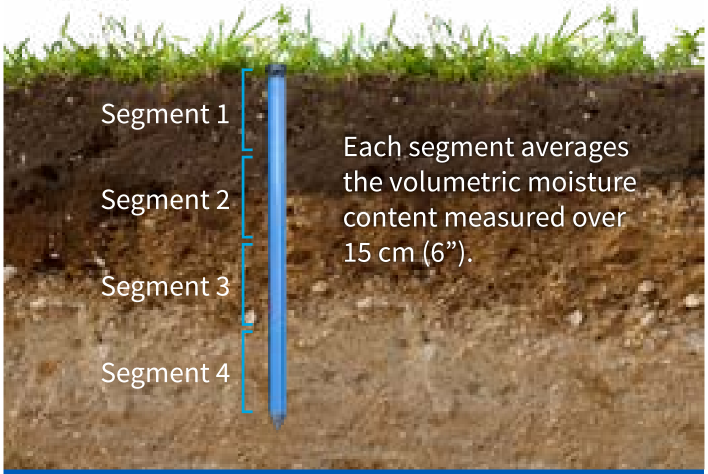
The use and function of a soil depends on the amount of each component. For example, a good soil for growing agricultural plants has about 45% minerals, 5% organic matter, 25% air, and 25% water. Plants that live in wetlands require more water and less air. Soils used as raw material for bricks need to be completely free of organic matter.

Soil Geomorphology

Soil sensors are a popular way of measuring soil moisture, salinity, temperature level, conductivity, and other characteristics that are important to researchers, farmers, and others who rely on soil data for their work.

When working with or studying the soil, it's important to know what type of soil is being examined. Each type of soil has different characteristics, and will have different effects on water infiltration rates, water holding capacity, evapotranspiration rate, and other soil characteristics.

Each area of soil on a landscape has unique characteristics. A vertical section at one location is called a soil profile. These layers are known as horizons. Soil horizons can be as thin as a few millimeters or thicker than a meter. Individual horizons are identified by the properties they contain that are different from the horizons above and below them. Some soil horizons are formed as a result of the weathering of minerals and decomposition of organic materials that move down the soil profile over time. This movement, called illuviation, influences the horizon's composition and properties. Other horizons may be formed by the disturbance of the soil profile from erosion, deposition, or biological activity. Soils may also have been altered by human activity. For example, builders compact soil, change its composition, move soil from one location to another, or replace horizons in a different order from their original formation.



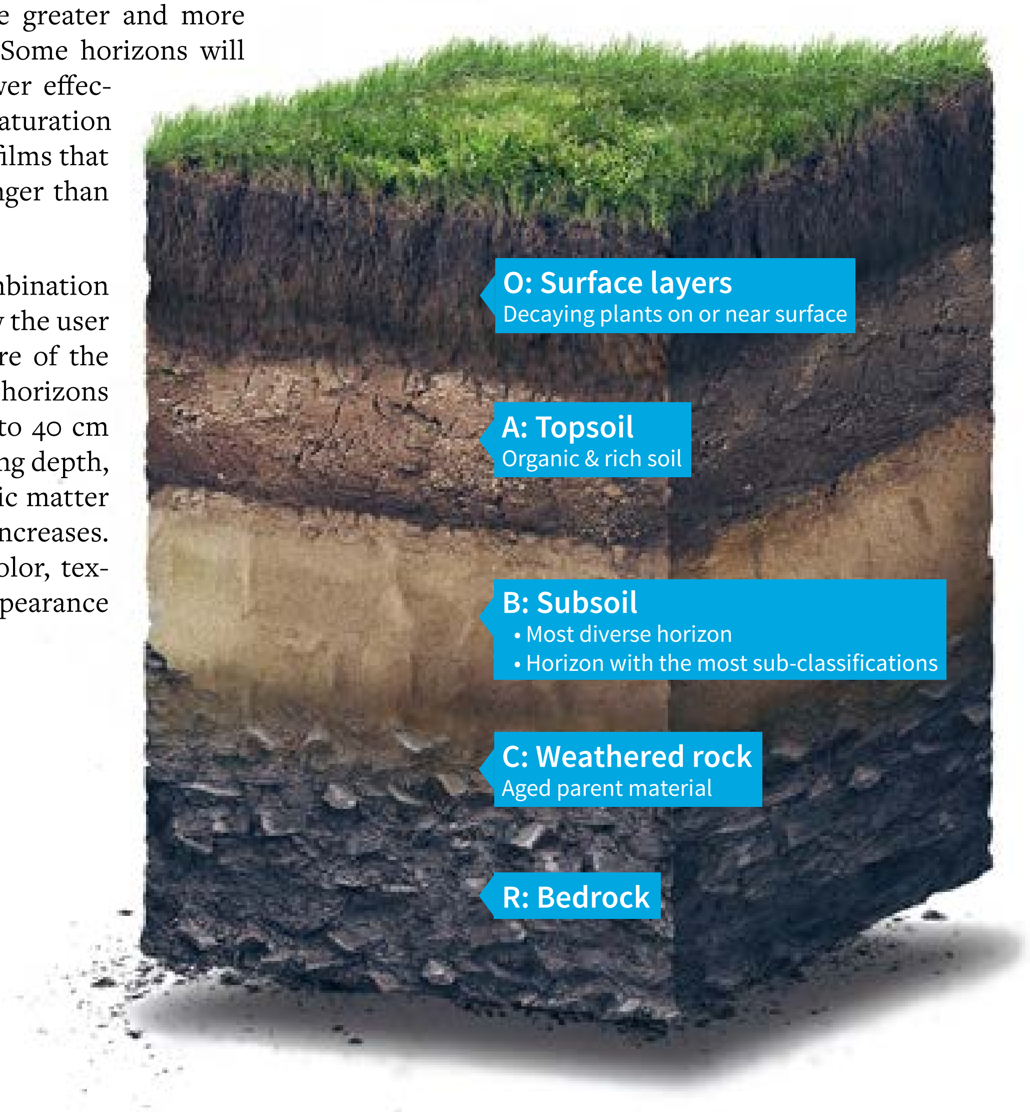
The Stevens GroPoint Profile is ideal for measuring water movement across multiple soil horizons.

Soil Horizons

Soil horizons are distinct layers of soil that form naturally in undisturbed soil over time. The formation of soil horizons is called soil geomorphology and the types of horizons are indicative of the soil order. Like other natural processes, the age of the horizon increases with depth.

The reason why it's useful to have a soil sensor in each horizon is because different horizons have different hydrological properties. Some horizons will have high hydraulic conductivities and thus have greater and more rapid fluctuations in soil moisture. Some horizons will have greater bulk densities with lower effective porosities and thus have lower saturation values. Some horizons will have clay films that will retain water at field capacity longer than other soil horizons.

Knowledge of the soil horizons in combination with an accurate soil sensor will allow the user to construct a more complete picture of the movement of water in the soil. The horizons that exist near the surface can be 6 to 40 cm in thickness. In general, with increasing depth, the clay content increases, the organic matter decreases and the base saturation increases. Soil horizons can be identified by color, texture, structure, pH and the visible appearance of clay films.



Soil Orders and Taxonomy

Soil, just like plants and animals, has been broken down by scientists into a hierarchical classification system, which is as follows: orders, suborders, great group, subgroup, family, and series. While there are thousands of types of soil around the world, they can all be classified under 12 major orders.

Soil orders occur from how the soil changes over centuries, thousands or millions of years. The different orders arise from many factors including:

- type of rock the soil formed from
- climate
- type of vegetation present
- floods
- volcanic activity
- availability of water
- and many other factors.

The 12 Orders of Soil Geomorphology

Alfisols are found in in semiarid to moist areas. They formed under forest or mixed vegetative cover and are productive for most crops.

Andisols tend to be highly productive soils. They are common in cool areas with moderate to high precipitation, especially those areas associated with volcanic materials.

Aridisols are soils that are too dry for the growth of mesophytic plants. They often accumulate gypsum, salt, calcium carbonate, and other materials that are easily leached from soil in more humid environments. Aridisols are common in the world's deserts.

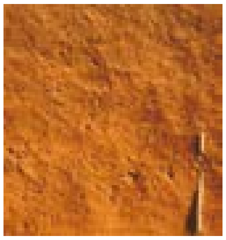
Entisols occur in areas of recently deposited parent materials or in areas where erosion or deposition rates are faster than the rate of soil development; such as dunes, steep slopes and flood plains.

Gelisols are soils that have permafrost near the soil surface, have evidence of frost churning, or ice segregation. These are common in the higher latitudes or high elevations.

Histosols have a high content of organic matter and no permafrost. Most are saturated year round, but a few are freely drained. They are commonly called bogs, moors, pears or mucks.

Inceptisols are soils of semiarid to humid environments that generally exhibit only moderate degrees of soil weathering and development. These occur in a wide variety of climates.

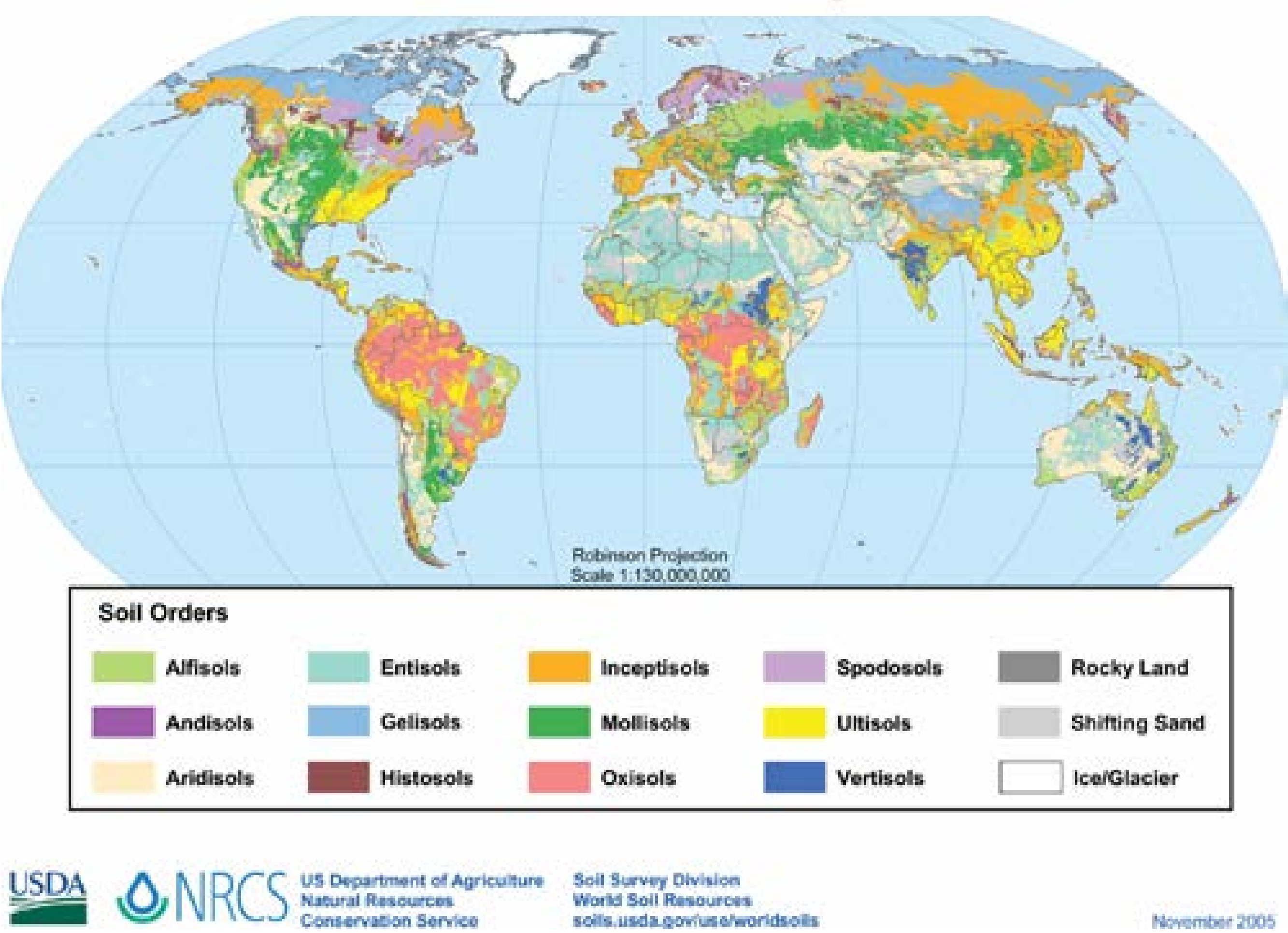
Mollisols are soils that have a dark colored surface horizon relatively high in content of organic matter. The soils are base rich throughout and therefore are quite fertile.



Oxisols are highly weathered soils of tropical and subtropical regions. They characteristically occur on land surfaces that have been stable for a long time. They have low natural fertility as well as a low capacity to retain additions of lime and fertilizer.

Spodosols formed from weathering processes that strip organic matter combined with aluminum from the surface layer and deposit them in the subsoil. These tend to be acid and infertile.

Global Soil Regions



Ultisols are soils in humid areas. They are typically acid soils in which most nutrients are concentrated in the upper few inches. They have a moderately low capacity to retain additions of lime and fertilizer.

Vertisols have a high content of expanding clay minerals. They undergo pronounced changes in volume with changes in moisture. Because they swell when wet, vertisols transmit water very slowly and have undergone little leeching. They tend to be fairly high in natural fertility.

Soil Textures

Soil texture refers to the composition of the soil in terms of the amounts of small (clays), medium (silts), and large (sands) size particles. The primary particles of sand, silt, and clay make up the inorganic solid phase of the soil. These particles often become aggregated together with each other and other parts of the soil, most importantly soil organic matter.

In general, the size of soil particles and their spacing determine how much water can flow through the soil. The larger the spacing, or pore size, the greater the infiltration rate. Thus, sandy soils will have high infiltration rates because pore sizes are large and there are no finer materials to block the pores. The soil texture also influences how much heat and nutrients will be stored in the soil profile.

Sandy soils drain better than soils that are clay rich. In general, the smaller the soil particle size distribution, the slower it will drain. Sometimes silt may have the same particle size distribution as clay, but clay will retain more water for longer periods of time than silt. This can be explained by the shape of the soil particles. Clay particles are planar whereas silt particles are spherical. Water basically gets stuck between the planar plate shaped clay particles and thus slows the flow of water.

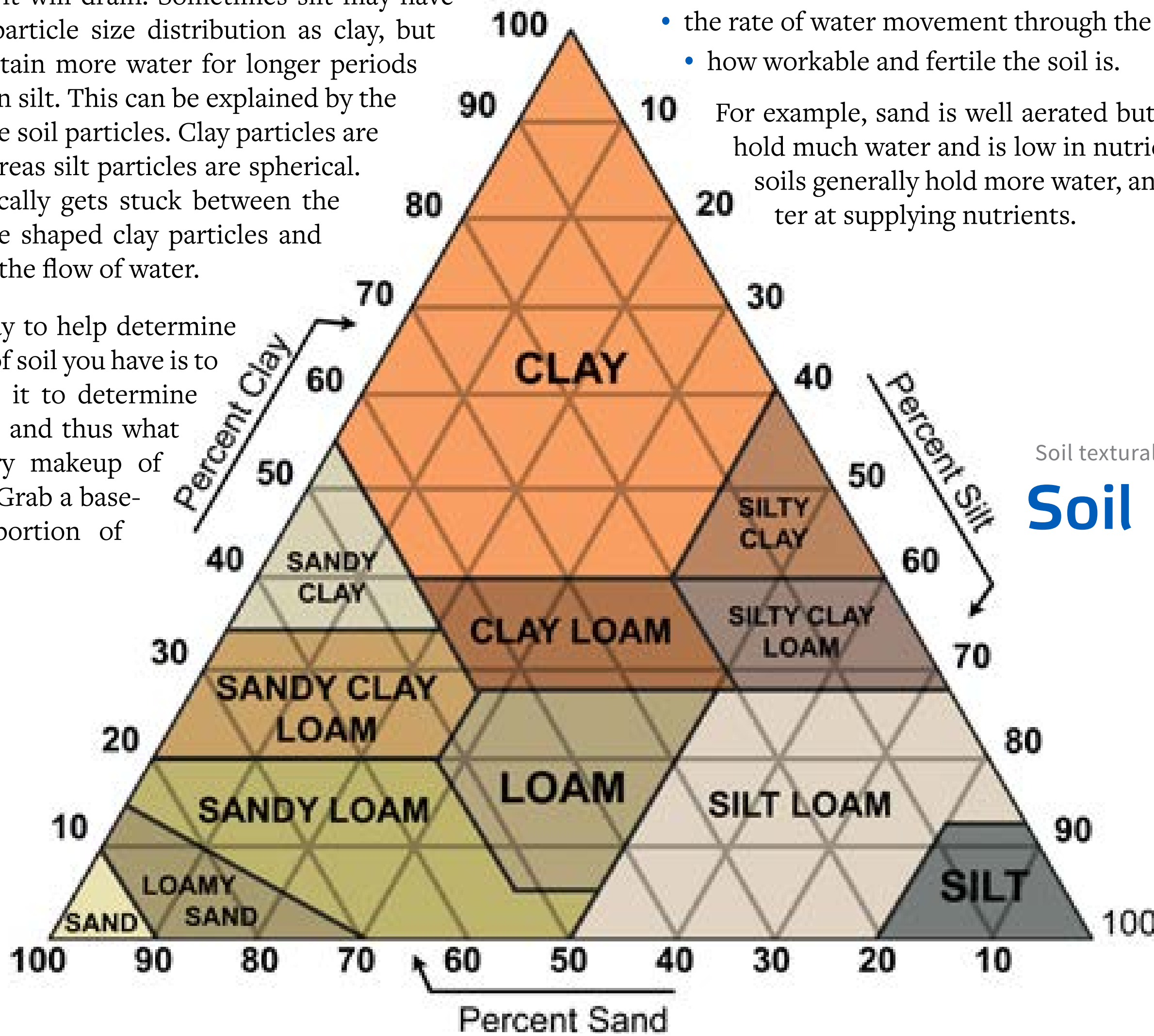
An easy way to help determine what type of soil you have is to simply feel it to determine the texture and thus what the primary makeup of the soil is. Grab a baseball size portion of the soil in your hands and wet the soil with water, working the moist soil with your hands. The stickier it is, the more clay there is. The "soapier" the soil feels the higher the silt content. Grittiness is indicative of sand.

In the United States, twelve major soil texture classifications are defined by the USDA. The twelve classifications are sand, loamy sand, sandy loam, loam, silt loam, silt, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, and clay. Soil textures are classified by the fractions of each soil component (sand, silt, clay) present in the soil. Classifications are typically named for the primary constituent particle size or a combination of the most abundant particles sizes, e.g. "sandy clay" or "silty clay". A fourth term, loam, is used to describe equal properties of sand, silt, and clay in a soil sample, and lends to the naming of even more classifications, e.g. "clay loam" or "silt loam".

Texture is important because it influences:

- the amount of water the soil can hold
- the rate of water movement through the soil
- how workable and fertile the soil is.

For example, sand is well aerated but does not hold much water and is low in nutrients. Clay soils generally hold more water, and are better at supplying nutrients.



Soil textural triangle.

Soil

Properties

Soils are typically about 45% mineral, 5% organic matter, and 50% voids (or pores) of which half is occupied by water and half by air or gas. The percent soil mineral and organic content can be treated as a constant (in the short term), while the percent soil water and gas content is considered highly variable whereby a rise in one is simultaneously balanced by a reduction in the other.

