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Societies

Assessing soil health: Soil water cycling

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The Cornell Sprinkle Infiltrometer can be used to measure wet aggregate stability. Photo courtesy of Robert Schindelbeck, Director, Cornell Soil Health Laboratory.

The following article is the first in a five-part series on assessing soil health. It focuses on soil water cycling. It is part of a larger Soil Science Society of America webinar series produced in partnership with The Soil Health Institute and sponsored by The Walton Family Foundation.

Measuring and assessing soil health are critical components to understanding how changes in agronomic management practices are affecting the capacity of soil to support cropping systems. Soil health is defined as the continued capacity of a soil to function as a vital, living ecosystem that sustains plants, animals, and humans. But, how do we measure soil health? Answering this question can be daunting. Most soil scientists and agronomists have experience in measuring a few soil properties and seeing soil test results from laboratories. Parsing out what to measure, when, and how can be overwhelming.

This article is the first in a series on assessing soil health. The intent of the series to provide useful explanations of soil health measurements. For each measurement, the method or methods will be described as well as a practical discussion of what the measurement means, especially to the crop adviser and grower. As the measurements are discussed below, insights from knowledge of the peer-review literature, the author's professional experience measuring soil physical properties, and recent insights from the Soil Health Institute project titled, "The North American Project to

Evaluate Soil Health Measurements (NAPESHM)," will be assimilated to help in understanding each measurement in the context of soil health management practices and soils.



Returning residue to the soil surface and reducing tillage improve soil organic matter content and soil water cycling. Source: USDA-NRCS.

Soil health management practices that regenerate agricultural soils to a healthier condition are primarily focused on creating better physical and chemical habitat to nurture microbial communities and plants in the soil. The soil health management principles, as described by the USDA–NRCS, include soil armor, minimizing soil disturbance, plant diversity, continued live

plant/roots, and livestock integration (USDA–NRCS, [2017](#)). When specific management practices are employed to achieve these fundamental principles, the next step is to see if soil health is improving by measuring and monitoring it. In general, soil health indicators revolve around specific physical, chemical, and biological measures useful for assessing soil health. Deciding what to measure involves establishing a few priorities. This article covers measurements of soil health that affect water cycling and are generally descriptive of soil physical properties.

Why measure soil water cycling? Weather events of drought, excessive rain, and intense rainfall events are excellent reasons for monitoring the capability of soil to infiltrate, redistribute, and supply plant–available water. How well these functions perform affects drought resiliency, trafficability, water use efficiency, nutrient use efficiency, erosion risk, and water quality and quantity of surface water and groundwater. All these benefits are important to on–farm profitability, and some result

in off-farm ecosystem services that benefit society and may add economic value as well.

Four types of soil physical measurements can be used to evaluate soil water cycling.

First, a measurement of the soil bulk density or penetration resistance can provide some

indication of the absence or presence of

compaction. Compaction limits air, water, and

root penetration into soil, and soil health-

promoting practices, such as reduced tillage,

cover cropping, and increasing soil organic

matter can ameliorate compaction. Second, measures of the soil surface infiltration

rate and saturated hydraulic conductivity indicate how well water will enter the soil

during a rainfall or irrigation event. Soil health management practices that minimize soil

crusting, improve aggregate stability, and improve surface soil structure all improve

surface infiltration. Third, available water-holding capacity describes the amount of

water that is stored and available to the plant. Again, practices that improve soil

structure and soil organic carbon improve plant-available water. Fourth, wet aggregate

stability describes the resistance of soil aggregates to break down when wetting.

Aggregate stability is a soil health indicator that integrates many outcomes of soil

functioning and is mechanistically related to compaction, infiltration, and plant-

available water-holding capacity.



Penetrometers are an inexpensive (fixed cost) method to measure soil compaction along a soil profile.

Source: Source: J. Grigar.

Soil health measurements made from in-field soil samples should represent the 0- to 6-inch depth. If soil health of a field is being monitored over time, soil samples should be collected and measurement should be taken at approximately the same time and location, annually. Spring, before planting, is a good time because moist soil makes

sampling and field measurements easier. Additional considerations when selecting soil health measurements include; convenience/ease, transferability (temporal and site comparisons), meaningfulness, and value. How a chosen measurement may address a local management concern or a grower priority should also be considered when choosing a soil health measurement. For example, a location with slopes and intense rainfalls may prioritize water capture and erosion risk over plant-available water.

Bulk Density or Compaction

Penetrometers are an inexpensive (fixed cost) method to measure soil compaction along a soil profile. Penetration resistance (PR) of a soil profile provides a measurement of what roots, air, or water encounter, regarding soil impedance. Penetration resistance is a function of compaction, soil texture, organic matter content, and moisture content, which complicates one's ability to compare PR measurement consistently over time and space. The ideal situation for PR is to compare side-by-side trials. Take the PR measurements on the same day and compare the treatments, but note that fields at different soil moisture contents will influence the comparison.

