

CHAPTER 5

SENSOR SELECTION

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Learning Outcomes

There are essentially four classes of sensor technologies; each may have an influence on data quality. No one sensor is the best fit for every purpose.

Recommendations from this chapter should be combined with those in Chapter 2 before making a network-level decision.

Today, there are many options in soil moisture sensors. Sensor choice is an important factor in producing long-term, quality data. Soil properties, site conditions, climate, and, to some extent, stakeholder data needs can drive the choice of sensor. It is important to note that few, if any, in situ sensors directly measure the amount of water in the soil. Most in situ soil moisture sensors infer soil water content (SWC)

from an electromagnetic response. An electromagnetic signal at a particular frequency or range of frequencies is generated and propagated along the sensor tines, which are in direct contact with the soil. Water, with its unique dielectric properties, changes the bulk electrical properties of the soils, causing a measurable change in the electromagnetic signal recorded by the sensor.

Commercially available sensors fall into four classes depending on the type of electromagnetic signal propagated and the method of measuring the response, including (1) capacitance, (2) impedance or frequency domain reflectometry (FDR), (3) time-domain reflectometry (TDR), and (4) transmission line oscillators (TLO) (Cosh et al., 2021).

Each technology uses a transfer equation to estimate SWC from the measured electromagnetic response. Soil properties like clay, salinity, and temperature induce a soil-based dependency in the function of particular technologies that impacts the relationship between the measured response variable of the soil and SWC. This means that certain technologies may be unsuitable for estimating water content in certain soil types. Broadly speaking, high clay content, organic matter, and/or saline soils often need special attention in terms of selecting an appropriate sensor. However, even if a sensing technology is suitable for various sites and soil types, the standardized transfer equations between soil properties and soil moisture that are provided by the factory may be insufficient because of differences in correlative relationships for the standard lab version of a soil type compared to sensor reading and SWC relationships for exact soil conditions in the field. Hence, the selection of an appropriate sensor followed by a soil-specific calibration are baseline steps required for producing good quality soil moisture data.

The various available technologies for soil moisture sensing, along with their advantages and disadvantages are provided in Table 4. Today, most sensors are low-power with internal processors that convert signals to SWC and use serial data interface at 1,200 baud (SDI-12) communication protocols to transmit digital data along a single communication cable (<http://www.sdi-12.org/>). The common communication wire of SDI-12 sensors forms a single circuit along with a power and ground wire, making wiring straightforward. Along with SWC, many sensors provide useful ancillary data including soil temperature and bulk electrical conductivity (BEC). These additional data provide important diagnostic information on sensor functionality (Caldwell et al., 2022).

Physical structure of most sensors includes parallel tines of varying number (2 to 4 tines) and length (10 to 30 cm), a sensor head that encloses the electronics, and a cable that transmits power and receives data from the data collection platform. The configuration of the tines and their length affect the size of the measurement volume. A thermistor for temperature measurements is generally housed inside the sensor head in contact with one of the tines. The attenuation of the signal (reduction of the electrical signal) along the tines is often used to estimate bulk electrical conductivity. Lastly, the cable generally contains continuous wires for sensor power, data transmission, and grounding. The cables itself are shielded to reduce external noise and sheathed in flexible plastic. Some sensors have cables that can be directly buried while others need additional external protection (e.g., PVC conduit).

In the most general terms, lower frequency operation and less durable cables are found in less expensive probes. High operating frequencies may not require soil-specific calibrations but come with a higher cost. Finally, sensor life expectancy may be correlated to sensor cost, but it also takes overall experiences of the entire soil moisture community to determine if there are particular issues that may appear for a given area or soil. *There is no single sensor that is perfect for all soils and climates.*