Pore space allows for the infiltration and movement of air and water, both of which are critical for life in soil. Compaction, a common problem with soils, reduces this space, preventing air and water from reaching plant roots and soil organisms.

Soil hydrology stands at the forefront of soil health due to its critical importance in regulating physical, chemical and biological processes in soils. Soil-water interactions are closely related to and create both positive and negative feedbacks with soil characteristics, landscape features and management practices that are closely tied to soil health.

Knowing the hydrological behavior of soils is essential for managing and protecting natural and agricultural ecosystems. Soil hydrological behavior determines crop responses to water and nutrients provided by irrigation and fertilization. Soil hydrology also controls deep percolation fluxes of water and nutrients, as well as water and nutrient runoff. Thus, it impacts the quality of soil, surface and groundwater resources.

Water is a critical agent in soil development due to its involvement in the dissolution, precipitation, erosion, transport, and deposition of the materials of which a soil is composed. Water is also key to the dissolution, precipitation and leaching of minerals from the soil profile. Finally, water affects the type of vegetation that grows in a soil, which in turn affects the development of the soil, a complex feedback which is exemplified in the dynamics of banded vegetation patterns in semi-arid regions.

Soils supply plants with nutrients, most of which are held in place by particles of clay and organic matter. Nutrients may be absorbed on clay mineral surfaces, bound within clay minerals (absorbed), or bound within organic compounds as part of the living organisms or dead soil organic matter. These bound nutrients interact with soil water to buffer the soil solution composition (attenuate changes in the soil solution) as soils wet up or dry out, as plants take up nutrients, as salts are leached, or as acids or alkalis are added.

Plant nutrient availability is affected by soil pH, which is a measure of the hydrogen ion activity in the soil solution. Soil pH is a function of many soil forming factors, and is generally lower (more acid) where weathering is more advanced.

Most plant nutrients, with the exception of nitrogen, originate from the minerals that make up the soil parent material. Some nitrogen originates from rain as dilute nitric acid and ammonia, but most of the nitrogen is available in soils as a result of nitrogen fixation by bacteria.

Dielectric Permittivity

Dielectric permittivity (ε) is grounded in complex physics but in simple terms it can be described as the ability of a substance to hold an electrical charge.

The dielectric constant (Ka) is the ratio of the permittivity of a substance to free space. The value of Ka in air is 1 and in water Ka is approximately 80.

Many materials have an ε or Ka. For example, the Ka of glass is between 5 and 10, the Ka of paper is between 2 and 4, and the Ka of body tissue is approximately 8.

The behavior of electromagnetic waves from 1 to 1000 MHz in soil can be used to measure or characterize the complex dielectric permittivity. Dielectric permittivity was first mathematically quantified by Maxwell's Equations in 1870s. In 1980, G. C. Topp proposed a method and a calibration to predict soil moisture based on the electrical properties of the soil known as the Topp Equation. Today, the many different kinds of soil moisture sensors commercially available in one way or another base their soil moisture estimation on the dielectric permittivity.

Among all of the electronic soil sensors commercially available, measurement involving the complex dielectric permittivity remains the most practical way to determine soil water content from an in-situ sensor or portable device. Electromagnetic soil sensors use an oscillating radio frequency and the resultant signal is related to the dielectric permittivity of the soil where the in-situ soil particle/water/air matrix is the dielectric. Subsequent calibrations then take the raw sensor response to a soil moisture estimation.

The Ka of water varies slightly with temperature and pressure. A Ka value of 80 assumes water is at room temperature. Owen et al (1961) cite Ka values for water across a range of temperature and pressure. There is an inverse relationship between temperature and the Ka of water, where Ka decreases with increasing temperature.

The temperature dependency of water's Ka has significant implications for the calibration of soil water content sensors. Typically, calibration of sensors is conducted at room temperature. However, soil temperature in the field can vary from extremely low to very high. Most researchers, and certainly most growers, ignore the effects of temperature on Ka when reporting soil water content values. Other variables, particularly soil electrical conductivity, can compound the effects of temperature on the accuracy of soil water content sensors.

Dielectric Theory

Complex dielectric permittivity describes a material's ability to permit an electric field. As an electromagnetic wave propagates through matter, the oscillation of the electric field is perpendicular to the oscillation of the magnetic field and these oscillations are perpendicular to the direction of propagation. The dielectric permittivity of a material is a complex number containing both real and imaginary components and is dependent on frequency, temperature, and the properties of the material. This can be expressed by:

$$K^* = \varepsilon_r - j\varepsilon_i \quad [1]$$

where K^* is complex dialectic permittivity, ε_r is the real dielectric permittivity, ε_i is the imaginary dielectric permittivity and j equals the square root of negative 1 end root (Topp 1980).

As the radio wave propagates and reflects through soil, the properties and water content of the soil will influence the wave. The water content, and to a lesser extent the soil properties will alter and modulate electromagnetic radio signals as they travel through the soil by changing the frequency, amplitude, impedance and the time of travel.

The dielectric permittivity can be determined by measuring these modulations to the radio frequency as it propagates through the soil. In general, the real component represents energy storage in the form of rotational or orientation polarization which is indicative of soil water content. The real dielectric constant of water is 78.54 at 25°C and the real dielectric permittivity of dry soil is typically about 4. Changes in the real dielectric permittivity are directly related to changes in the water content and all electromagnetic soil sensors base their moisture calibrations on either a measurement or estimation of the real dielectric permittivity of the soil particle/water/air matrix. (Jones 2005, Blonquist 2005). The imaginary component of the dielectric permittivity:

$$\varepsilon_i = \varepsilon_{rel} + \frac{\sigma_{dc}}{2\pi f \varepsilon_v} \quad [2]$$

represents the energy loss where ε_{rel} is the molecular relaxation, f is the frequency, ε_v permittivity of a vacuum, and σ_{dc} is DC electrical conductivity. In most soils, ε_{rel} is relatively small and a measurement of the imaginary component yields a good estimation of the electrical conductivity from 1 to 75 MHz (Hilhorst 2000). In sandy soils, the molecular relaxation can be negligible.

The storage of electrical charge is capacitance in Farads and is related to the real component (non-frequency dependent) by:

$$C = g\varepsilon\, \varepsilon_v \quad [3]$$

where g is a geometric factor and ε is the dielectric constant. If the electric field of the capacitor is oscillating (i.e. electromagnetic wave), the capacitance also becomes a complex number and can be describe in a similar fashion as the complex dielectric permittivity in equations [1] and [2] (Kelleners 2004).

The apparent dielectric permittivity ε_a, is a parameter that contains both the real and the imagery dielectric permittivities and is the parameter used by most soil sensors to estimate soil moisture.

$$\varepsilon_a = \{1+[1+\tan^2(\varepsilon_i/\varepsilon_r)]^{1/2}\}\varepsilon_r/2 \quad [4]$$

From equation [4], the apparent dielectric permittivity is a function of both real and imaginary components (Logsdon 2005). High values of ε_i will inflate the ε_a which may cause errors in the estimation of soil moisture content. In an attempt to shrink the errors in the moisture calibration from the ε_i, some soil sensor technologies such as time domain reflectometry (TDR) and time domain transmissometry (TDT) will operate at high frequencies giving the ε_a more real character. In practice, soils high in salt content will inflate the soil moisture measurement because ε_a will increase due to the DC conductivity component of ε_i. Also, the ε_i is much more sensitive to temperature changes than ε_r, creating diurnal temperature drifts in the soil moisture data (Blonquist 2005, Seyfried 2007). Soil moisture sensors that can best isolate the real component and delineate it from the imaginary will be the most accurate and will have a lower inter-sensor variability.

Water is a polar molecule, meaning that one part of the water molecule carries a negative charge while the other half of the molecule carries a positive charge. While water is very polar, soils are rather non-polar. The polarity of water causes a rotational dipole moment in the presence of an electromagnetic wave while soil remains mostly uninfluenced.

> 1. Terminology note. The term “real dielectric constant” generally refers to a physical property that is constant at a specified condition. The term “real dielectric permittivity” or “real permittivity” refers to the real dielectric constant of a media that is undergoing change, such as soil.

This means that water will rotate and reorientate with the rise and fall of the oscillating electric field (i.e. the electromagnetic wave) while soil remains mostly stationary. From 1 to 1000 MHz, the water rotational dipole moment will occur at the same frequency of the electromagnetic wave. It is this rotational dipole moment of water that is responsible for water’s high dielectric constant$_{(1)}$ of about 80. Large changes in the dielectric permittivity are directly correlated to changes in soil moisture.

How Temperature Affects Dielectric Permittivity

Both the real and imaginary dielectric permittivities will be influenced by temperature. The imaginary component is much more sensitive to changes in temperature than the real component. (Seyfried 2007).

The real dielectric permittivity of water will have a slight dependence on temperature. As the temperature increases, molecular vibrations will increase. These molecular vibrations will impede the rotational dipole moment of liquid water in the presence of an oscillating electric field; consequently, the real dielectric permittivity of water will decrease as the temperature increases. The empirical relationship with temperature found in the literature is shown in equation [5] (Jones 2005):

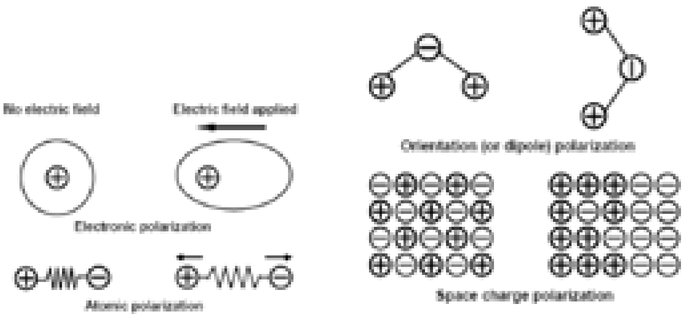
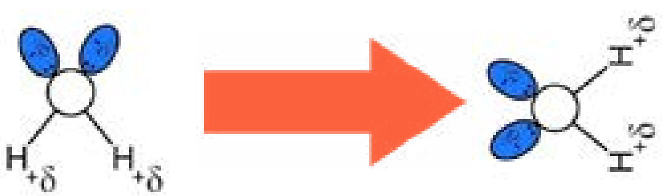


Illustration of polarization. The real dielectric permittivity of soil is mostly due to orientation polarization of water (Taken from Lee et al. 2003)

The dielectric constant of water in liquid form decreases with increasing temperature, but in soil, water’s dielectric dependence on temperature is more complicated due to bound water effects. As temperature changes, the molecular vibrations of the water and cations (positive ions) that are bonded to soil particles at a microscopic level can affect the dipole moments in the presence of a radio frequency. In practical terms, temperature correction to soil moisture calibrations are highly soil-dependent. In some soils, the real dielectric can trend downward with increasing temperature as it does in liquid form, or it can trend upward with increasing temperature (Seyfried 2007).

The imaginary permittivity is highly temperature-dependent and that dependence is similar to that of the bulk electrical conductivity.



A water molecule in the liquid phase reorienting i.e. rotational dipole moment.

$$\varepsilon_{r,w}(T)=78.54[1-4579X10^{-3}(T-298)+1.19X10^{-5}(T-298)^{2}-2.8X10^{-8}(T-298)^{3}] \quad [5]$$

Measuring Apparent vs. Imaginary Dielectric Permittivity

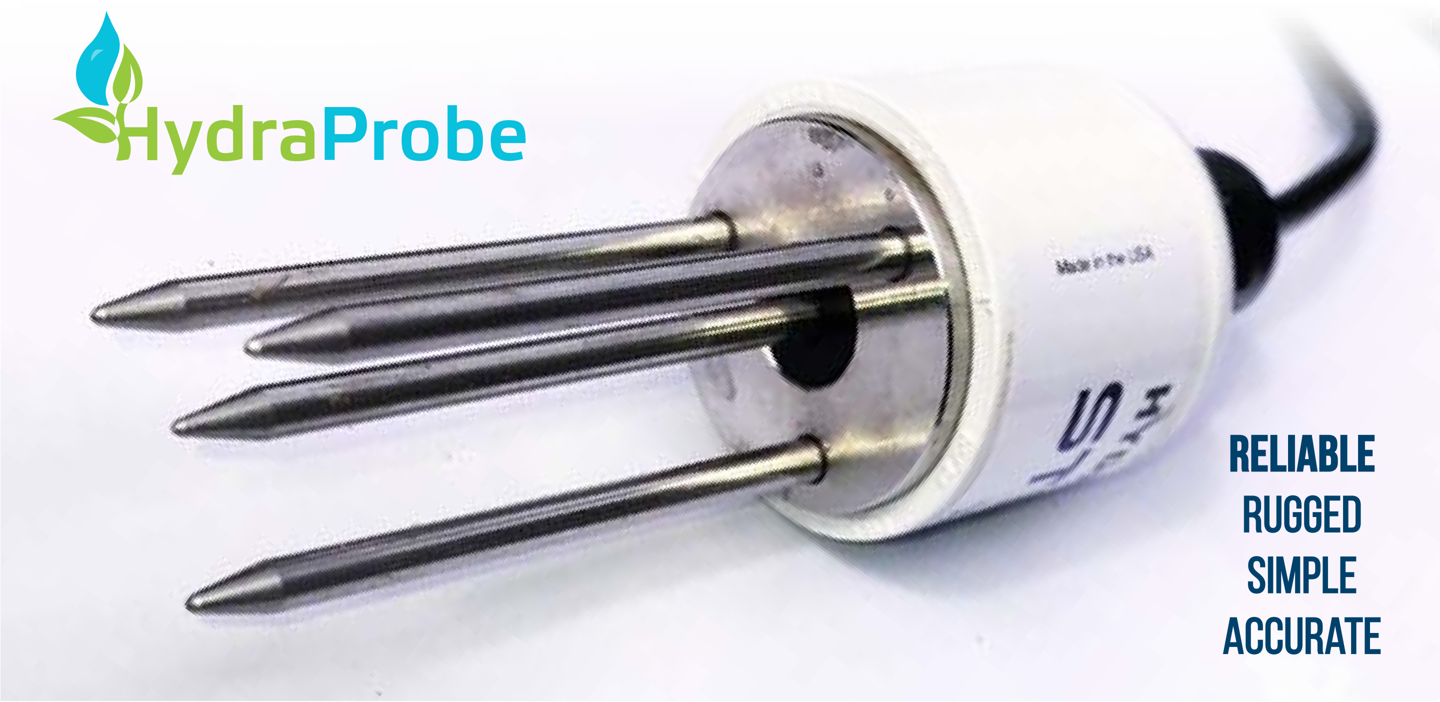
Most soil sensors measure the apparent dielectric permittivity by making an assumption of the imaginary permittivity. That is, the apparent dielectric permittivity measurement mixed together the real and imaginary permittivity (Logsdon 2010). Such a mixed measurement is prone to error since soil is not all about water. Other variables such as salinity, temperature, conductivity, and mineralogy can independently influence the real and the imaginary permittivity. Errors can occur when such variables are not independently characterized in measuring the real and the imaginary permittivity. The "real dielectric" represents water alone. The "imaginary dielectric" represents the other things that are not related to water.

The variability of soil properties in space, time, and geographical location presents a challenge for each site assessment and the detection of changes in soil conditions within and among sites. Spatial variations include horizontal variations across a landscape and vertical variations with horizon depth. These variabilities are due to numerous factors including mineralogy, animal/insect activity, windthrow, litter and wood inputs, human activity, plants, precipitation chemistry, tillage, compaction, seasonality, etc. These soil variables have an impact on the apparent dielectric permittivity.

Most sensors based on universal standards (such as NIST traceable standards) do not have such changing site-specific variables, and make assumptions about the imaginary dielectric permittivity (which are impacted by such variables). For the highest accuracy, sensors should base the soil moisture calibration on the real dielectric permittivity only.

Only one sensor technology—Coaxial Impedance Dielectric Reflectometry—measures both the real and the imaginary components of the dielectric permittivity as separate parameters. Basing the soil moisture calibration on the real dielectric permittivity instead of the apparent permittivity has several advantages: soil moisture calibrations are less affected by soil salinity, temperature, soil variability and inter-sensor variability. **The only sensor that uses this technology is the Stevens HydraProbe.**

Basing the soil moisture calibration on the real dielectric permittivity instead of the apparent permittivity has several advantages: soil moisture calibrations are less affected by soil salinity, temperature, soil variability and inter-sensor variability.



Salinity / Electrical Conductivity (EC)

Electrical conductivity (EC) is the most common measure of soil salinity and is indicative of the ability of an aqueous solution to carry an electric current. Soil salinity refers to dissolved salts such as sodium chloride, calcium chloride and magnesium chloride. The salts may not only be chlorides but carbonates as well. Fertilizers such as nitrates do not have strong conductivities, therefore the EC measured in a soil is primarily attributed to sodium.

Many nutrients are salts—a source of salinity. Nutrient accumulation, poor drainage, salt water intrusion in coastal areas and saline irrigation water can lead to the unwanted buildup of salinity in soil. High EC can affect moisture readings and create errors with capacitance-based (time-of charge and frequency) moisture sensors.

Salt or specifically the dissolved ions in the solution is the primary component of the soil matrix that conducts electricity. While EC is highly dependent on the level of soil salinity, it will also rise and fall with soil moisture.

The effect of EC on the moisture available to a plant's roots is great. The buildup of salinity in the soil is typically not beneficial to crops, grasses or the microbial community in the soil. Soil salinity also affects the soil hydrology. Plant diseases and pathogens, reduced crop yields or even crop failures may occur from excessive soil salinity, therefore the proper monitoring of soil salinity will help ensure the health of crops.

Soil EC can change dramatically with water content and can be affected by the quality of the irrigation water, fertilization, drainage, and other natural processes. Compaction, clay content and organic matter, can influence moisture holding trends over time, also affecting EC capacities in soil.

Bulk EC Versus Pore Water EC

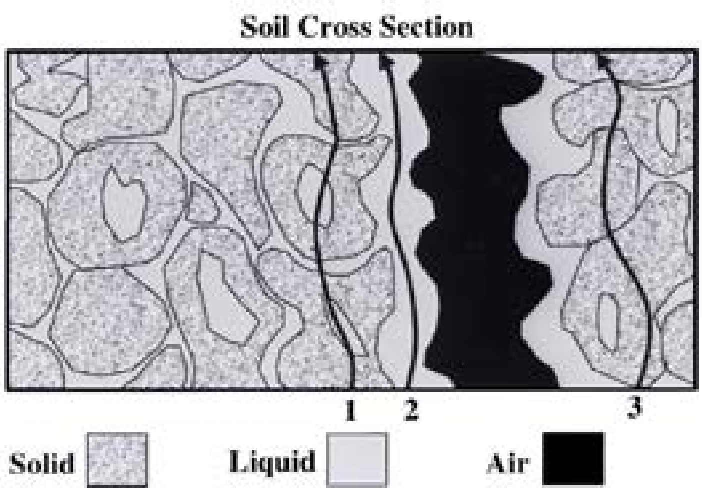
The EC in soil is more complex than it is in a water sample and can be difficult and confusing to interpret. The bulk soil electrical conductivity (σ_b) is the EC of the undisturbed soil/water/air matrix and is the parameter measured by soil sensors. It is important not to confuse the bulk EC with the soil pore water EC (σp). Soil pore water EC is the electrical conductivity of the water in the pore spaces of the soil. Because the pore water EC may be difficult to directly measure, a soil slurry can be prepared by taking one part dry soil and two parts distilled water and measuring the EC of the water extract from the slurry. The EC of the extract (ECe or σe) is the parameter traditionally found in soil science or agriculture literature because is relativity easy to measure and provides an "apples to apples" comparison of soil salinity conditions.