Bulk density measurements are repeatable and comparable across space and time. Bulk density measurement is difficult to do well because the sample volume is never large enough (no matter how much soil you sample). When possible, a 3-inch-diameter soil core is a recommended size. Bulk density is needed for quantifying soil organic carbon stock (to be discussed in a subsequent article).

Surface Infiltration and Saturated Hydraulic Conductivity



Single-ring infiltrometers being used to determine infiltration rates in a conventionally tilled cotton field near Weinert, TX. Source: Paul B. De Laune.

Measuring soil infiltration is so useful because it is a direct measurement of a desired soil function and units like “inches of water infiltrated in one hour” are meaningful. The NRCS field infiltration test has a simple, inexpensive setup with clear instructions (<https://bit.ly/32Ap86l>) on using a single-ring, falling-head measurement. The soil moisture at which an infiltration test is initiated has a significant effect on the magnitude of the infiltration rate. Drier soil

will have greater infiltration rates. A second infiltration measurement is meant to help standardize for initial soil moisture, but this test is not ideal to compare infiltration rates collected at different times of the year. This field infiltration method is best suited for comparing side-by-side treatments. A more robust method is to measure saturated hydraulic conductivity (K_{sat}) of the soil surface. Surface K_{sat} is reported in the same useful units, but because the measurement is made at saturation, the initial soil moisture at the time of measurement has much less influence. The trouble with surface K_{sat} is the complexity of making the measurement. There are many options for field instruments, and those that automate the measurement and calculation are desirable. The SATURO1 (Meter Group, Pullman WA) is a single-ring, dual-head infiltrometer that automates surface K_{sat} and can be easily operated with little training. The Soil Health Institute used this device in the NAPESHM project (Norris et al., 2020), and the project scientists reported it to be robust and straightforward to use. However, surface K_{sat} is a measurement with high variance; hence, sometimes multiple measurements need to be made to distinguish treatment differences.

Plant-Available Water

Plant-available water (PAW) is the water held by the soil between field capacity and permanent wilting point. Both field capacity and permanent wilting point are functions of soil texture and organic carbon content. Field capacity depends on soil structure.

Management practices that increase soil organic carbon and improve soil structure thereby enhance drought resilience. If you choose to measure PAW, use intact cores for the field capacity measurement (Figure 1).

Permanent wilting point can be made with a psychrometer or using a repacked soil sample on a pressure plate. Like surface Ksat and infiltration rate, the benefit of measuring

PAW is communicating to farmers that “an extra 0.25-inch of water was available to the crop during the month of July,” for example. The PAW measurement is repeatable and comparable in time and space. The Soil Health Institute anticipates publishing a pedotransfer function that relates soil texture and organic carbon to changes in PAW. When this function is available, measuring PAW directly could be eliminated if desired.



Minimizing soil disturbance is a good start to rebuilding soil aggregates, pore spaces, soil glue, and soil organic matter. This is an essential step for long term soil productivity. This photo shows that 20+ years of no-tillage and crop diversity results in a healthy, well-aggregated soil. Source: USDA-NRCS.

What is a Pedotransfer Function?

A pedotransfer function is a translation of soil measurements we have into soil measurements we need (Bouma, 1989).

Wet Aggregate Stability



Diverse crop rotations are important to the long-term sustainability of our soil resource and food security. This photo shows harvesting spring wheat. Previous crops grown on this field include corn, pea, soybean, and cover crops. Source: USDA-NRCS.

Wet aggregate stability is a measure of the resistance of a soil aggregate to slake into smaller aggregates or primary soil particles when wet. Water-stable aggregates indicate that soil porosity, plant-available water, and infiltration are greater and erosion risk is less compared with non-water-stable aggregates. There are many ways to measure wet aggregate stability, and most of them are very useful to monitor how the health of a soil is changing (see Table 1 for summary and references). The different wet aggregate stability measurements are not strongly

correlated with each other. In other words, once you start monitoring with a wet aggregate stability method, try to stick to the same method to maintain the ability to continuously monitor soil health. All methods appear to be sensitive to changes to improved soil health management systems, especially those known to increase soil organic matter (decreasing tillage intensity, adding organic amendments, adding cover crops, and increasing residue returns). Aggregate stability measurements are comparable across sites and over time, as long as the method is the same. Each of the aggregate stability tests in Table 1 require laboratory equipment for measurement except the SLAKES test, which uses a smartphone app. SLAKES is an attractive measurement because the SLAKES smartphone app is free and the measurement can be made by individuals without aid of specialized lab equipment.