Table 4. Commercially available sensor technologies

Sensing Technology	Advantages	Limitations	Example Sensors	References
<p>Capacitance</p> <p>Capacitor charge time, which depends on the apparent dielectric permittivity of the soil</p>	<ul style="list-style-type: none"> • Less expensive • Shorter tines, easier installation • Some are easily installed at depth in a borehole 	<ul style="list-style-type: none"> • Operates at lower frequencies that can lead to temperature sensitivity and lower accuracy in clay or saline soils • Can respond to some property of the soil–water system that is not Soil Water Content (SWC) alone 	<p>TEROS-series, ECH-20, EC-5, WET</p>	<p>Wyseure et al., 1997; Evett et al., 2005, 2012; Fares et al., 2011; Mittelbach et al., 2012; Datta et al., 2018; Ferrarezi et al., 2020; Wilson et al., 2020</p>
<p>Impedance or Frequency Domain Reflectometry (FDR)</p> <p>Probe impedance to measure the dielectric permittivity, based on a swept frequency collected over a wide range</p>	<ul style="list-style-type: none"> • Use a range of lower frequencies • Shorter tines, easier installation 	<ul style="list-style-type: none"> • Interference in high-salinity soils • Soil texture dependence in calibration equations 	<p>HydraProbe, ThetaProbe, WET-2</p>	<p>Seyfried et al., 2005; Kelleners et al., 2009; Cosh et al., 2005, 2016</p>

<p>Time-Domain Reflectometry (TDR)</p> <p>Travel time for ~1000 MHz wave to propagate along a transmission line; a waveform is collected and analyzed</p>	<ul style="list-style-type: none"> • Considered most accurate and least sensitive to soil type • May avoid need for soil-specific calibration • Insensitive to temperature and bulk electrical conductivity (BEC) 	<ul style="list-style-type: none"> • Installation can be challenging for sensors with longer tines and an independent coaxial signal wire • Signal attenuation in high salinity due to collapse of waveform • More expensive 	<p>TDR-315, SoilVUE10, TDR-200,</p>	<p>Topp et al., 1980; Wilson et al., 2020, 2023</p>
<p>Transmission Line Oscillators</p> <p>Similar to TDR, but generally at a lower frequency and no waveform collected</p>	<ul style="list-style-type: none"> • Two tines, easier installation • Simple electronics and no need for full waveform analysis 	<ul style="list-style-type: none"> • Sensitive to temperature and BEC • Sensitive to air-gaps 	<p>CS615, CS655, CS655, PICO32, PICO64</p>	<p>Chandler et al., 2004; Caldwell et al., 2018; Patrignani et al., 2022.</p>

SENSOR SELECTION CRITERIA

The most common in situ soil moisture sensors primarily differ in the specific frequency and technology used for estimating the dielectric constant of the bulk soil, size of the sensor, and method of installation (Table 4). *The following factors, along with limitations of the several sensors mentioned in Table 4, should be considered when selecting an appropriate sensor for your network.*

SOIL TYPE

Typically, soils with large bulk electrical conductivity (BEC) attenuate electromagnetic signals and are problematic for in situ sensors. Such problematic soils include soils with high clay content, high organic matter, and/or high salinity. Under such conditions, it is best to select a sensor that works with high frequencies, has shorter tines, and reports bulk electrical conductivity as a response variable. Bulk electrical conductivity values can also aid the quality control process later.

SENSOR CONFIGURATION AND INSTALLATION TECHNIQUES

Varying sensor configurations can provide different information about sub-surface soil moisture. Most in situ soil moisture sensors have tines that must be physically pushed into the soil, as shown in Figure 4a (Ferrarezi et al., 2020). Shorter, more stout tines can be more easily inserted and, therefore, be useful in hard or dry soils, but short tines may also decrease the sensing volume. Regardless, the tines of any in situ sensors must be pushed into undisturbed soil in a way that ensures complete contact with the soil. Gaps around the tines or incomplete insertion will affect the quality of SWC by decoupling the electromagnetic wave from the soil or reducing the measured permittivity by including air. These sensors can be installed in different orientations from horizontal to vertical or on angles. There are advantages to each orientation, but generally, a horizontal installation ensures a depth-specific reading, proper protection of the sensor electronics, and thermally consistent conditions along the entire probe (Caldwell et al., 2022). Note: Buried probes are difficult to remove and should be protected if used to monitor activities such as prescribed burning or around active farm operations such as tilling. Lastly, buried in situ sensors are difficult to troubleshoot or replace when issues arise.