Bulk EC and EC Pathways in Soil

Soil is a matrix that is basically composed of solid material, water in the pore spaces and air. In-situ soil sensors (soil sensors in the ground) measure the bulk electrical conductivity (σ_b) which is the electrical conductivity of the soil/water/air matrix combined.

The image above shows the three pathways the electrical conductivity can propagate in soil. The bulk density, the porosity, the tortuosity, the water content, and the dissolved ion concentration working in concert with the different pathways, dramatically influences the bulk electrical conductivity of a soil.

Pathway 1 is the electrical pathway that goes from water to the soil and back through the water again. The electrical conductivity contribution of pathway 1 is a function of the conductivity of the water and soil. As water increases, the electrical conduit of pathway 1 increases which may increase the electrical conductivity of the soil as a whole.



Pathway 2 is the pathway that is attributed to the electrical conductivity of the just the water in the soil pores. Increasing the dissolved salts will increase the conductivity of pathway 2; however, like pathway 1, increases in the soil water content will increase the size of the pathway thus increasing the overall bulk electrical conductivity. That is to say, that there are two factors influencing the electrical conductivity of pathway 2, namely the dissolved salt concentration and the size of the pathway attributed to the amount of water in the soil.

Pathway 3 is the electrical conductivity of the soil particles. Like the other pathways, the contribution of pathway 3 is influenced by a number of factors that include bulk density, soil type, oxidation/reduction reactions and translocation of ions.

The bulk EC measurements provided by soil sensors is the electrical conductivity of the dynamic soil matrix as a whole, which is the sum of the electrical conductivities from all of the different pathways. No in-situ soil sensor can directly distinguish the difference between the different pathways nor can any conventional in-situ soil sensor distinguish the difference between sodium chloride and any other number of ions in the solution that all have some influence on electrical conductivity of the soil/water/air matrix.

Application of Bulk EC Measurements

While it is difficult to make apples to apples comparisons with the bulk EC, we can identify certain benchmarks. For example, if the soil moisture reaches a threshold such as field capacity, the bulk EC can be recorded at that threshold to make a comparison. This would be useful in situations where soil salinity is a problem and monitoring is necessary.

In some circumstances, the pore water EC can be estimated from knowledge about the dielectric permittivity of the soil (Hilhorst 1999). This equation allows us to make comparable pore water EC estimates from bulk EC measurement in most soils:

$$\sigma_p = \frac{\varepsilon_{rp}\sigma_b}{\varepsilon_{rb} - e_{rb\_}O}$$

Where σ_p is the pore water EC, ε_{rp} is the real dielectric content of water (≈80), σ_b is the bulk EC measured in the soil, and ε_{rb} is the real dielectric permittivity of the soil. $\varepsilon_{rb\_}O$ is an offset, and 3.4 can be used as the offset for most inorganic soils. **Note that only sensors that use the Coaxial Impedance Dielectric Reflectometry method of moisture measurement (i.e. the HydraProbe) can determine the real dielectric permittivity.**

Total Dissolved Solids (TDS)

The total dissolved solids (in g/L or ppm) of a water sample can be estimated from the electrical conductivity. To assess the TDS in soil you need to first obtain the pore water EC from either the equation above or from a slurry water extract. TDS calculated from EC may be less meaningful for soil pore water because there could be other constituents dissolved in the water that do not contribute to the EC of the water, such and nitrates, phosphates and other factures that exist in soil but do not occur in a water sample. Another source of error with TDS estimation from EC is the fact that different salts have different EC strengths and solubility. Calcium chloride will be under-represented in a TDS calculation because it has a lower EC value and will fall out of solution much quicker than sodium chloride (McBride 1994). Despite the challenges associated with estimating TDS from EC, the equation below can be used with a soil sensor's EC measurements to estimate the TDS in a water or slurry extract sample.

Water Salinity (g/L) ≈ EC (S/m) x 6.4

To verify the TDS estimation from EC or perhaps correct this equation for a specific water sample, one can dry down a water sample and obtain the weight of the material left behind for a true gravimetric measurement of TDS. Note that if the EC measurement is used to estimate the TDS, the sensor's tines need to be completely submerged in the water sample or the water extract of the slurry.

Soil Matric Potential

Capillary matric potential, sometimes referred to as tension or pressure head (ψ, hPa) is the cohesive attractive force between a soil particle and water in the pore spaces in the soil particle/water/air matrix. Typical ranges are 0 to 10,000,000 hPa where 0 is near saturation and 10,000,000 hPa is dryness. The drier the soil the more energy it takes to pull water out of it. Capillary forces are the main force moving water in soil and it typically will move water into smaller pores and into drier region of soil. This process is also called wicking.

Because of the wide pressure ranges that can be observed from very wet to very dry conditions, matric potential is often expressed as the common log of the pressure in hPa. The log of the pressure is called pF. For example 1,000,000 hPa is equal to a pF of 6.

Water potential is highly texture dependent. Clay particles have a larger surface area and thus will have a higher affinity for water than that of silt or sandy soils. The most common methods for measuring or inferring the matric potential include granular matrix sensors such as gypsum electrical resistance blocks, and tensiometers which measure pressure directly.

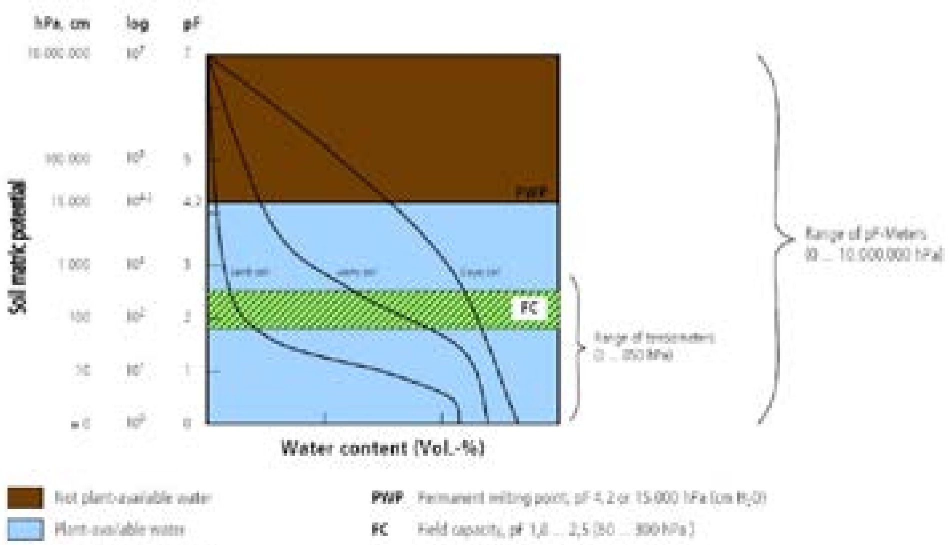
Heat dissipation-type matric potential sensors measure the matric potential indirectly by measure the heat capacitance of a ceramic that is in equilibrium with the soil. With heat up and cool down cycles of heating elements in the ceramic, the heat capacitance can be calculated and in turn calibrated to the matric potential. Heat capacitance-based matric potential sensors such as the ecoTech Tensiomark offer advantages in accuracy, range and maintenance over other technologies.

Matric potential is important for irrigation scheduling because it can represent the soil water that would be available to a crop. Many unsaturated flow models require a soil water retention curve where water fraction by volume is plotted with the matric potential in a range of moisture conditions. A soil water retention curve can help understand the movement and distribution of water such as infiltration rates, evaporation rates and water retentions (Warrick 2003).

Soil pH

Soil pH defines the relative acidity or alkalinity of the soil solution. The pH scale in natural systems ranges from 0 to 14. A pH value of 7.0 is neutral. Values below 7.0 are acid and those above 7.0 are alkaline, or basic. Many agricultural soils have a soil pH between 5.5 and 6.5.

Soil pH is a measurement of hydrogen ion (H+) activity, or effective concentration, in a soil and water solution. Soil pH is expressed in logarithmic terms, which means that each unit change in soil pH amounts to a tenfold change in acidity or alkalinity. For example, a soil with a pH of 6.0



The soil matric potential (also called water potential) represents the energy it takes to pull water out of soil where the water is held within the soil by capillary and absorptive forces. The drier the soil, the more energy is required to pull the water out.

ecoTech Tensiomark

This heat capacitance technology offers advantages over traditional tensiometers or lysimeters by providing more stable measurements without user calibration.

- Can have ranges that capture very dry conditions.
- Quick response to changes of soil moisture.
- Low inner sensor hydrological hysteresis and variability.
- Not sensitive to soil salinity.
- Quick equilibration time.
- Not damaged by frost.
- Maintenance-free (no filling required).
- No calibration needed.

has 10 times as much active H+ as one with a pH of 7.0.

The pH of a soil horizon is determined by the parent material from which the soil is formed, the chemical nature of the rain or other water entering the soil, land management practices, and the activities of organisms (plants, animals, and microorganisms) living in the soil. Soil pH is an indication of the soil's chemistry and fertility. The activity of the chemical substances in the soil affects the pH levels. Different plants grow at different pH values. Farmers sometimes add materials to the soil to change its pH depending on the types of plants they want to grow. The pH of the soil also affects the pH of groundwater or nearby water bodies such as streams or lakes.

Soil Texture

The texture describes how a soil feels and is determined by the amounts of sand, silt, and clay particles present in the soil sample. To read more about soil textures, see page 8.

Soil Bulk Density

In general, the greater the soil density, the less water it will hold and the slower water will move through it. There will often be soil horizons that will be denser than others giving the soil different hydrological properties with depth. Occasionally, water will stop or slow down and rest on a dense, less permeable layer of soil. This phenomenon is called perched water. If two soil sensors 20 cm apart have very different soil moisture readings, chances are that one of the probes is residing in perched water.

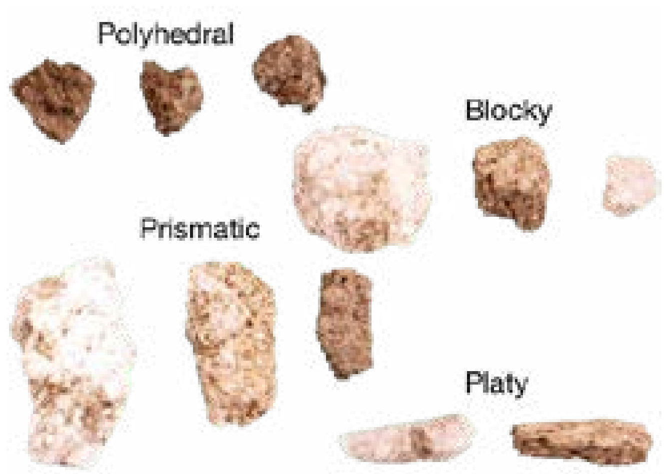
There is also a relationship between soil bulk density and the complex dielectric permittivity. The bulk density is associated with the density of a soil ped or a soil core sample. The particle density is the density of an individual soil particle such as a grain of sand. The two densities should not be confused with one another. Because the dielectric permittivity of dry soil is a function of both the bulk and particle densities, the soil density often creates the need for soil-specific calibrations.

Shrink/Swell Clays

Shrink/swell clays belong to the soil taxonomic order vertisol and are composed of smectite clays. These clays have a large ion exchange capacity and will shrink and swell seasonally with water content. The seasonal expansion and contraction homogenizes the top soil and the subsoil. As the clay shrinks during a drying period, the soil will crack open and form large crevasses or fissures. If a fissure forms in the measurement volume of a soil sensor, the probe will signal the average of the fissure and potentially generate biased results. If the fissure fills with water, the soil moisture measurement will be high, and if the fissure is dry the soil moisture measurement will be lower than expected. If the sensor measurements are being affected by shrink/swell clays, it is recommend to relocate the probe to an adjacent location.

Ped Wetting

A soil ped is a single unit of soil structure. Ped shapes include granular, platy, blocky and prismatic and ped sizes can range from 1 mm granules to 10 cm prisms. The preferential pathway water travels through soil is between the peds. This is evident by clay film coatings that develop around a ped. The clay film precursors become dissolved in the pore water. As the pore water subsides the clay film precursors fall out of solution and adhere to the surface of the peds creating the clay film. The clay film will often delay the infiltration of water into the ped. Thus as the wetting front moves down into the soil, the regions between the peds will be the preferential water pathway. As the wetting front moves through the soil column the soil moisture measurements may be temporarily biased by the peds. For example, if the soil probe's measurement volume is residing entirely in a single ped, the probe would not detect the wetting front until the water infiltrates the ped. Likewise, if the sensing volume is residing between several peds, the soil moisture measurements will reflect the movement of water between the peds. During installation, if a horizon



Soil ped types

has thick clay films around the peds, you may want to use daily averages of soil moisture reading to accommodate soil moisture variations in the peds.

Rock and Pebbles

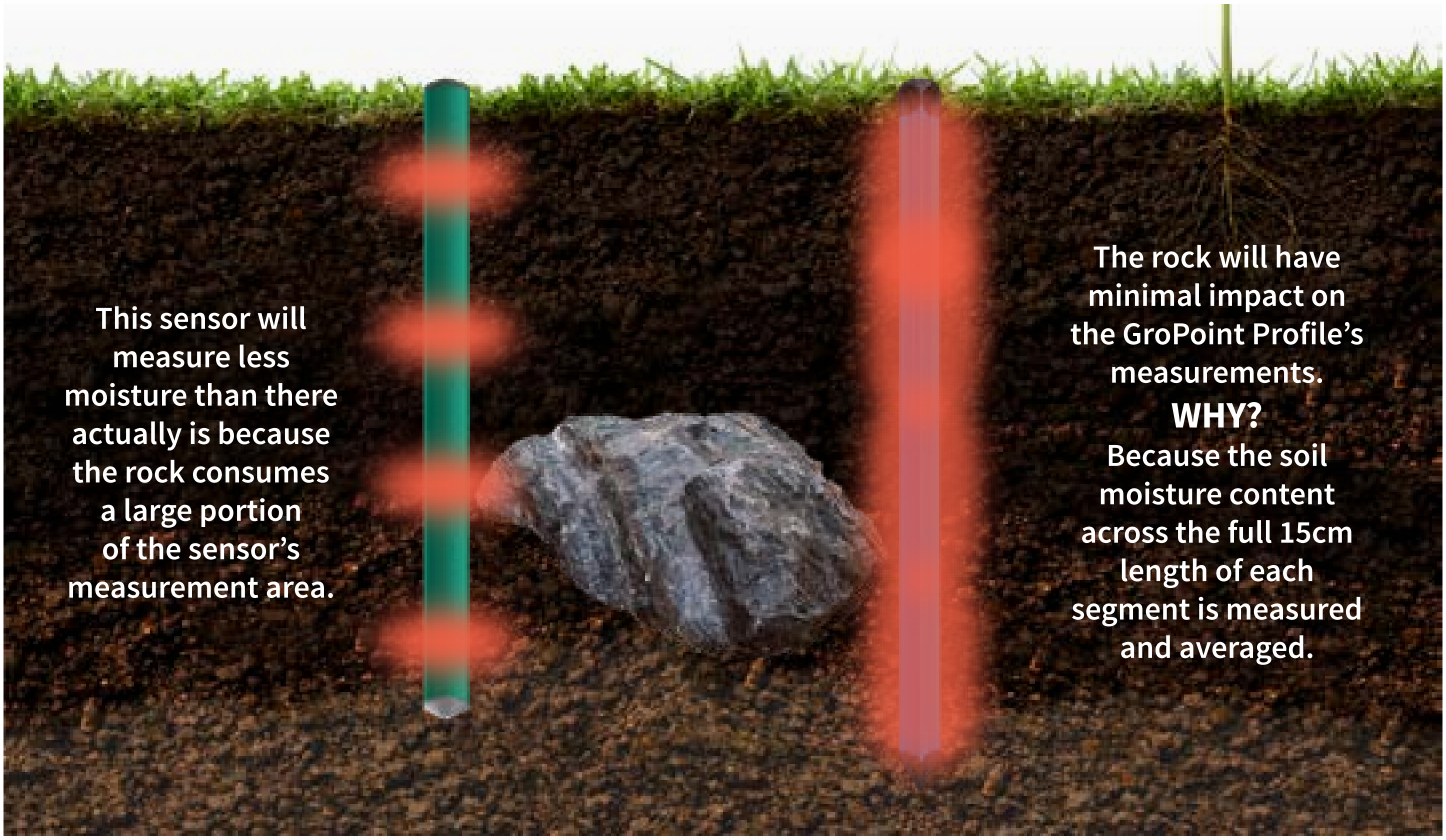
Usually it will be obvious if a rock is encountered during an installation of a soil sensor. Never use excessive force to insert the probe into the soil. Some soils will have a distribution of pebbles. If a pebble finds its way between the a probe's mental tines, it will create an area in the measurement volume that will not contain water. The probe's moisture measurement will be artificially lowered. This is of particular concern with soil profile probes, because the presence of a rock will generally not be known since the a hole is dug or augered from the surface. The GroPoint Profile, because it averages the measurement across each each 15 cm segment, will maintain accuracy even if a rock is next to the probe.

If the pebble is an anomaly, relocating the probe would provide more representative soil measurements. However, if it is revealed from the soil survey that there exists a random distribution of pebbles, a pebble between the tines may provide realistic measurements because of the way pebbles influence soil hydrology.

Bioturbation

Organisms such as plants and burrowing animals can homogenize soil and dislodge soil probes. A tree root can grow between the tines affecting the measurements and in some cases, tree roots can bring a buried soil probe to the soil surface. Each of these instances will have an effect on the accuracy of the measurements.

The cable leading to the probe may also become a tasty treat for some animals. If communication between the data logger and the probe fails, check the cable for damage. Wherever possible, a metal or PVC conduit can help protect the cable.



Soil Monitoring Applications

Over the past few decades, environmental monitoring has become increasingly important. Environmental factors such as climate change, dwindling water resources, and threatened habitats are driving the need to monitor the environment and implement better policies to protect it. Many natural processes in the environment are driven by, or in some ways are related to soil hydrological processes. Monitoring soil moisture conditions provides important information for the protection of and understanding of local and regional water resources.

Agriculture

Irrigation of crops represents 90% of the water used worldwide. Monitoring soil moisture in the root zone of crops will optimize irrigation. The benefits of optimizing irrigation scheduling with soil moisture sensors includes increasing crop yields, saving water, protecting local water resources from runoff, saving on energy costs, saving on fertilizer costs and increasing the farmer profitability.

Archeology

In arid parts of the world, ancient people farmed and irrigated crops to feed themselves and their livestock. In the desert southwestern US, Mesoamericans were able to grow crops in seemly waterless desert environments, and the irrigation practices of these ancient people remain a mystery. It is believed by some archeologists that the ancient Mesoamericans extracted water from clay-confining layers for their crops. Soil moisture probes are deployed in archeological sites to better understand the soil hydrology and to help us understand the day-to-day lives of our distant ancestors.