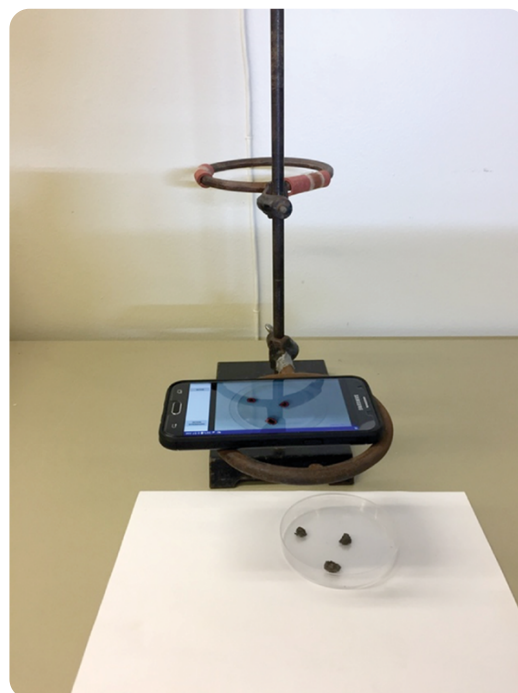
Table 1. A summary of methods to measure wet aggregate stability

^a Costs are approximated using published lab rates.

Method	Aggregate diameter(mm)	Sample mass(g)	Output unit	Cost ^a	Reference
Cornell Sprinkle Infiltrometer	0.25 to 2.0	20	% water-stable aggregates	\$20	Schindelbeck et al., 2016
Wet sieve	1 to 2	4	% water-stable aggregates	\$10–30	Kemper and Rosenau, 1986
SLAKES	3 to 10	8	% water-stable at 10 min	\$3	Fajardo et al., 2016 Flynn et al., 2020
Soil stability index	< 4.75	19	mean weighted diameter of stable aggregates/total weight of aggregates	\$20	Franzluebbers et al., 2000

Much information on a few soil health measures has been discussed. One cannot go wrong with choosing any of these methods (Table 2), as long as the measurement is providing useful information to the crop adviser, farmer, and any other stakeholder. When choosing a method, trade-offs in cost, value and relevance exist. In considering trade-offs of cost, transferability across time and between fields, ease of measurement in the field, and the expectation that a measurement will quantify changes in soil health, the following guidance is provided:

1. Aggregate stability responds to a wide array of soil health practices, and the smartphone application can be used by individuals without sending a soil sample to the lab (see Table 1).
2. Plant-available water responds well to practices that improve soil structure and increase soil organic carbon content. For now, the best way to monitor is through direct laboratory measurement. The Soil Health Institute intends to release a pedotransfer function that estimates plant-available water increase as a function of soil texture and increases in soil carbon content (a less expensive lab measurement).
3. Surface infiltration rate is either loved or hated by practitioners. Surface infiltration has a high variance and takes time to perform in the field. If this measurement is



SLAKES is an attractive measurement for aggregate stability because the smartphone app is free and the measurement can be made by individuals without aid of specialized lab equipment. Source: <https://doi.org/10.1002/saj2.20012>.

valuable to the stakeholder, it is better to measure the surface-saturated hydraulic conductivity. If the goal is to demonstrate differences between two management systems (at the same time and at comparable soil moisture content), the falling-head infiltration measurement used in the NRCS soil quality handbook is reliable and useful.

4. Bulk density is an essential measurement for monitoring soil carbon stock. For this use, bulk density samples from both 0- to 6- and 6- to 12-inch depths need to be collected. The same samples can be used to measure plant-available water. Using a penetrometer to measure penetration resistance is inexpensive and provides real-time demonstration. If a field demonstration is called for, this one is fun and provides good visual comparisons.

Table 2. A summary of measurements that indicate soil health relative to water cycling and development and functioning of soil structure

^a Fixed-cost estimates include a one-time cost of equipment (for the year 2020).

Measurement	Ease	Transferability	Cost ^a
Penetration resistance	Easy	best for side-by-side comparisons	Fixed \$50 to \$3500
Bulk density	Moderate	Yes	\$10 per sample
Falling-head infiltration	Moderate; time consuming	best for side-by-side comparisons	Fixed <\$20 set up
Surface-saturated hydraulic conductivity (Ksat)	Moderate; time consuming	Yes	Fixed \$3,600 per instrument
Plant-available water	Moderate	Yes	\$20 per sample
Aggregate stability-lab	Very easy	Yes	\$20 per sample

Measurement	Ease	Transferability	Cost ^a
Aggregate stability–smartphone	Very easy	Yes	Fixed <\$ 20 set up

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