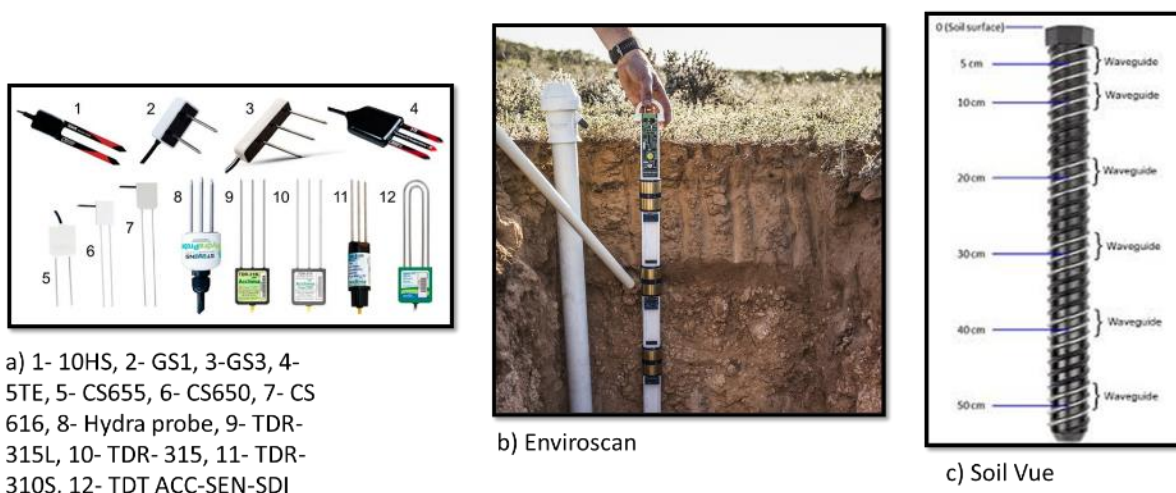


Figure 4. (4a) Sensors divided based on installation requirements. Image Credit: Ferrarezi et al., 2020. (4b) An overlaid image visualizing an Enviroscan sensor inserted in the soil. Image Credit: Sentek PTY Ltd. (4c) Diagram of a Soil Vue sensor. Image Credit: Sentek PTY Ltd.

Borehole sensors can either be installed from the surface, in a plastic tube, without direct soil contact (Figure 4b) or in a pre-augured borehole. Either method is relatively easier to manage when working in a place where operational activities require sensors to be removed, but the limited soil-contact can reduce total sensitivity to changing soil moisture conditions. Direct insertion sensors, like Soil Vue (Figure 4c), are new and require skill for installation to ensure complete contact with the soil. Wilson et al. (2023) highlights low accuracies in Soil Water Content (SWC) estimation from the use of such sensors, since installation is not easy and often results in poor contact with the soil. Refer to [Caldwell et al., 2022](https://app.jove.com/v/64498/in-situ-soil-moisture-sensors-in-undisturbed-soils)⁷ for more detailed instructions

⁷ <https://app.jove.com/v/64498/in-situ-soil-moisture-sensors-in-undisturbed-soils>

for installation of different soil moisture sensors. Further general information about sensor installation and maintenance can be found in the NCSMMN [Strategic Plan](#), Chapter 5.

SENSOR SIZE

Generally, the length and separation of the sensor tines determine the total volume of soil measured. Soil moisture is inherently heterogeneous, particularly at smaller scale. Estimations or measurements of a larger volume of soil may provide better spatial representation, while a smaller volume may be more variable or miss important processes like preferential flow. For shallow installations (i.e., 5-cm or less), sensor with larger measurement volumes may also incorporate the air above the surface and be biased towards lower SWC. In problematic soils with high bulk electrical conductivity, larger waveguides (Figure 4b) can cause more errors and should be avoided (Caldwell et al., 2022).

GENERAL RECOMMENDATIONS

There is no specific sensor that will meet every network's needs, and technologies are constantly changing. For example, non-contact technologies, such as cosmic ray neutron sensing (Zreda et al., 2012) or gamma-attenuation (Balducini et al., 2018), may become more operational as research continues to make advances. After following these guidelines, consultation with members of the soil moisture community is recommended before making large investments. A point of contact can either be determined by contacting vendors of the different moisture sensors, by connecting with mesonet listservs, or if need be, by searching for the same sensor type in the metadata provided by other networks.