Biofuel Studies

For thousands of years, people have been growing corn and other crops to sustain the nutritional requirements of the population and livestock. Over the centuries, crops have been domesticated and changed genetically from their wild counterparts for this specific purpose. Now that biofuels are a possible alternative energy source, crops need to be cultivated in order to produce ethanol. In recent years, a new branch of agronomy emerged called biomass studies. Agronomists that specialize in biomass look at new ways to ferment crops to increase the ethanol yields. The goal is to be able to produce ethanol from not only the fermentation of the fruit, but the stems, leaves, and roots. Soil moisture sensors are used in this research to characterize the hydrological requirements of the biomass crops.

Erosion Studies

Each year, erosion from changes in land use causes millions of dollars in damage to property and natural water systems. In order to understand the causes of erosion and make predictions about when and where erosion occurs, hydrologists need to record rainfall, sediment and soil moisture. The water infiltration rate of soil is a function of soil moisture. If the soil is dry, the infiltration rate will be sufficient to prevent run off. Overland water flow may occur if rain events happen at a time when soil is saturated. Monitoring soil moisture is an important input parameter into erosion prediction models.

Drought Forecasting Models

Regional drought can severely affect the economy and even lead to starvation in some areas of the world. With advances in computer processing and environmental modeling methods, scientists are beginning to understand regional water budgets and hydrological processes. An important input into drought forecasting models includes changes in regional soil moisture. Long-term soil moisture data over large regions can be used to predict and characterize harmful droughts.

Dust Control

Poor air quality from particulates in air can have negative consequences to not only human health but regional ecosystems. Vehicular traffic on unpaved roads can lead to major dust problems. In areas of the Southwestern US, the soil is naturally abundant in several types of asbestos. Local officials close unpaved roads based on soil moisture conditions to prevent dangerous dust situations.

Phytoremediation

Phytoremediation is the method by which plants are used to remove pollution from soil. After the pollution is taken up by the plant, the pollutant accumulates in the plant tissue and the plant can be disposed of, or the pollutant is transpired into the air where the sun will chemically break it down into harmless components. Phytoremediation has successfully removed chemicals such as PCBs, arsenic, and petroleum products. These phytoremediation plants often require irrigation. Soil moisture sensors insure that the toxins are not leached downward from over irrigation and ensure that the plants get enough water to effectively remove the pollutant from the soil.

Landslide Studies

Changes in land use may increase the likelihood of landslides dangers. Each year, millions of dollars in damage to property and lives are lost due to landslides. Predicting and preventing landslide hazards is becoming very important in some urban areas. The inputs to landslide prediction models are slope, vegetation, toe slope, soil cohesiveness, and soil moisture. In some areas that experience perched water tables, the soil in the perched water table becomes very heavy as the soil becomes saturated thus becoming more influenced by gravity. Monitoring soil moisture is an important indicator for landslide hazards.

Mesonets and Weather Station Networks

Due to the increasing need to model and understand our environment and our changing climate, governments are increasing the number of weather station networks (mesonets) and the number of stations within existing networks. Soil moisture monitoring is an important part of most mesonets.

Reservoir Recharge from Snowpack

In western North America, a large percentage of the water used for irrigation comes from the melting snowpack. There is increasing concern that climate change will affect not only the depth of the seasonal snowpack but when the snow melt will occur. Soil represents a large reservoir for water storage under snowpack. For example, a larger than average snowpack will still result in low reservoir recharge if the soil is dry in the autumn. Likewise, flooding will result from a below average snowpack if there is a lot of rain in the fall. Monitoring soil moisture is a critical parameter for the estimation of reservoir recharge. The US Department of Agriculture SNOTEL program has hundreds of sites in the United States monitoring soil moisture for reservoir recharge models.

Soil Carbon Sequestration Studies

In recent years, climate change modelers have identified soil as a major source and a major sink for greenhouse gases. As the fields are tilled in preparation for spring time planting, organic soil becomes more available to microorganisms. The microorganisms will consume the organic portion of the soil releasing carbon dioxide and methane into the atmosphere. Each year, tons of greenhouse gases are released into the atmosphere from agricultural tillage. Agronomists are now conducting “no tillage” studies on certain crops. Cultivating crops without tilling the field will keep the carbon in the soil and reduce the emission of greenhouse gases from the soil. Increases in the organic component in soil increases the soil’s water holding capacity. The water holding capacity of a soil can be correlated to the organic carbon content. Agronomists use data from soil sensors to help characterize the effectiveness of the no tillage method and estimate the rate of greenhouse gas production in specific soil.

Sports Turf

Worldwide, there are many thousands of golf courses and sports playing fields that are regularly irrigated. Just as in any other type of crop production, over-irrigating will waste water, energy, fertilizer and will generate run off that will negatively affect the surrounding environment. Soil moisture sensors are an excellent tool to help optimize irrigation of sports turf.

Watershed Hydrology Studies

Soil sensors are used by many hydrologists in watershed studies from many different institutions. The reason for a watershed study could vary from recharge issues to protecting the water quality of the surface water. The soil moisture is an important factor in the hydrological budget of any watershed.

Wetland Delineation Indicators

Wetlands play a critical role sustaining natural habitats and are crucial recharge locations for aquifers. In the planning of construction of new roads, bridges and building developments, it is important to identify all of the wetlands that will be impacted. In the US, environmental laws protect wetlands and impact to wetlands from construction activity is often a legal issue. Soil moisture data can now be used to help regulators identify the boundaries of wetlands.

Satellite Ground Truth Studies

In an effort to increase the amount of land that can be involved in scientific research at any given time, advanced satellite systems are being used to measure soil temperature, CO2 levels, and more. In order to ensure these systems are recording data accurately, agencies such as NASA are employing soil sensors to check and calibrate readings taken by the satellites. The sensors allow scientist to be sure that the data they collect for these remote studies is accurate and reliable.

Soil Moisture and Irrigation

Most soil moisture sensors provide measurements in the unit "water fraction by volume" (wfv or m_3m-$_3$) and is symbolized with the Greek letter theta (θ). Multiplying the water fraction by volume measurement by 100 will equal the volumetric percent of water in soil. For example, a water content of 0.20 wfv means that a 1 cubic meter soil sample contains 200 cubic centimeters of water, or 20% by volume. Full saturation (all the soil pore spaces filled with water) occurs typically between 0.35-0.55 wfv for mineral soil and is quite soil-dependent.

There are a number of other units used to measure soil moisture. They include % water by weight, % available (to a crop), inches of water to inches of soil, % of saturation, and tension (or pressure). The conversion between units can also be highly soil-dependent.

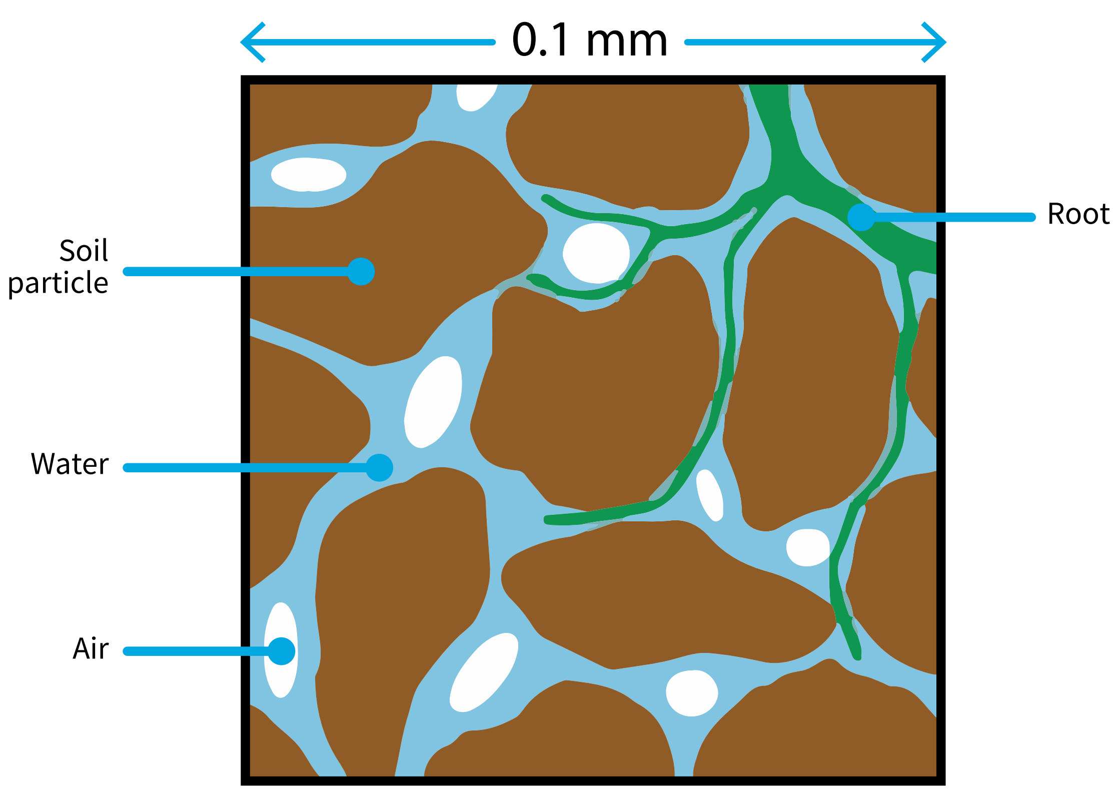
Because the bulk density of soil is so highly variable, soil moisture is most meaningful as a water fraction by volume or volumetric percent. If weight percent were used, it would represent a different amount of water from one soil texture to the next and it would be very difficult to make comparisons.

Soil Moisture Measurement Considerations for Irrigation

Soil moisture values are particularly important for irrigation optimization and the health of a crop. There are two different approaches for determining an irrigation schedule from soil moisture data: the fill point method and the mass balance method.

Other common irrigation scheduling methods that do not include soil moisture sensors use evapotranspiration (ET). ET is the rate of water leaving the soil by the combination of direct evaporation of water out of the soil and the amount of water being transpired by the crop. ET can be thought of as negative precipitation. ET is determined from calculations based on meteorological conditions such as air temperature, solar radiation and wind.

The most common ET irrigation scheduling determination is called the Penman-Monteith Method, published in FAO-



Unsaturated soil is composed of solid particles, organic material and pores. The pore space will contain air and water.

56 1998 Food and Agriculture Organization of the UN. The FAO 56 method is also a mass balance approach where the amount of water that is leaving the soil can be determined and matched by the irrigation schedule. In practice, due to the high importance of the success of the crop, ET methods in combination with soil sensor data can be used by irrigators to best manage irrigation.

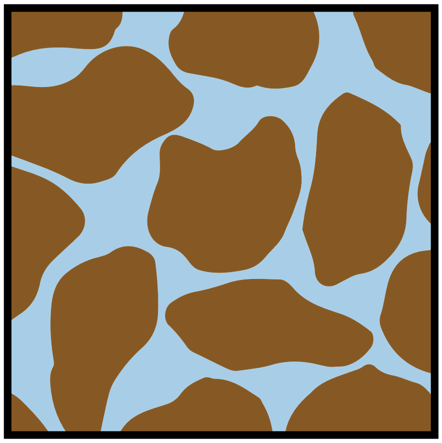
Fill Point Irrigation Scheduling

The fill point method is qualitative in that the irrigator looks at changes in soil moisture. With experience and knowledge of the crop, an irrigation schedule can be developed to fill the soil back up to a fill point. The fill point is an optimal soil moisture value that is related to the soil's field capacity. The fill point for a particular sensor is determined by looking at soil moisture data containing a number of irrigation events. This can be an effective and simple way to optimize irrigation. Because it is qualitative, accuracy of the soil moisture sensor is less important because the fill point is determined by looking at changes in soil moisture and not the actual soil moisture itself. This in some ways can be more efficient because lower cost soil moisture sensors can be used without calibration. While the fill point method can be easy to implement and is widely used for many crops, the mass balance method however can better optimize the irrigation, provide better control of salinity build up, and minimize the negative impacts of over-irrigation.

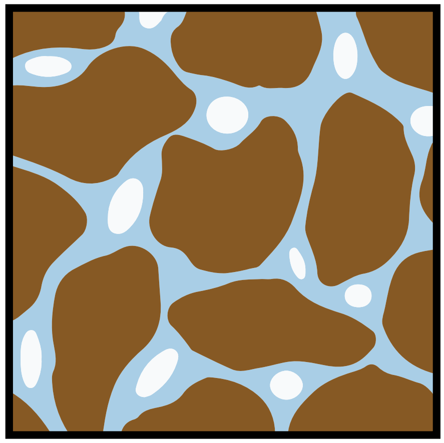
Mass Balance Irrigation Scheduling

The mass balance method (sometimes called scientific irrigation scheduling) is an irrigation schedule determined by calculating how much water is needed based on accurate soil moisture readings and from the soil properties. Equations [1], [2] and [3] can help to determine how much water to apply. The following are terms commonly used in soil hydrology:

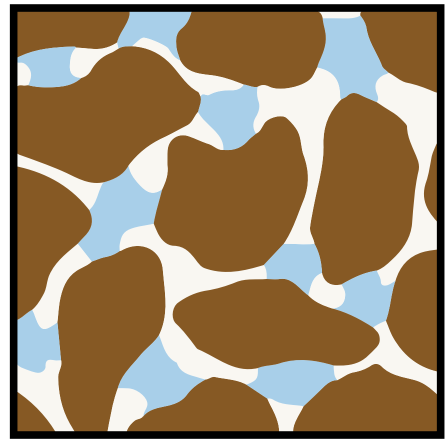
Soil saturation (θ_{SAT}) refers to the situation where all the soil pores are filled with water. This occurs below the water table and in the unsaturated zone above the water table



Soil saturation θ_{SAT}



Field capacity θ_{FC}



Permanent wilting point θ_{PWP}

after a heavy rain or irrigation event. After the rain event, the soil moisture (above the water table) will decrease from saturation to field capacity.

Field Capacity (θ_{FC}) refers to the amount of water left behind in soil after gravity drains saturated soil. Field capacity is an important hydrological parameter for soil because it can help determine the flow direction. Soil moisture values above field capacity will drain downward recharging the aquifer/water table. Also, if the soil moisture content is over field capacity, surface runoff and erosion can occur. If the soil moisture is below field capacity, the water will stay suspended in between the soil particles from capillary forces. The water will basically only move upward at this point from evaporation or evapotranspiration.

Permanent Wilting Point (θ_{PWP}) refers to the amount of water in soil that is unavailable to the plant.

Allowable Depletion (θ_{AD}) depletion represents the amount of soil moisture that can be removed by the crop from the soil before the crop begins to stress.

Lower soil moisture Limit (θ_{LL}) is the soil moisture value below which the crop will become stressed because it will have insufficient water. When the lower limit is reached, it is time to irrigate.

Maximum Allowable Depletion (MAD) is the fraction of the available water that is 100% available to the crop. MAD can depend on soil or crop type.

Available Water Capacity (θ_{AWC}) is the amount of water in the soil that is available to the plant.

The lower soil moisture limit is a very important value because dropping to or below this value will affect the health of the crops. The equations below show how to calculate the lower soil moisture limit and the soil moisture target for irrigation optimization.

$$\theta_{AD} = (\theta_{FC} - \theta_{PWP})\ x\ MAD \quad [1]$$

$$\theta_{AWC} = \theta_{FC} - \theta_{PWP} \quad [2]$$

$$\theta_{LL} = \theta_{FC} - \theta_{AD} \quad [3]$$

Example

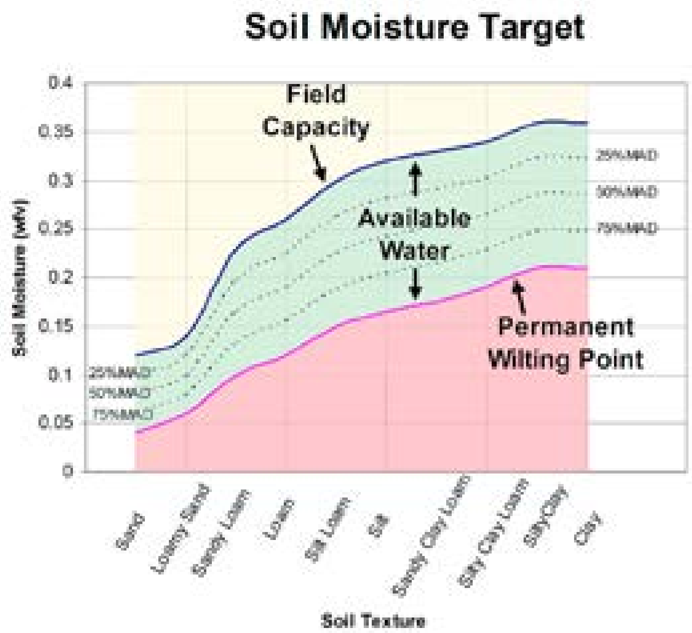
The soil is a silt, the MAD is 50%, and the soil moisture is 20% throughout the root zone which is down to 24 cm. The sprinkler is 75% efficient. How much water should be applied?

Answer: From the table above, the MAD = 0.5. From the graph (or a soil survey) the permanent wilting point (θ_{PWP}) = 16% and the field capacity (θ_{FC}) is 32%. Using the three equations above, the optimal soil moisture is 24% to 32%. $\theta_{FC} - \theta$ = 32% – 16% = 16%. Therefore, the soil needs to be irrigated to increase the soil moisture by 16% down to 24 cm, 16% X 24 cm = 3.8 cm of water applied.

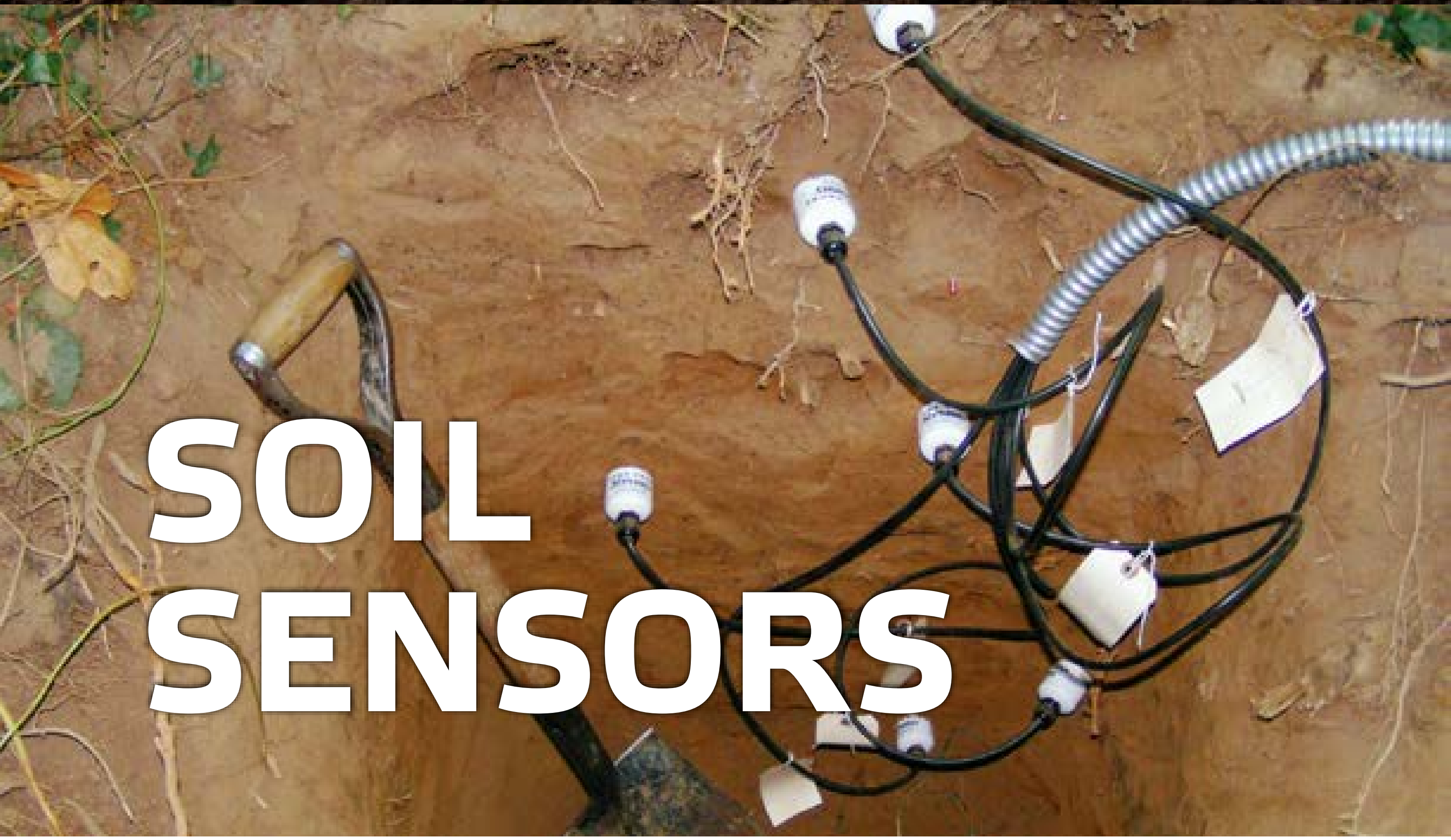
If the sprinkler is 75% efficient then 3.8 cm/0.75 = 5.12 cm of water should be applied. Note the rate of water coming out of the sprinkler should not exceed the infiltration rate of the soil and the run time of the sprinklers would depend on the specification of the sprinkler.

Crop	Maximum Allow-able Depletion (MAD)	Effective Root Depth (Inches)
Strawberry	50%	12
Table beet	50%	18
Green beans	50%	18
Carrot	50%	18
Blueberries	50%	18
Leafy greens	40%	18
Cauliflower	40%	18
Sweet corn	50%	24
Cucumber	50%	24
Peppermint	35%	24
Potatoes	35%	35
Apples	75%	36
Winter squash	60%	36
Grass	50%	7

Typical maximum allowable depletion based on crop and effective root zone depth. Taken from Smesrud 1998. Note that these values may be region or crop type specific.



This graph can be used to help determine the soil moisture targets based on soil texture. Soil texture is determined by the percentages of sand, silt, and clay using the soil textural triangle. The actual MAD, field capacity and permanent wilting point varies with region, soil morphologies, and the crop. Note that these are general trends.



SOIL SENSORS

With all the different types of soil sensors and measurement technologies on the market and the different technologies that they employ, choosing the right one can be a confusing and time consuming process. Here we outline the different types of soil sensors available as well as their advantages and disadvantages.

Across the many different applications that soil sensors are used for, the primary attribute involved is soil moisture. Soil moisture sensors measure the volumetric water content in soil indirectly by using some other property of the soil, such as electrical resistance, dielectric constant, or interaction with neutrons as a proxy for the moisture content. The relation between the measured property and soil moisture must be calibrated and may vary depending on environmental factors such as soil type, temperature, and salinity (electrical conductivity).

Whereas soil moisture sensors measure volumetric water content, another class of sensors such as tensiometers and gypsum blocks measure water matric potential—the pressure it takes to pull water out of the soil.

Volumetric Water Content Sensors

Sensors that measure the volumetric water content are typically referred to as soil moisture sensors. "Volumetric Water Content" or VWC is a measure of the amount of water held in a soil expressed as a percentage of the total mixture, and is often called simply "soil moisture". The amount of water that can be stored by a soil and its availability to plants both depend on soil type.

Soil moisture is an important attribute to measure for many applications (not limited to irrigation). There are several methods and technologies for measuring soil moisture in sensors.

Tensiometers (Soil Matric Potential Sensors)

Tensiometers measure the soil water potential or matric potential. Soil matric potential is the pressure it takes to pull water out of the soil and is an indicator of stress to plants and crops. It can be used to determine soil water fluxes and available water held in the soil.

Single-Point Measurement

Most soil sensors are single-point sensors, which means they take a measurement (or series of measurements if more than one soil attribute is being measured) at a single location. Examples of single-point measurement sensors include the ECH20 EC-5 (Meter group), CS650 (Campbell Scientific Intruments), Watermark (Irrometer) and the **Stevens HydraProbe**.

HydraProbe

Reliable soil insight

HydraProbe is a rugged soil sensor with patented technology that provides continual, consistent accuracy measuring the three most significant soil parameters simultaneously—moisture, salinity and temperature.

As the most scientifically researched soil sensor available, it has been depended on by the USDA, NOAA, farmers, leading irrigation companies, and many universities for over 25 years. It's been engineered to be exceptionally rugged and will provide data you can trust year after year.

The HydraProbe's "dielectric impedance" measurement principle differs from TDR, capacitance, and frequency soil sensors by taking into account the energy storage and energy loss across the soil area using a 50 MHz radio frequency wave.

Unlike other soil sensors, this unique, patented method separates the energy storage (real dielectric permittivity) from the energy losses (imaginary dielectric permittivity). The HydraProbe's detailed mathematical and signal characterization of the dielectric spectrum helps factor out errors in the soil moisture measurement such as temperature effects, errors due to salinity, and soil type.

Patented Sensor Technology

HydraProbe uses unique "Coaxial Impedance Dielectric Reflectometry" to provide consistent long-term accuracy of moisture, bulk EC and temperature in any soil type. This also provides low inter-sensor variability, so every sensor measures the same without the need to calibrate.

Soil Profiling Probes

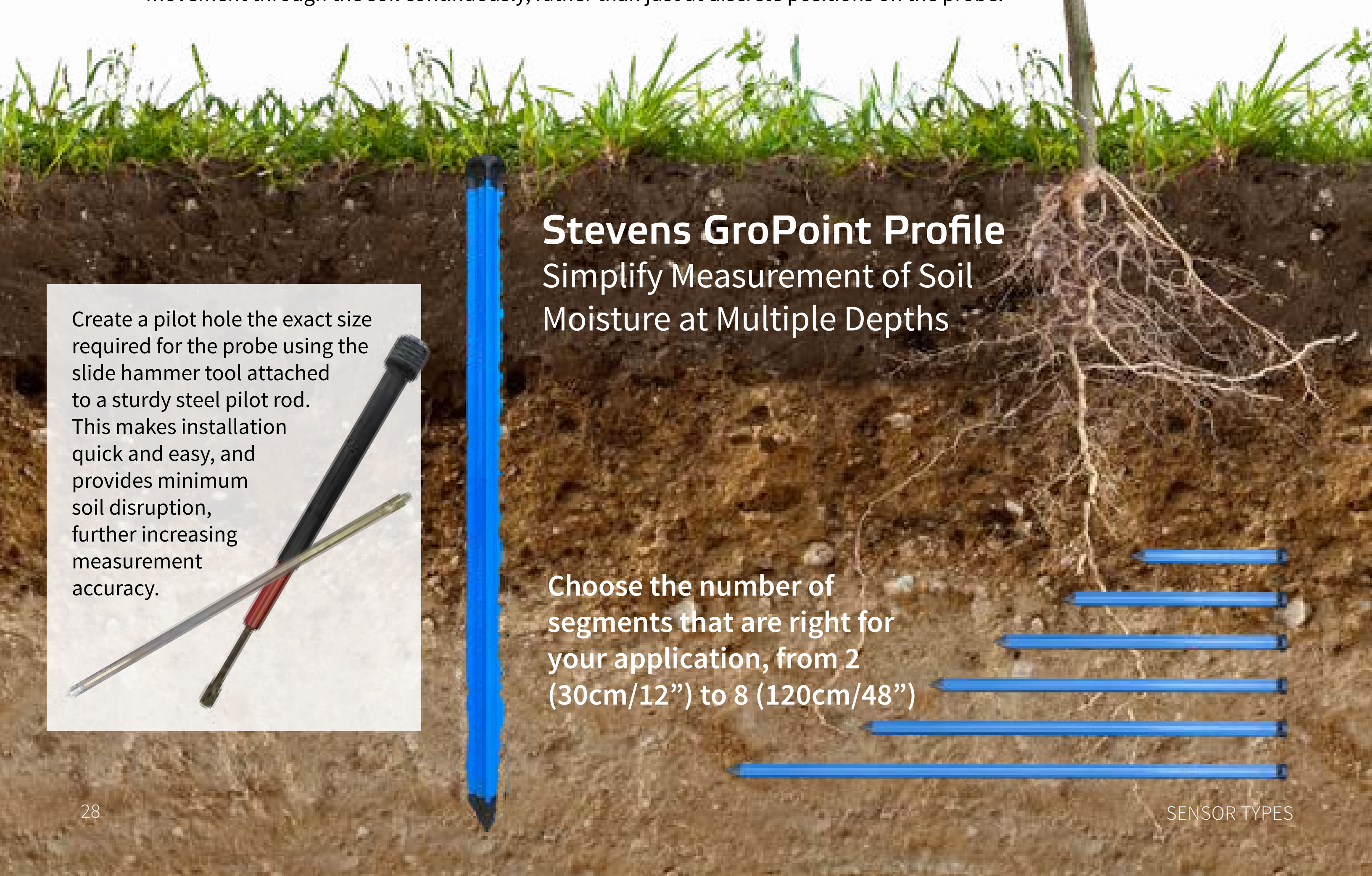
Profiling probes measure soil moisture (and often other attributes like temperature) across a vertical soil profile, typically spanning a range of 30cm to 120cm. Soil profiling probes typically consist of multiple single-point sensors housed within an elongated enclosure, although some, like the GroPoint Profile feature modular segments which form a single antenna for continuous measurement across the entire length. A soil profiling probe is installed in the soil vertically.

Measuring soil moisture at multiple depths is important for optimizing irrigation, as it helps to characterize the penetration of water throughout the root zone.

The chief advantage of using a soil profiling probe is the elimination of the cost of multiple single-point sensors and the need to excavate a large hole in order to bury them at the appropriate depths.

Profiling probes are usually manufactured as parallel pairs of rings along a probe or rod, and are typically installed in plastic or PVC access tubes where the electric field between the sensor and the soil must pass through the plastic tube. This design imposes uncertainties as to whether the access tube, soil, or meniscus that can form on the outside of the access tube following rainfall or irrigation, is being measured. The volume of measurement and its geometry are also uncertain (Topp 2003). Profiling probes which don't require an access tube (such as the **Stevens GroPoint Profile**) will typically provide greater accuracy for this reason.

- Measure moisture and temperature at multiple depths using a single probe.
- No excavation required.
- Installs quickly with minimal soil disruption using a pilot rod and slide hammer tool.
- Measures average moisture across each segment. This unique feature allows measuring the water movement through the soil continuously, rather than just at discrete positions on the probe.



Stevens GroPoint Profile

Simplify Measurement of Soil Moisture at Multiple Depths

Create a pilot hole the exact size required for the probe using the slide hammer tool attached to a sturdy steel pilot rod. This makes installation quick and easy, and provides minimum soil disruption, further increasing measurement accuracy.

Choose the number of segments that are right for your application, from 2 (30cm/12") to 8 (120cm/48")

Permanent and Semi-Permanent Installations

Soil sensors are typically buried and left for continuous long-term monitoring (if connected to a data logger or wireless remote telemetry) or on-demand monitoring (using a handheld reader). They can remain buried indefinitely, subject to the durability of the sensor and especially the cable.

Portable Soil Sensors

Portable soil sensors are designed to provide the user an instantaneous reading of soil moisture in a battery-powered, self-contained unit that can be taken anywhere. Readings are displayed either on an integrated display, or on the user's smartphone which communicates with the sensor unit wirelessly (Bluetooth or WiFi).

Take soil measurements anywhere for those applications not requiring a permanent soil monitoring system. Your Apple or Android device communicates wirelessly with the HydraGO using Bluetooth.

HydraGO features a rugged, engineered resin housing that contains a rechargeable battery good for a full day's heavy use. It comes with a detachable ergonomic pole so it can be inserted without bending over.

Simply insert the probe into the soil, and tap the "Sample" button in the HydraGO app. The app will display soil moisture content, temperature, conductivity, and dielectric permittivity on-screen for immediate viewing.

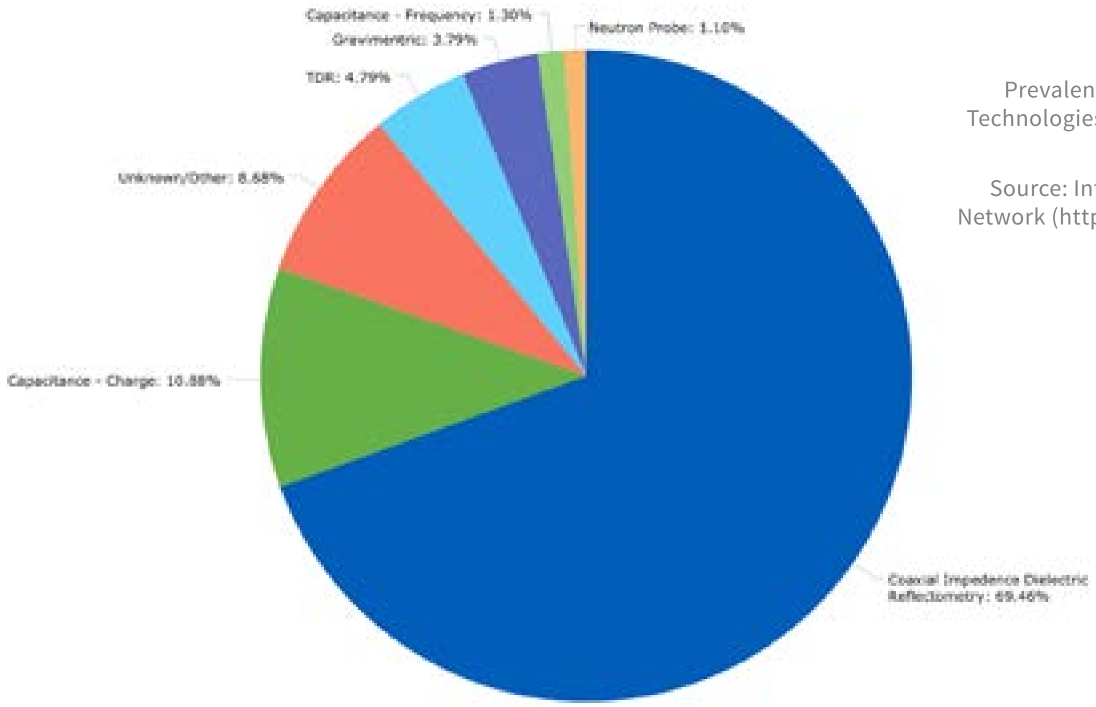
All data can be saved and emailed as a .CSV file for analysis in Excel. Notes and location names can be added to the data records.

HydraGO uses the same patented soil sensor as the HydraProbe.

Soil Sensor Technologies

There are several different technologies used to measure the volumetric water content of soil in today's commercial electromagnetic soil sensors. They differ primarily in the accuracy provided and cost to manufacture, but also affect the overall durability of the probe.

Technology	Principal of Operations	Physical Measurement	Basis for Soil Moisture	Typical Frequency
Time Domain Reflectometry (TDR)	Measures time for an electromagnetic wave to travel out and be reflected back from the end of the probe. Transmission line oscillators generate a voltage pulse inside the sensor head which propagates along the waveguide, with the arrival of the reflected pulse triggering the next pulse. The number of voltage pulse reflections over a certain time interval is recorded and a period (microseconds) that is inversely related to the number of reflections per second is output. The period is directly related to volumetric soil moisture via empirical calibration.	Time for a voltage pulse to travel along parallel rods and reflect back	Apparent permittivity	1000 MHz
Time Domain Transmissometry (TDT)	Measures electromagnetic wave time of travel in one direction over the length of the probe.	Time for a voltage pulse to travel the length of looped or closed circuit rod	Apparent permittivity	150 to 2000 MHz
Capacitance (Frequency) / Frequency Domain Reflectometry (FDR)	Measures the change in frequency of an electromagnetic wave traveling out and being reflected back to the sensor head.	Difference between output wave and the return wave frequency	Apparent permittivity	150 MHz
Capacitance (charge)	Measures the charge time of a capacitor that uses the medium surrounding the probe as the dielectric material.	Capacitor charge time	Capacitance	n/a
Differential amplitude / Simplified Impedance	Measures the difference between the incident signal and the reflected signal to calculate impedance and apparent permittivity.	Difference in reflected amplitudes	Apparent permittivity	75 MHz
Coaxial Impedance Dielectric Reflectometry	Measures the ratio of reflected voltage to an incident voltage of a 50 MHz signal, which is dependent on the impedance of medium between the probe rods. The tines serve as wave guides for a 50-MHz-signal that is generated in the probe body. When the tines are pushed into soil material, the probe measures the behavior of an electromagnetic wave in the soil between conductors.	Ratio of reflected amplitudes to measure the impedance	Real dielectric permittivity	50 MHz
Neutron Probe	Based on measuring fast-moving neutrons that are slowed (thermalised) by an elastic collision with existing hydrogen particles in the soil.	Collisions of emitted neutrons with hydrogen atoms	Apparent permittivity	n/a
Gravimetric Soil Analysis	Gravimetric water content is measured by weighing a soil sample, drying the sample to remove the water, then weighing the dried soil.	Difference in mass (weight) of soil before and after being dried to remove all water	Mass of water	n/a



Prevalence of Soil Measurement Technologies in Soil Moisture Networks Worldwide.

Source: International Soil Moisture Network (https://ismn.geo.tuwien)ac.at), 2016

Capacitance (Charge)

Capacitance determines the dielectric constant (Ka) by measuring the charge time of a capacitor, which uses soil as a dielectric medium. The charge time of the capacitor is a linear function of the dielectric permittivity of the soil. Capacitance sensors measure the dielectric constant of the soil in order to find its water content. Since the dielectric constant of water is much higher than that of air or soil minerals, the dielectric constant of the soil is a sensitive measure of water content.

The sensor applies a voltage and creates a circuit (flow of electrical current). This current will oscillate or vibrate at a (resonant) frequency that is dependant on the amount of water in the soil. When you add water to the soil its ability to hold charge (capacitance) changes, which then changes the vibration (resonant frequency) of the circuit.

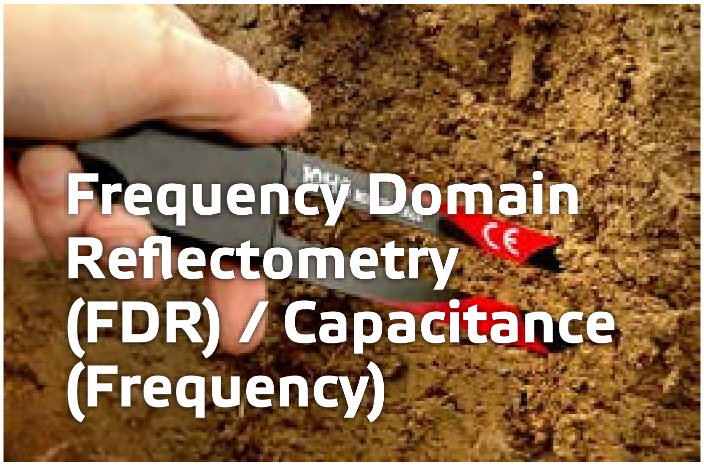
The probe measures this change in (resonant frequency), and uses it to determine the soil moisture content.

Because of the difference in the dielectric constant between water and air and the very small amount of soil the sensor evaluates, any air gap around the sensor will cause large errors. Capacitance sensors need to have excellent contact with the medium they are measuring with no air gaps.

The volume of measurement is dependent on sensor size with most sensors in the order of 5cm to 10cm in length but one sensor is 3m in length. The field of influence is greatest at the sensor to substrate interface and declines rapidly from there. Generally, the field of influence is approximately 1cm distance from the sensor. Given a 3m length sensor with 1cm distance into the soil, extreme caution needs to be taken with installation to ensure no air gaps.

Capacitance probes need to be calibrated for the specific soil in which they will be placed.

The advantage of capacitance sensors is the cost of electronic components is relatively low. Because of this, they are the most common fully electronic soil water sensors for non-critical moisture measurements.



Frequency Domain Reflectometry (FDR) / Capacitance (Frequency)

Capacitance can be measured from the change in frequency of a reflected radio wave or resonance frequency (Kelleners 2004). This method of measurement uses an oscillator to propagate an electromagnetic signal through a metal tine or other wave guide. The difference between the output wave and the return wave frequency is measured to determine soil moisture.

FDR probes are considered accurate but must be calibrated for the type of soil they will be buried in. They offer a faster response time compared to Time Domain Reflectometer (TDR) probes.

These sensors are often referred to as frequency domain reflectometers (FDR), however the term FDR is often misused because most frequency sensors are using a single frequency and not a domain of frequencies. Other capacitance probes and amplitude impedance-based probes are often mistakenly referred to as "FDRs".

FDR sensors need to have good contact with the medium they are measuring with no air gaps. The volume of measurement is dependent on sensor size with most sensors in the order of 5cm to 10cm in length but one sensor is 3m in length. The field of influence is greatest at the sensor to substrate interface and declines rapidly from there. Generally, the field of influence is approximately 1cm distance from the sensor. Given a 3m length sensor with 1cm distance into the surrounding medium, extreme caution needs to be taken with installation to ensure there are no air gaps.

FDR probes need to be calibrated for the specific soil in which they will be placed.

Coaxial Impedance Dielectric Reflectometry

The Coaxial Impedance Dielectric Reflectometry (also referred to as "Ratiometric Coaxial Impedance Dielectric Reflectometry") method of soil moisture measurement employs an oscillator to generate an electromagnetic signal that is propagated through the sensor by metal tines and into the soil. It characterizes the ratio of the amplitudes of reflected radio waves at 50 MHz with a coaxial wave guide. A numerical solution to Maxwell's equations first calculates the complex impedance of the soil and then delineates the real and imaginary dielectric permittivity (Seyfried 2004, Campbell 1990). The mathematical model that delineates the real and imaginary component from the impedance of the reflected signal resides in the microprocessor inside the sensor. These computations are based on the work of J. E. Campbell at Dartmouth College (Campbell 1988, Campbell 1990, Kraft 1988).

The term “ratiometric” refers to the process by which the ratio of the reflected signal over incident signal is first commutated which eliminates any variability in the circuit boards from one probe to the next. This step is performed on several reflections. The term “coaxial” refers to the metal wave guide that is inserted into the soil. It has three outer tines with a single tine in the center that both receives and emits a radio frequency at 50 MHz. “Impedance” refers to the intensity of the reflected signal, and “dielectric reflectometer” refers to the reflected signal that is used to measure the dielectric.

The **Stevens HydraProbe** is the only commercially available sensor to use the Coaxial Impedance Dielectric Reflectometry method along with complex computations in soil measurement, resulting in very high measurement accuracy through the lifetime of the sensor. One advantage is that sensors using this technology do not require calibration for most soils.

Unlike most soil moisture methods, Coaxial Impedance Dielectric Reflectometry measures both the real and the imaginary components of the dielectric permittivity as separate parameters. The sensor bases the soil moisture calibration on the real dielectric permittivity while most other soil moisture methods base their soil moisture estimation on the apparent permittivity which is a combination of the real and imaginary components. (Logsdon 2010). Basing the soil moisture calibration on the real dielectric permittivity instead of the apparent permittivity has many advantages. Because the Coaxial Impedance Dielectric Reflectometry separates the real and imaginary components, soil moisture calibrations are less affected by soil salinity, temperature, soil variability and inter-sensor variability than other methods.

Complex mathematical computations performed by an onboard microprocessor process the reflected signal measurements to accurately determine the soil’s dielectric permittivities, the key parameters behind the soil moisture and bulk EC measurement. Because the soil measurement computations are performed by a microcontroller inside the sensor, the probe can output results in standard engineering units.

Time Domain Reflectometry (TDR)

Sensors that use the Time Domain Reflectometry (TDR) are somehwhat similar to FDR probes, but the mechanics behind the measurement system are different. TDR sensors use parallel rods, acting as transmission lines. A voltage is applied to the rods and reflected back to the sensor for analysis. The speed or velocity of the voltage pulse along the rod is related to the apparent permittivity of the substrate (Blonquist 2005-A). In relatively wet soil the velocity of the pulse is slower than in drier soil.

Examples of this sensor include the Campbell Scientific CS650 and the IMKO Trime-Piko 32.

TDR probes are repeatable and do not require a large amount of maintenance. Since soil dielectric properties are affected by salt content, their readings can be affected by salinity. However, many probes independently measure EC and use this to compensate for the effect of salinity on moisture readings. TRD probes respond quickly to varying soil moisture.

Similar to capacitance and frequency domain sensors, TDR sensors must have good contact with the soil, because any air gaps will lead to erroneous measurements. The measurement volume of TDR sensors depends on the length of the rods. The probability of air gaps forming during installation increases with longer rods. Additionally, longer rods will measure a greater length of the soil profile and moisture content can vary significantly from shallow to deeper depths making interpretation of data difficult.

TDR sensors should not be used in high saline soils or soils with high bulk electrical conductivity or high attenuation. In soils with high EC values, the voltage pulse is not reflected back along the rod and, therefore, is not measured. The pulse is attenuated beyond the length of the rod. TDR probes have been found to have errors in soils with EC values of 1.32 dS/m (McIsaac 2010).

Time Domain Transmissometry (TDT) is similar to TDR, however it measures the transmission, rather than reflection, of a pulse along a looped, or closed circuit, rod. TDT measures the time taken for an electromagnetic wave to propagate (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 threshold is detected at the other end of the transmission line. There is no complex waveform analysis as with TDR. The shape of the transmitted waveform is not relevant, but a measurement of the pulse travel time through the transmission line will allow an estimate of the dielectric constant of the medium.

Similar to TDR, a pulse measured via TDT will be slower in wetter soils than drier soils. The velocity of the pulse is related to the dielectric constant.

TDT sensors, being a more refined version of TDR, generally provide greater accuracy and lower power consumption than TDR sensors. However, they are usually more expensive.

Examples of this type of sensor include the GroPoint sensor family and the Acclima TDT Soil Moisture Sensor.

Neutron Probe

Neutron probes are another way to measure soil moisture content. A probe inserted in the ground emits low-level radiation in the form of neutrons. These collide with the hydrogen atoms contained in water, which is detected by the probe. The more water content in the soil, the more neutrons are scattered back at the device.

Neutron probes are very accurate measurement devices when used properly but are expensive compared to most other measurement methods and generally have to be registered with the federal government due to radioactive elements used to emit the neutrons.

Gypsum Block

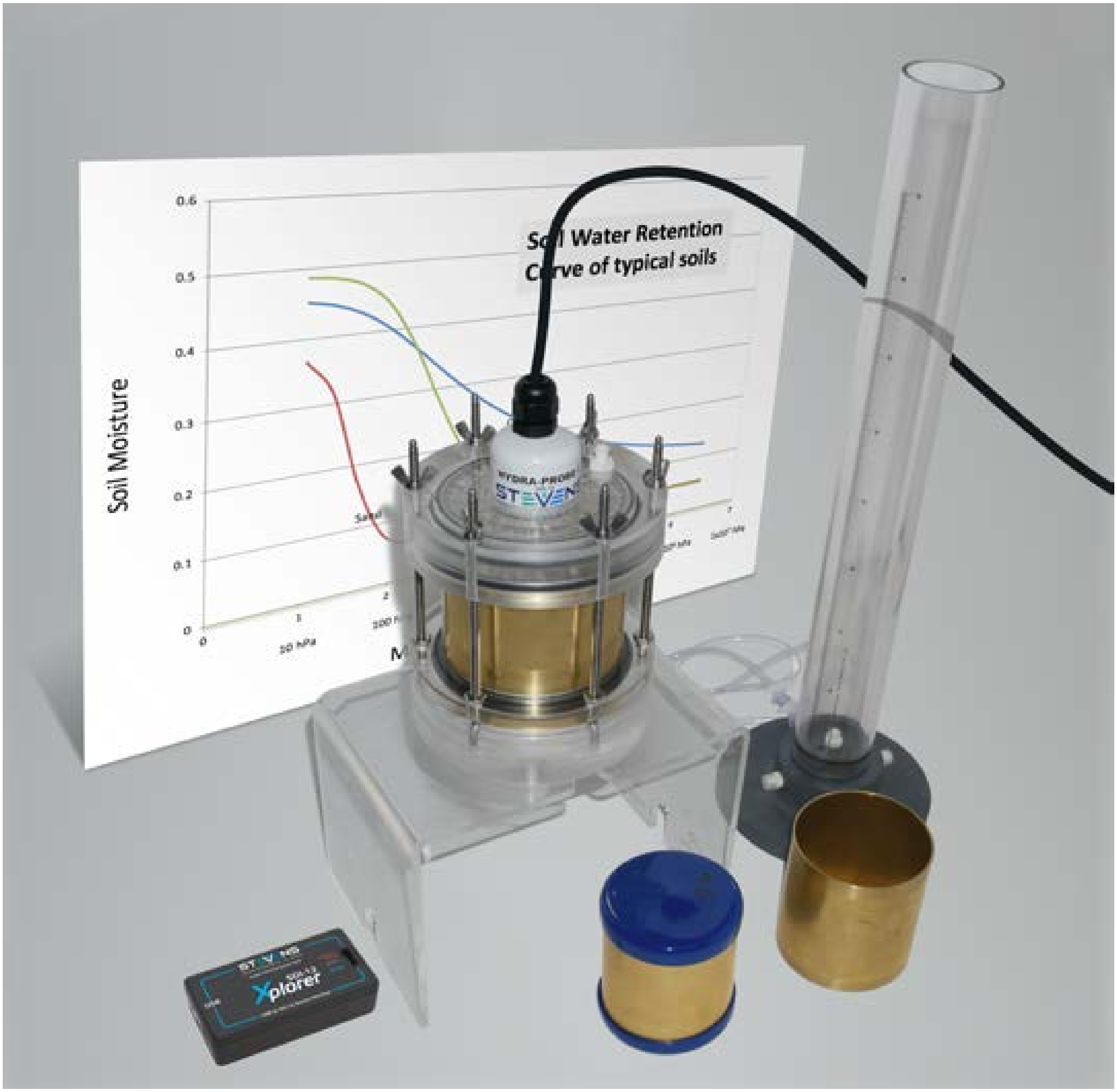
Gypsum blocks use two electrodes placed into a small block of gypsum to measure soil water tension. Wires connected to the electrodes are connected to either a portable hand-held reader or a data logger. The amount of water in the soil is determined by the electrical resistance between the two electrodes within the gypsum block. More water present in the soil will reduce the resistance, while less water will increase it.

While gypsum blocks can be relatively inexpensive and easy to install compared to other types of soil sensors, they have to be replaced periodically as the gypsum disintegrates. Gypsum blocks are also more sensitive to having readings thrown off by soil with high salinity (electrical conductivity).

Determining Soil Moisture Content Without Sensors

A variety of techniques are available for direct measurement of soil water content and most of them are based on the fact that water is removed from soil by evaporation, leaching, or chemical reaction. One of the most common methods of soil water content determination is gravimetric method with oven drying. This method involves weighing a moist sample, oven drying it at 105°C for 24 to 48 hours, reweighing, and calculating the mass of water lost as a percentage of the mass of the dried soil.

A tempe cell can also be used to determine volumetric water content gravimetricallty. A tempe cell uses a gravimetric method to measure soil moisture to obtain the actual volumetric water content, and develop a soil moisture calibration equation to validate and/or program into soil moisture sensors. The **Stevens Tempe Cell System** can employ five different methods to eliminate the uncertainties from soil moisture measurements and achieve the highest level



The Stevens Tempe Cell System

of accuracy. In addition, the system's outputted data can be used to develop a soil-specific calibration curve, and to develop an algorithm to determine the soil's matric potential using the HydraProbe.

Soil Sensor Calibration

With the exception of sensors based on the Coaxial Impedance Dielectric Reflectometry method of measurement (i.e. the Stevens Hydraprobe), all sensors measuring the dielectric constant require calibration to obtain accurate volumetric soil moisture. Most manufacturers provide a universal "factory calibration", others provide calibration(s) based on soil texture (normally sand, silt or clay) and nearly all recommend field calibration.

In almost every case, a sensor's published accuracy specification can only be achieved with soil-specific field calibration.

Soil moisture sensors are typically delivered from a manufacturer with a percentage output. This value is often derived from a generic soil probably from the yard where the manufacturer is located. Needless to say, this calibration will be different from your particular soil.

Field calibration is not as simple as applying a correction factor. Soil moisture must be measured at different levels of soil moisture content to develop a relationship—an equation to correct the sensor measurements.

Manufacturers of soil water content sensors supply their product with an output registering volumetric water content (VWC), typically expressed as a percentage. But where does this number come from and what does it actually mean?

In all likelihood, the output value from the sensor will not be equal to the actual VWC of your particular soil. The output value is not entirely incorrect, per se, rather it is an estimation of the actual, or true, value of VWC of your soil. Where this number comes from, and how it is derived, can be a major source of error in soil moisture measurements.

The second biggest source of error is sensor to sensor variation. There will inevitably be slight variations in sensor output due to electronics and the manufacturing process. Even a variation of 1% to 2% VMC can cause serious miscalculations in scientific modelling, catchment water budgets, or irrigation scheduling. Note that when calibrating your soil moisture sensor, you will need to consider an acceptable level of accuracy. Many researchers calibrate a particular model of soil moisture sensor for each different type of soil or substrate they will encounter (for example, a sandy soil versus a loam soil). However, soil moisture sensors are never exactly the same even if they are the same model or produced from the same manufacturer. This leads to sensor to sensor variation in measurements. Therefore, many researchers calibrate every single soil moisture sensor for each type of soil or substrate they will be measuring.

Note that due to how Coaxial Impedance Dielectric Reflectometry measures both the real and imaginary dielectric permittivity, sensor-to-sensor variation is not a problem.

Sensor Accuracy

The accuracy stated by sensor manufacturers is not necessarily a measurement in a real application, but is a measurement of the dielectric permittivity of water based on a specified range. Accuracy is influenced by temperature, salinity, mineralogy, and more. But in a controlled environment, the stated accuracy measurement of sensors makes assumptions about the imaginary dielectric permittivity. It does not and cannot take into account all these real application variables that influence the imaginary permittivity. This is why stated accuracy may not align with stated (if disclosed) inter-sensor variability of such sensors. Manufacturers may also not clearly state the dielectric range of their stated accuracy.

Because a sensor's claimed accuracy is based on the real dielectric permittivity in water only, making an assumption of the imaginary dielectric permittivity, and not taking take into account the variables of soil properties, most sensor manufacturers recommend calibration at each site, and often indicate that accuracy is based on such a site-specific calibration process.

Only if the real and imaginary dielectric permittivities are measured can a sensor automatically calibrate for most soil types and therefore provide an accuracy that matches that observed in a controlled environment and across all sensors produced.

Most soil moisture sensor manufacturers don't typically discuss inter-sensor variability, and instead only focus on accuracy as measured in the lab. But this inter-sensor variability impacts the confidence that climatologists, scientists, and international soil monitoring networks can have that a measurement at one place on earth can be compared to a measurement at another place on earth. Or that two or more sensors of the same make and model side-by-side will provide the same measurements.

The range of the real dielectric permittivity used by sensor manufacturers to state accuracy may not be the full dielectric range (that is, 0 to 80). This means that when the accuracy is based on a limited dielectric permittivity range such as 0 to 50, the accuracy of such sensors can be significantly compromised when the moisture is above 40% WFV. The calibration will be less applicable to different soils, with different moisture levels, than what was used for calibration

For most users, accuracy is hard to see. Actual soil moisture percentage using the gravitational method, while the most accurate, is time-consuming to calculate, prone to error, and a difficult process to determine. Since the accuracy of soil conditions cannot be seen like other environmental sensor such as water level and rainfall, most users just take what is stated in a sensor's official technical specification as true without question. While that is the easiest approach, one must be careful to choose the right sensor measurement technology for their application.

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DATA COLLECTION
SMART SENSORS

Glossary

A

A– Name of a soil horizon. Horizon "A" is a top soil rich in organic matter. Typically found 2 to 10 inches below the surface.

Aeration – The exchange of air in soil with air from the atmosphere. The air in a well aerated soil is similar to that in the atmosphere; the air in a poorly aerated soil is considerably higher in carbon dioxide and lower in oxygen.

Alfisols – One of the 12 orders of soil. Alfisols are in semiarid to moist areas. They formed under forest or mixed vegetative cover and are productive for most crops.

Allowable depletion – Represents the amount of soil moisture that can be removed by the crop from the soil before the crop begins to stress.

Aggregate – Many fine particles held in a single mass or cluster. Natural soil aggregates, such as granules, blocks, or prisms, are called peds. Clods are aggregates produced by tillage or logging.

Alkali (basic) soil – A soil having so high a degree of alkalinity (pH 8.5 or higher), or so high a percentage of exchangeable sodium (15 percent or more of the total exchangeable bases), or both, that plant growth is restricted.

Allowable depletion – Represents the amount of soil moisture that can be removed by the crop from the soil before the crop begins to stress.

Alluvium – Material, such as sand, silt, or clay, deposited on land by streams.

Andisols – One of the 12 orders of soil. Andisols tend to be highly productive soils. They are common in cool areas with moderate to high precipitation, especially those areas associated with volcanic materials.

Apparent permittivity – A measure of the combination of both the real and imaginary dielectric permittivity. Most soil sensors determine soil moisture by measuring this.

Aridisols – One of the 12 orders of soil. Aridisols are soils that are too dry for the growth of mesophytic plants. They often accumulate gypsum, salt, calcium carbonate, and other materials that are easily leached from soil in more humid environments. Aridisols are common in the world's deserts.

Available water capacity (AWC) – The amount of water in the soil that is available to the plant.

B

B – Name of a soil horizon. Horizon "B" is a subsoil, the most diverse horizon and the horizon with the most sub classifications. Typically found 10 to 30 inches below the surface. B horizons are zones of accumulation of soil constituents (such as clay, iron, or salts).

Basal till – Compact glacial till deposited beneath the ice (Lodgement Till is preferred).

Base saturation –The degree to which material having cation-exchange properties is saturated with exchangeable bases (sum of Ca, Mg, Na, K), expressed as a percentage of the total cation-exchange capacity.

Bedding planes – Fine stratifications, less than 5 millimeters thick, in unconsolidated alluvial, eolian, lacustrine, or marine sediments.

Bedding system – A drainage system made by plowing, grading, or otherwise shaping the surface of a flat field. It consists of a series of low ridges separated by shallow, parallel dead furrows.

Bedrock – The solid rock that underlies the soil and other unconsolidated material or that is exposed at the surface.

Bisequum – Two sequences of soil horizons, each of which consists of an illuvial horizon and the overlying eluvial horizons.

Bk horizon – B horizons that display an accumulation of pedogenic calcium carbonate

Blowout – A shallow depression from which all or most of the soil material has been removed by wind. A blowout has a flat or irregular floor formed by a resistant layer or by an accumulation of pebbles or cobbles. In some blowouts the water table is exposed.

Bog – Waterlogged, spongy ground, consisting primarily of mosses, containing acidic, decaying vegetation such as sphagnum, sedges, and heaths, that may develop into peat. Compare – fen, marsh, swamp.

Bottom land – The normal floodplain of a stream, subject to flooding.

Boulders – Rock fragments larger than 2 feet (60 centimeters) in diameter.

Bulk density – A measure of the weight of the soil per unit volume (g/cc), usually given on an oven-dry (110°C) basis.

Bw horizon – B horizons that display the initial stages of pedogenesis such as the development of soil structure, oxidation.

C

C – Name of a soil horizon. Horizon "C" is made up of weathered/aged parent material and can usually be found 30 to 48 inches below the surface.

Calcareous soil – A soil containing enough calcium carbonate (commonly combined with magnesium carbonate) to effervesce visibly when treated with cold, dilute hydrochloric acid.

Caliche – A more or less cemented deposit of calcium carbonate in soils of warm-temperate, sub-humid to arid areas. Caliche occurs as soft, thin layers in the soil or as hard, thick beds just beneath the solum, or it is exposed at the surface by erosion.

Capillary water – Water held as a film around soil particles and in tiny spaces between particles. Surface tension is the adhesive force that holds capillary water in the soil.

Carbon dioxide (CO_2) – Carbon Dioxide is a gas that is found naturally in the atmosphere, in the human bloodstream and is used by plants as part of photosynthesis. However, because of its ability to absorb light and stay in the atmosphere for extended periods of time it has been thought that CO_2 may be one factor in global warming.

Carbon flux, soil – Also known as soil respiration, this is the result of bacteria and other microorganisms in the soil consuming organic material or decaying plant matter, which in turn produces CO_2 that is off-gassed into the atmosphere and groundwater.

Carbon sink – A carbon sink is anything that is collecting more CO_2 from the atmosphere than it's releasing. Major carbon sinks include the world's oceans and young plants and forests. Carbon sequestering can be used to further enhance the ability of these sinks to capture carbon from the atmosphere.

Catena – A sequence, or "chain," of soils on a landscape that formed in similar kinds of parent material but have different characteristics as a result of differences in relief and drainage.

Cation – An ion carrying a positive charge of electricity. The common soil cations are calcium, potassium, magnesium, sodium, and hydrogen.

Cation-exchange capacity – The total amount of exchangeable cations that can be held by the soil, expressed in terms of milliequivalents per 100 grams of soil at neutrality (pH 7.0) or at some other stated pH value. The term, as applied to soils, is synonymous with base-exchange capacity but is more precise in meaning.

Cement rock – Shaly limestone used in the manufacture of cement.

Channery soil – A soil that is, by volume, more than 15 percent thin, flat fragments of sandstone, shale, slate, limestone, or schist as much as 6 inches along the longest axis. A single piece is called a channer.

Chiseling – Tillage with an implement having one or more soil-penetrating points that shatter or loosen hard compacted layers to a depth below normal plow depth.

Clay – As a soil separate, the mineral soil particles less than 0.002 millimeter in diameter. As a soil textural class, soil material that is 40 percent or more clay, less than 45 percent sand, and less than 40 percent silt.

Clay film – A thin coating of oriented clay on the surface of a soil aggregate or lining pores or root channels. Synonyms: clay coating, clay skin.

Claypan – A slowly permeable soil horizon that contains much more clay than the horizons above it. A claypan is commonly hard when dry and plastic or stiff when wet.

Climax vegetation – The stabilized plant community on a particular site. The plant cover reproduces itself and does not change so long as the environment remains the same.

Coarse fragments – If round, mineral or rock particles 2 millimeters to 25 centimeters (10 inches) in diameter; if flat, mineral or rock particles (flagstone) 15 to 38 centimeters (6 to 15 inches) long.

Coarse textured soil – A soil with USDA Soil textures of loamy fine sand or coarser (loamy sand or sand).

Cobblestone (or cobble) – A rounded or partly rounded fragment of rock 3 to 10 inches (7.5 to 25 centimeters) in diameter.

Colluvium – Soil material, rock fragments, or both moved by creep, slide, or local wash and deposited at the base of steep slopes.

Complex slope – Irregular or variable slope. Planning or constructing terraces, diversions, and other water-control measures on a complex slope is difficult.

Complex – A map unit of two or more kinds of soil in such an intricate pattern or so small in area that it is not practical to map them separately at the selected scale of mapping. The pattern and proportion of the soils are somewhat similar in all areas.

Concretions – Grains, pellets, or nodules of various sizes, shapes, and colors consisting of concentrated compounds or cemented soil grains. The composition of most concretions is unlike that of the surrounding soil. Calcium carbonate and iron oxide are common compounds in concretions.

Congeliturbate – Soil material disturbed by frost action.

Conservation tillage – A tillage system that does not invert the soil and that leaves a protective amount of crop residue on the surface throughout the year.

Consistence – The feel of the soil and the ease with which a lump can be crushed by the fingers. Terms commonly used to describe consistence are:

- Loose: Noncoherent when dry or moist; does not hold together in a mass.
- Friable: When moist, crushes easily under gentle pressure between thumb and forefinger and can be pressed together into a lump.
- Firm: When moist, crushes under moderate pressure between thumb and forefinger, but resistance is distinctly noticeable.
- Plastic: When wet, readily deformed by moderate pressure but can be pressed into a lump; will form a “”wire” when rolled between thumb and forefinger.
- Sticky: When wet, adheres to other material and tends to stretch somewhat and pull apart rather than to pull free from other material.
- Hard: When dry, moderately resistant to pressure; can be broken with difficulty between thumb and forefinger.
- Soft: When dry, breaks into powder or individual grains under very slight pressure.
- Cemented: Hard; little affected by moistening.

Contour stripcropping – Growing crops in strips that follow the contour. Strips of grass or close-growing crops are alternated with strips of clean-tilled crops or summer fallow.

Control section – The part of the soil on which classification is based. The thickness varies among different kinds of soil, but for many it is that part of the soil profile between depths of 10 inches and 40 or 80 inches.

Coprogenous earth (sedimentary peat) – Fecal material deposited in water by aquatic organisms.

Corrosive – High risk of corrosion to uncoated steel or deterioration of concrete.

Cover crop – A close-growing crop grown primarily to improve and protect the soil between periods of regular crop production, or a crop grown between trees and vines in orchards and vineyards.

Crop susceptibility -A measurement of crop response to a unit of stress.

Crop water use rate – Maximum daily rate at which a crop can extract water from a moist soil to satisfy PET; controlled by stage of crop development.

D

Dense layer – A very firm, massive layer that has a bulk density of more than 1.8 grams per cubic centimetre. Such a layer affects the ease of digging and can affect filling and compacting.

Depletion volume – The amount of plant-available water removed from the soil by plants and evaporation from the soil surface.

Depth to rock – Bedrock is too near the surface for the specified use.

Dielectric constant – The ratio of the permittivity of a substance to free space. The value of the dielectric constant in air is 1 and in water the dielectric constant is approximately 80.

Dielectric permittivity – The ability of a substance to hold an electrical charge.

Dioxane (1,4-dioxane) – This clear organic, carcinogenic compound is oftentimes used as a solvent in manufacturing processes. It has been found in contaminated groundwater.

Diversion (or diversion terrace) – A ridge of earth, generally a terrace, built to protect downslope areas by diverting runoff from its natural course.

Drainage class (natural) – Refers to the frequency and duration of periods of saturation or partial saturation during soil formation, as opposed to altered drainage, which is commonly the result of artificial drainage or irrigation but may be caused by the sudden deepening of channels or the blocking of drainage outlets.

Drainage, surface – Runoff, or surface flow of water, from an area.

E

E – Name of a soil horizon. Horizon “E” has been leached of organic or mineral content and is light in color.

Effective root depth – The upper portion of the root zone where plants get most of their water. Effective root depth is estimated as one-half the maximum rooting depth.

Electrical conductivity (EC) – Measured in Siemens per meter, soil electrical conductivity is indicative of dissolved salts, dissolved solids, and fertilizers. It may also be indicative of very high pH conditions.

Eluviation – The movement of material in true solution or colloidal suspension from one place to another within the soil. Soil horizons that have lost material through eluviation are eluvial; those that have received material are illuvial.

Eolian soil material – Earthy parent material accumulated through wind action; commonly refers to sandy material in dunes or to loess in blankets on the surface.

Entisols – One of the 12 orders of soil. Entisols occur in areas of recently deposited parent materials or in areas where erosion or deposition rates are faster than the rate of soil development; such as dunes, steep slopes and flood planes.

Erosion – The wearing away of the land surface by water, wind, ice, or other geologic agents and by such processes as gravitational creep.

Erosion (geologic) – Erosion caused by geologic processes acting over long geologic periods and resulting in the wearing away of mountains and the building up of such landscape features as flood plains and coastal plains. Synonym: natural erosion.

Erosion (accelerated) – Erosion much more rapid than geologic erosion, mainly as a result of the activities of man or other animals or of a catastrophe in nature, for example, fire, that exposes the surface.

Erosion pavement – A layer of gravel or stones that remains on the surface after fine particles are removed by sheet or rill erosion.

Evapotranspiration – The process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants.

F

Field capacity – The amount of water left behind in soil after gravity drains saturated soil. Field capacity is an important hydrological parameter for soil because it can help determine the flow direction. Soil moisture values above field capacity will drain downward recharging the aquifer/water table. Also, if the soil moisture content is over field capacity, surface runoff and erosion can occur. If the soil moisture is below field capacity, the water will stay suspended in between the soil particles from capillary forces. The water will basically only move upward at this point from evaporation or evapotranspiration.

Fallow – Cropland left idle in order to restore productivity through accumulation of moisture. Summer fallow is common in regions of limited rainfall where cereal grains are grown. The soil is tilled for at least one growing season for weed control and decomposition of plant residue.

Fen – Waterlogged, spongy ground containing alkaline decaying vegetation, characterized by reeds, that develops into peat. It sometimes occurs in sinkholes of karst regions. Compare – bog, marsh, swamp.

Fast intake – The rapid movement of water into the soil.

Fertility – The quality that enables a soil to provide plant nutrients, in adequate amounts and in proper balance, for the growth of specified plants when light, moisture, temperature, tilth, and other growth factors are favorable.

Fibric soil material (peat) – The least decomposed of all organic soil material. Peat contains a large amount of well preserved fiber that is readily identifiable according to botanical origin. Peat has the lowest bulk density and the highest water content at saturation of all organic soil material.

Field moisture capacity – The moisture content of a soil, expressed as a percentage of the oven-dry weight, after the gravitational, or free, water has drained away; the field moisture content 2 or 3 days after a soaking rain; also called normal field capacity, normal moisture capacity, or capillary capacity.

Fine textured soil – Sandy clay, silty clay, and clay.

First bottom – The normal flood plain of a stream, subject to frequent or occasional flooding.

Flagstone – A thin fragment of sandstone, limestone, slate, shale, or (rarely) schist, 6 to 15 inches (15 to 38 centimeters) long.

Flood plain – A nearly level alluvial plain that borders a stream and is subject to flooding unless protected artificially.

Foot slope – The inclined surface at the base of a hill.

Forb – Any herbaceous plant not a grass or a sedge.

Fragipan – A loamy, brittle subsurface horizon low in porosity and content of organic matter and low or moderate in clay but high in silt or very fine sand. A fragipan appears cemented and restricts roots. When dry, it is hard or very hard and has a higher bulk density than the horizon or horizons above. When moist, it tends to rupture suddenly under pressure rather than to deform slowly.

Frost action – Freezing and thawing of soil moisture. Frost action can damage roads, buildings and other structures, and plant roots.

G

Genesis – The mode of origin of the soil. Refers especially to the processes or soil-forming factors responsible for the formation of the solum, or true soil, from the unconsolidated parent material.

Gelisols – One of the 12 orders of soil. Gelisols are soils that have permafrost near the soil surface, have evidence of frost churning, or ice segregation. These are common in the higher latitudes or high elevations.

Gilgai – Commonly a succession of microbasins and microknolls in nearly level areas or of microvalleys and microridges parallel with the slope. Typically, the microrelief of Vertisols; clayey soils having a high coefficient of expansion and contraction with changes in moisture content.

Glacial drift – Pulverized and other rock material transported by glacial ice and then deposited. Also, the sorted and unsorted material deposited by streams flowing from glaciers.

Glacial outwash – Gravel, sand, and silt, commonly stratified, deposited by glacial meltwater.

Glacial till – Unsorted, non-stratified glacial deposits consisting of clay, silt, sand, and boulders transported and deposited by glacial ice.

Glacial fluvial deposits – Material moved by glaciers and subsequently sorted and deposited by streams flowing from the melting ice. The deposits are stratified and occur as kames, eskers, deltas, and outwash plains.

Glacial lacustrine deposits – Material ranging from fine clay to sand derived from glaciers and deposited in glacial lakes mainly by glacial meltwater. Many deposits are interbedded or laminated.

Gleyed soil – Soil that formed under poor drainage, resulting in the reduction of iron and other elements in the profile and in gray colors and mottles.

Graded stripcropping – Growing crops in strips that grade toward a protected waterway.

Grassed waterway – A natural or constructed waterway, typically broad and shallow, seeded to grass as protection against erosion. Conducts surface water away from cropland.

Gravel – Rounded or angular fragments of rock up to 3 inches (2 millimeters to 7.6 centimeters) in diameter. An individual piece is a pebble.

Gravelly soil material – Material that is 15 to 50 percent, by volume, rounded or angular rock fragments, not prominently flattened, up to 3 inches (7.6 centimeters) in diameter.

Gravitational water – Water in the soil that is free to drain or move due to the forces of gravity. Gravitation water is the volume of water in the soil between saturation and field capacity. This water is not usually used by plants.

Groundwater – Water filling all the unblocked pores of underlying material below the water table.

H

Hardpan – A hardened or cemented soil horizon, or layer. The soil material is sandy, loamy, or clayey and is cemented by iron oxide, silica, calcium carbonate, or other substance.

Hemic soil material (**mucky peat**) – Organic soil material intermediate in degree of decomposition between the less decomposed fibric and the more decomposed sapric material.

Histosols – One of the 12 orders of soil. Histosols have a high content of organic matter and no permafrost. Most are saturated year round, but a few are freely drained. They are commonly called bogs, moors, pears or mucks.

Horizon – Soil horizons are distinct layers of soil that form naturally in undisturbed soil over time. The types of horizons are indicative of the soil order. Like other natural processes, the age of the horizon increases with depth.

Humus – The well decomposed, more or less stable part of the organic matter in mineral soils.

Hydrologic soil groups – Refers to soils grouped according to their runoff-producing characteristics. The chief consideration is the inherent capacity of soil bare of vegetation to permit infiltration. The slope and the kind of plant cover are not considered but are separate factors in predicting runoff. Soils are assigned to four groups. In group A are soils having a high infiltration rate when thoroughly wet and having a low runoff potential. They are mainly deep, well drained, an-d sandy or gravelly. In group D, at the other extreme, are soils having a very slow infiltration rate and thus a high runoff potential. They have a claypan or clay layer at or near the surface, have a permanent high water table, or are shallow over nearly impervious bedrock or other material. A soil is assigned to two hydrologic groups if part of the acreage is artificially drained and part is undrained.

I

Illuviation – The movement of soil material from one horizon to another in the soil profile. Generally, material is removed from an upper horizon and deposited in a lower horizon.

Imaginary dielectric permittivity – One of two components of the apparent dielectric permittivity. High values of imaginary dielectric permittivity will inflate the apparent permittivity, which may cause errors in the estimation of soil moisture content.

Impervious soil – A soil through which water, air, or roots penetrate slowly or not at all. No soil is absolutely impervious to air and water all the time.

Inceptisols – One of the 12 orders of soil. Inceptisols are soils of semiarid to humid environments that generally exhibit only moderate degrees of soil weathering and development. These occur in a wide variety of climates.

Increasers – Species in the climax vegetation that increase in amount as the more desirable plants are reduced by close grazing. Increasers commonly are the shorter plants and the less palatable to livestock.

Infiltration – The downward entry of water into the immediate surface of soil or other material, as contrasted with percolation, which is movement of water through soil layers or material.

Infiltration capacity – The maximum rate at which water can infiltrate into a soil under a given set of conditions.

Infiltration rate – The rate at which water penetrates the surface of the soil at any given instant, usually expressed in inches per hour. The rate can be limited by the infiltration capacity of the soil or the rate at which water is applied at the surface.

Intake rate – The average rate of water entering the soil under irrigation. Most soils have a fast initial rate; the rate decreases with application time. Therefore, intake rate for design purposes is not a constant but is a variable depending on the net irrigation application.

Irrigation – Application of water to soils to assist in production of crops.

L

Lacustrine deposit – Material deposited in lake water and exposed when the water level is lowered or the elevation of the land is raised.

Landslide – The rapid downhill movement of a mass of soil and loose rock, generally when wet or saturated. The speed and distance of movement, as well as the amount of soil and rock material, vary greatly.

Large stones – Rock fragments 3 inches (7.6 centimeters) or more across. Large stones adversely affect the specified use of the soil.

Leaching – The removal of soluble material from soil or other material by percolating water.

Liquid limit – The moisture content at which the soil passes from a plastic to a liquid state.

Loess – Fine grained material, dominantly of silt-sized particles, deposited by wind.

Lowmoor bog – A bog that is at or only slightly above the water table, on which it depends for accumulation and preservation of peat (chiefly the remains of sedges, reeds, shrubs, and various mosses).

Low strength – The soil is not strong enough to support loads.

Lower soil moisture limit – The soil moisture value below which the crop will become stressed because it will have insufficient water. When the lower limit is reached, it is time to irrigate.

M

Macropore – Pores ranging in size from >5000 to 75 µm (SSSA, 1997).

Matric potential –Sometimes called water potential, matric potential represents the energy it takes to pull water out of soil where the water is held within the soil by capillary and absorptive forces. The drier the soil, the more energy that is required to pull the water out.

Maximum Allowable Depletion (**MAD**) – The fraction of the available water that is 100% available to the crop.

Maximum rooting depth – Deepest rooting depth attained by a crop under specific soil conditions. Physical and chemical barriers in the soil often limit actual rooting depths to less than potential rooting depth.

Medium textured soil – Very fine sandy loam, loam, silt loam, or silt.

Metamorphic rock – Rock of any origin altered in mineralogical composition, chemical composition, or structure by heat, pressure, and movement. Nearly all such rocks are crystalline.

Mesopore – Pores ranging in size from 5–30 µm (SSSA, 1997).

Micropore – Pores ranging in size from 30–75 µm (SSSA, 1997).

Mineral soil – Soil that is mainly mineral material and low in organic material. Its bulk density is more than that of organic soil. Mineral soil is basically a mixture of sand silt and clay and the weight ratio is called the soil's textural.

Minimum tillage – Only the tillage essential to crop production and prevention of soil damage.

Miscellaneous area – An area that has little or no natural soil and supports little or no vegetation.

Moderately coarse textured soil – Coarse sandy loam, sandy loam, and fine sandy loam.

Moderately fine textured soil – Clay loam, sandy clay loam, and silty clay loam.

Mollisols – One of the 12 orders of soil. Mollisols are soils that have a dark colored surface horizon relatively high in content of organic matter. The soils are base rich throughout and therefore are quite fertile.

Morphology, soil – The physical makeup of the soil, including the texture, structure, porosity, consistence, color, and other physical, mineral, and biological properties of the various horizons, and the thickness and arrangement of those horizons in the soil profile.

Moss peat – An accumulation of organic material that is predominantly the remains of mosses (e.g. sphagnum moss). Compare – Herbaceous peat, sedimentary peat, woody peat, peat, muck, and mucky peat.

Mottling, soil – Irregular spots of different colors that vary in number and size. Mottling generally indicates poor aeration and impeded drainage.

Muck – Unconsolidated soil material consisting primarily of highly decomposed organic material in which the original plant parts are not recognizable (i.e. "sapric" in Soil Taxonomy). It generally contains more mineral matter and is usually darker in color, than peat.

Mucky peat – Unconsolidated soil material consisting primarily of organic matter that is in an intermediate stage of decomposition such that a significant part of the original material can be recognized and a significant part of the material can not be recognized (i.e. "hemic" in Soil Taxonomy).

Munsell chroma – A system used to describe soil color according to hue (spectral color), value (degree of lightness or darkness) and chroma. Chroma refers the intensity of color.

N

Neutral soil – A soil having a pH value between 6.6 and 7.3.

Nitrogen – A chemical compound that can be found in all living organisms, the atmosphere, and animal wastes. It is commonly found in nutrients used in fertilization, and can cause problems to local ecosystems if too much is washed into waterways.

Nutrient, plant – Any element taken in by a plant essential to its growth. Plant nutrients are mainly nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, manganese, copper, boron, and zinc obtained from the soil and carbon, hydrogen, and oxygen obtained from the air and water.

O

O - Name of a soil horizon. Horizon "O" is made up of decaying plants on or near surface and is typically up to 2 inches thick.

Organic matter – Plant and animal residue in the soil in various stages of decomposition.

Organic materials – Unconsolidated sediments or deposits in which carbon is an essential, substantial component. Several types of organic materials (deposits) can be identified based on the composition of the dominant fibers (grassy organic materials, herbaceous organic materials, mossy organic materials, woody organic materials). Compare – herbaceous peat, moss peat, sedimentary peat, woody peat.

Outwash, glacial – Stratified sand and gravel produced by glaciers and carried, sorted, and deposited by glacial meltwater.

Oxisols – One of the 12 orders of soil. Oxisols are highly weathered soils of tropical and subtropical regions. They characteristically occur on land surfaces that have been stable for a long time. They have low natural fertility as well as a low capacity to retain additions of lime and fertilizer.

P

Pan – A compact, dense layer in a soil that impedes the movement of water and the growth of roots. For example, hardpan, fragipan, claypan, plowpan, and traffic pan.

Parent material – The unconsolidated organic and mineral material in which soil forms.

Peat – Unconsolidated soil material consisting largely of undecomposed, or slightly decomposed, organic matter (i.e. "fibric" in Soil Taxonomy) accumulated under conditions of excessive moisture. Compare – muck, mucky peat, herbaceous peat.

Ped – An individual natural soil aggregate, such as a granule, a prism, or a block.

Pedon – The smallest volume that can be called ""a soil." A pedon is three dimensional and large enough to permit study of all horizons. Its area ranges from about 10 to 100 square feet (1 square meter to 10 square meters), depending on the variability of the soil.

Perchloroethylene (**PCE**) – See Tetrachloroethylene (TCE).

Percolation – The downward movement of water through the soil.

Percs slowly – The slow movement of water through the soil, adversely affecting the specified use.

Permafrost – Layers of soil, or even bedrock, occurring in arctic or subarctic regions, in which a temperature below freezing has existed continuously for a long time.

Permanent wilting point (**PWP**) – The soil water content of which healthy plants can no longer extract water from the soil at a rate fast enough to recover from wilting. The permanent wilting point is considered the lower limit of plant-available water.

Permeability – The quality of the soil that enables water to move downward through the profile. Permeability is measured as the number of inches per hour that water moves downward through the saturated soil.

Phase, soil – A subdivision of a soil series based on features that affect its use and management. For example, slope, stoniness, and thickness.

pH value – A numerical designation of acidity and alkalinity in soil. (See Reaction, soil.)

Phosphorus – A highly reactive chemical element used in fertilizers to aid in plant growth. Phosphorus can cause oxygen problems and unwanted algae blooms if too much is washed into bodies of water, creating hardship for the local ecosystem.

Phytoremediation – A remediation method by which trees are used to pull contamination out of groundwater. When the trees absorb the water and then off-gas it during photosynthesis, the toxic chemicals are rendered into relatively harmless by-products such as methane and carbon dioxide.

Piping – Formation of subsurface tunnels or pipelike cavities by water moving through the soil.

Pitting – Pits caused by melting ground ice. They form on the soil after plant cover is removed.

Plant-available water (**PAW**) – The amount of water held in the soil that is available to plants; the difference between field capacity and permanent wilting point.

Plasticity index – The numerical difference between the liquid limit and the plastic limit; the range of moisture content within which the soil remains plastic.

Plastic limit – The moisture content at which a soil changes from semisolid to plastic.

Plinthite – The sesquioxide-rich, humus-poor, highly weathered mixture of clay with quartz and other diluents. It commonly appears as red mottles, usually in platy, polygonal, or reticulate patterns. Plinthite changes irreversibly to an ironstone hardpan or to irregular aggregates on repeated wetting and drying, especially if it is exposed to heat from the sun. In a moist soil, plinthite can be cut with a spade. It is a form of laterite.

Plowpan – A compacted layer formed in the soil directly below the plowed layer.

Ponding – Standing water on soils in closed depressions. Unless the soils are artificially drained, the water can be removed only by percolation or evapotranspiration.

Poor filter – Because of rapid permeability, the soil may not adequately filter effluent from a waste disposal system.

Poorly graded – Refers to a coarse grained soil or soil material consisting mainly of particles of nearly the same size. Because there is little difference in size of the particles, density can be increased only slightly by compaction.

Poor outlets – Refers to areas where surface or subsurface drainage outlets are difficult or expensive to install.

Potential evapotranspiration (**PET**) – Maximum amount of water that could be lost through evapotranspiration under a given set of atmospheric conditions, assuming that the crop covers the entire soil surface and that the amount of water present in the soil does not limit the process.

Potential rooting depth – The deepest rooting depth attained by crop roots depending on the type of crop and independent of soil conditions.

Probe, soil – The end of a soil probe that is buried or otherwise sunk into the ground in order to take measurement readings of the surrounding soil. The name "soil probe" is also used as a general name for any number of devices designed to measure soil, and is also interchangeably referred to as a "soil sensor".

Productivity, soil – The capability of a soil for producing a specified plant or sequence of plants under specific management.

Profile, soil – A vertical section of the soil extending through all its horizons and into the parent material.

R

Reaction, soil – A measure of acidity or alkalinity of a soil, expressed in pH values. A soil that tests to pH 7.0 is described as precisely neutral in reaction because it is neither acid nor alkaline.

Real dielectric permittivity – one of two components of the apparent dielectric permittivity, the real component represents energy storage in the form of rotational or orientation polarization of water molecules when an electrical field is applied, which is indicative of soil water content.

Redistribution (**percolation**) – Downward movement of gravitational water through the soil profile.

Redoximorphic features (**redox features**) – Soil features associated with prolonged or seasonal wetness that result from reduction and oxidation of iron and manganese.

Regolith – The unconsolidated mantle of weathered rock and soil material on the earth's surface; the loose earth material above the solid rock.

Relief – The elevations or inequalities of a land surface, considered collectively.

Residuum (**residual soil material**) – Unconsolidated, weathered or partly weathered mineral material that accumulated as consolidated rock disintegrated in place.

Rill – A steep-sided channel resulting from accelerated erosion. A rill is generally a few inches deep and not wide enough to be an obstacle to farm machinery.

Rippable – Bedrock or hardpan can be excavated using a single-tooth ripping attachment mounted on a tractor with a 200-300 draw bar horsepower rating.

Rock fragments – Rock or mineral fragments having a diameter of 2 millimeters or more; for example, pebbles, cobbles, stones, and boulders.

Rooting depth – Shallow root zone. The soil is shallow over a layer that greatly restricts roots.

Root zone – The part of the soil that can be penetrated by plant roots.

Runoff – The precipitation discharged into stream channels from an area. The water that flows off the surface of the land without sinking into the soil is called surface runoff. Water that enters the soil before reaching surface streams is called groundwater runoff or seepage flow from groundwater.

S

Saline soil – A soil containing soluble salts in an amount that impairs growth of plants. A saline soil does not contain excess exchangeable sodium.

Salty water – Water that is too salty for consumption by livestock.

Sand – As a soil separate, individual rock or mineral fragments from 0.05 millimeter to 2.0 millimeters in diameter. Most sand grains consist of quartz. As a soil textural class, a soil that is 85 percent or more sand and not more than 10 percent clay.

Sandstone – Sedimentary rock containing dominantly sand-size particles.

Sapric soil material (**muck**) – The most highly decomposed of all organic soil material. Muck has the least amount of plant fiber, the highest bulk density, and the lowest water content at saturation of all organic soil material.

Saprolite – Unconsolidated residual material underlying the soil and grading to hard bedrock below.

Saturation, soil – The situation where all the soil pores are filled with water. This occurs below the water table and in the unsaturated zone above the water table after a heavy rain or irrigation event. After the rain event, the soil moisture (above the water table) will decrease from saturation to field capacity.

Saturated hydraulic conductivity – The ease with which water moves through soil when at a saturated state. The water flux of water per unit gradient of hydraulic potential (SSSA, 1997).

Sedimentary rock – Rock made up of particles deposited from suspension in water. The chief kinds of sedimentary rock are conglomerate, formed from gravel; sandstone, formed from sand; shale, formed from clay; and limestone, formed from soft masses of calcium carbonate. There are many intermediate types. Some wind-deposited sand is consolidated into sandstone.

Seepage – The movement of water through the soil. Seepage adversely affects the specified use.

Sensor, soil – A device that measures soil parameters such as temperature and soil moisture content. Also know as a "soil probe", these names can be used interchangeably.

Sequum – A sequence consisting of an illuvial horizon and the overlying eluvial horizon. (See Eluviation.)

Series, soil – A group of soils that have profiles that are almost alike, except for differences in texture of the surface layer or of the underlying material. All the soils of a series have horizons that are similar in composition, thickness, and arrangement.

Shale – Sedimentary rock formed by the hardening of a clay deposit.

Sheet erosion – The removal of a fairly uniform layer of soil material from the land surface by the action of rainfall and surface runoff.

Shrink-swell – The shrinking of soil when dry and the swelling when wet. Shrinking and swelling can damage roads, dams, building foundations, and other structures. It can also damage plant roots.

Silica – A combination of silicon and oxygen. The mineral form is called quartz.

Silica-sesquioxide ratio – The ratio of the number of molecules of silica to the number of molecules of alumina and iron oxide. The more highly weathered soils or their clay fractions in warm-temperate, humid regions, and especially those in the tropics, generally have a low ratio.

Silt – As a soil separate, individual mineral particles that range in diameter from the upper limit of clay (0.002 millimeter) to the lower limit of very fine sand (0.05 millimeter). As a soil textural class, soil that is 80 percent or more silt and less than 12 percent clay.

Siltstone – Sedimentary rock made up of dominantly silt-sized particles.

Similar soils – Soils that share limits of diagnostic criteria, behave and perform in a similar manner, and have similar conservation needs or management requirements for the major land uses in the survey area.

Sinkhole – A depression in the landscape where limestone has been dissolved.

Site index – A designation of the quality of a forest site based on the height of the dominant stand at an arbitrarily chosen age. For example, if the average height attained by dominant and codominant trees in a fully stocked stand at the age of 50 years is 75 feet, the site index is 75 feet.

Slickensides – Polished and grooved surfaces produced by one mass sliding past another. In soils, slickensides may occur at the bases of slip surfaces on the steeper slopes; on faces of blocks, prisms, and columns; and in swelling clayey soils, where there is marked change in moisture content.

Slick spot – A small area of soil having a puddled, crusted, or smooth surface and an excess of exchangeable sodium. The soil is generally silty or clayey, is slippery when wet, and is low in productivity.

Slippage (**in tables**) – Soil mass susceptible to movement downslope when loaded, excavated, or wet.

Slope – The inclination of the land surface from the horizontal. Percentage of slope is the vertical distance divided by horizontal distance, then multiplied by 100. Thus, a slope of 20 percent is a drop of 20 feet in 100 feet of horizontal distance.

Sloughed till – Water-saturated till that has flowed slowly downhill from its original place of deposit by glacial ice. It may rest on other till, on glacial outwash, or on a glaciolacustrine deposit.

Slow intake – The slow movement of water into the soil.

Slow refill – The slow filling of ponds, resulting from restricted permeability in the soil.

Small stones – Rock fragments less than 3 inches (7.6 centimeters) in diameter. Small stones adversely affect the specified use of the soil.

Soil – A natural, three-dimensional body at the earth's surface. It is capable of supporting plants and has properties resulting from the integrated effect of climate and living matter acting on earthy parent material, as conditioned by relief over periods of time.

Soil organic matter – Soil organic matter consists of living microorganisms, weakly and/or partially decomposed residues and highly decomposed materials (humus).

Soil separates – Mineral particles less than 2 millimeters in equivalent diameter and ranging between specified size limits.

Solum – The upper part of a soil profile, above the C horizon, in which the processes of soil formation are active. The solum in soil consists of the A, E, and B horizons. Generally, the characteristics of the material in these horizons are unlike those of the underlying material. The living roots and plant and animal activities are largely confined to the solum.

Spodosols – One of the 12 orders of soil. Spodosols formed from weathering processes that strip organic matter combined with aluminum from the surface layer and deposit them in the subsoil. These tend to be acid and infertile.

Stone line – A concentration of coarse fragments in a soil. Generally, it is indicative of an old weathered surface. In a cross section, the line may be one fragment or more thick. It generally overlies material that weathered in place and is overlain by recent sediment of variable thickness.

Stones – Rock fragments 10 to 24 inches (25 to 60 centimeters) in diameter.

Stony – Refers to a soil containing stones in numbers that interfere with or prevent tillage.

Stripcropping – Growing crops in a systematic arrangement of strips or bands which provide vegetative barriers to wind and water erosion.

Structure, soil – The arrangement of primary soil particles into compound particles or aggregates. The aggregation of sand, silt and clay particles into aggregates that are characterized by shape, size and degree of aggregate stability.

Subsoil – Technically, the B horizon; roughly, the part of the solum below plow depth.

Subsoiling: – Breaking up a compact subsoil by pulling a special chisel through the soil.

Substratum – The part of the soil below the solum.

Subsurface layer – Any surface soil horizon (A, E, AB, or EB) below the surface layer.

Summer fallow – The tillage of uncropped land during the summer to control weeds and allow storage of moisture in the soil for the growth of a later crop. A practice common in semiarid regions, where annual precipitation is not enough to produce a crop every year. Summer fallow is frequently practiced before planting winter grain.

Surface layer – The soil ordinarily moved in tillage, or its equivalent in uncultivated soil, ranging in depth from about 4 to 10 inches (10 to 25 centimeters). Frequently designated as the “plow layer” or the “AP horizon”.

Surface soil – The A, E, AB, and EB horizons. It includes all subdivisions of these horizons.

Swamp – An area of low, saturated ground, intermittently or permanently covered with water, and predominantly vegetated by shrubs and trees, with or without the accumulation of peat.

T

Temporary Wilting – Daily cycle of plant wilting during the day followed by recovery at night.

Texture – The relative proportion of sand, silt and clay.

U

Ultisols – One of the 12 orders of soil. Ultisols are soils in humid areas. They are typically acid soils in which most nutrients are concentrated in the upper few inches. They have a moderately low capacity to retain additions of lime and fertilizer.

Unavailable water – Water in thin, tightly held films around soil particles; not available to plants.

V

Valley fill – In glaciated regions, material deposited in stream valleys by glacial meltwater. In nonglaciated regions, alluvium deposited by heavily loaded streams.

Variant, soil – A soil having properties sufficiently different from those of other known soils to justify a new series name, but occurring in such a limited geographic area that creation of a new series is not justified.

Variegation: Refers to patterns of contrasting colors assumed to be inherited from the parent material rather than to be the result of poor drainage.

Varve – A sedimentary layer of a lamina or sequence of laminae deposited in a body of still water within a year. Specifically, a thin pair of graded glaciolacustrine layers seasonally deposited, usually by meltwater streams, in a glacial lake or other body of still water in front of a glacier.

Vertisols – One of the 12 orders of soil. Vertisols have a high content of expanding clay minerals. They undergo pronounced changes in volume with changes in moisture. Because they swell when wet, vertisols transmit water very slowly and have undergone little leeching. They tend to be fairly high in natural fertility.

W

Water Fraction by Volume (WFV) – This term describes the percentage of water found in the soil displayed in decimal form. For example, a water content of 0.20 wfv means that a one liter soil sample contains 200 ml of water. Full saturation (all the soil pore spaces filled with water) occurs typically between 0.3-0.45 wfv and is quite soil dependent. WFV is a desirable way to measure water content of soils because you can compare the content directly between different types of soil with no conversion between units.

Water potential – The amount of work that must be done per unit quantity of pure water to transport water over a defined distance.

Weathering – All physical and chemical changes produced in rocks or other deposits at or near the earth's surface by atmospheric agents. These changes result in disintegration and decomposition of the material.

Well graded – Refers to soil material consisting of coarse grained particles that are well distributed over a wide range in size or diameter. Such soil normally can be easily increased in density and bearing properties by compaction. Contrasts with poorly graded soil.

Wilting point (**or permanent wilting point**) – The moisture content of soil, on an oven-dry basis, at which a plant (specifically a sunflower) wilts so much that it does not recover when placed in a humid, dark chamber.

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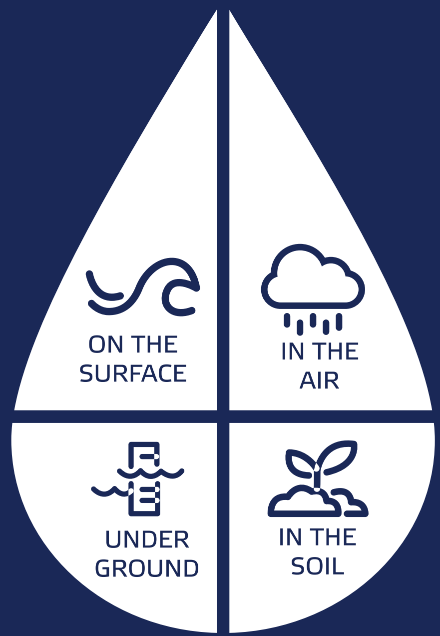

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