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Soil Health

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Soil Health Testing to Support Conservation Planning

Acknowledgments

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Content

Objective

The purpose of the technical note provides an explanation to NRCS staff and partners with guidance on NRCS supported soil health lab indicators, methods used to assess indicators, and reading a soil health laboratory report. This technical note replaces Technical Note 450-03 Soil Health Indicators and Associated Laboratory Procedures and provides applied information to implement soil health testing.

1. Introduction to Soil Health Testing

1.1 Connection Between Soil Process, Resource Concerns, and Soil Health Testing

Our soils are one of our nation's most precious resources. American farms contributed over $136 billion to the U.S. economy in 2019 (Economic Research Service, USDA 2022). This economic output relies on the health and resiliency of the soil system and its ability to function in perpetuity. Soil health is defined by NRCS as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans." Poor soil health can lead to erosion, nutrient loss, reduced water holding capacity, and higher vulnerability to extreme weather events or pests, ultimately leading to lost productivity. The negative effects of nutrient loss and reduced productivity can cost farmers and communities billions of dollars per year (Dodds et al. 2009).

Soil degradation has economic costs for farming. Research from Iowa estimates that for each ton of soil lost to erosion, 2.32 lbs. of nitrogen (N) and 1 lb. of phosphorus (P) are lost along with critical micronutrients (Duffy 2012). Depending on the price of fertilizer, this could equate to a financial loss of $2.50 per ton per acre. The average erosion rate in the United States is 2.6 tons per acre per year. For a 500-acre farm, soil erosion could cost the business $3,250 annually in lost soil fertility alone. In Iowa, research documented 3-7% lower value for farms with degraded soil compared to those with good soil health (Duffy 2012).

Soil health is critical to protecting one of our nation's most valuable resources and helps us create efficient, productive, and sustainable agricultural systems (Lehman et al. 2015).
When incorporating soil health into management decisions, we must monitor and evaluate environmental and production (for example: yield and quality) outcomes to optimize our management systems. Soil health is connected to almost every aspect of management. Soil health is influenced by and in turn can affect:

- Cropping system decisions (for example: rotations, timing, tillage)
- Nutrient management and cycling
- Soil organic carbon quantity and quality
- Soil pH and nutrient availability
- Beneficial organisms and pest management

- Water infiltration and storage
- Soil aggregation
- Ease of field operations (for example: compaction, gully and rill formation, and soil moisture that either prevents or promotes operations)

The catastrophic consequences of the Dust Bowl demonstrated soil health is inextricably linked to human health and prosperity (Lehmann et al. 2020, and Ohno and Hetterachichi 2018). Degraded soil lost its ability to function and resulted in widespread suffering of communities around the nation. Monitoring the health of our soils is a critical component to the resilience of our agricultural systems. By using soil health indicators to evaluate changes to the soil ecosystem, we can address natural resource concerns, and better meet our short-term *and* long-term economic, environmental, and individual goals. Through practical, goal-oriented planning, implementation, and evaluation steps, we can meet our land use needs while protecting our soil resources for generations to come.

1.2 Soil Monitoring and Soil Health Testing

The primary goal of monitoring soil health is to provide producers, managers, and planners with useful information to optimize management and improve economic, social, and environmental wellbeing. Monitoring soil health and connecting results to production measures, such as ease of management, yield, or input costs, is the cornerstone of integrating soil health into the farm management system in a goal-oriented manner.

A central part of the goal orientated conservation planning process is the ability to identify and monitor resource concerns. Resource concerns are driven by soil processes and functions that are often difficult, if not impossible, to measure. Therefore, we use soil health indicators that represent important soil processes and resource concerns and are sensitive to management changes. Many soil health indicators have been identified that meet these criteria and can be incorporated into the conservation planning process.

The NRCS has recommended soil health indicators to assess specific soil processes that represent chemical, physical, and biological aspects of the soil ecosystem. These soil processes are critical to the functional health of the soil (Karlen et al. 2021a). A change in the soil processes outlined in table 1 are directly related to NRCS resource concerns such as erosion, compaction, aggregate instability, organic matter depletion, and soil organism habitat loss or degradation.

Table 1. Soil processes important to soil health and the function of the soil ecosystem.

Soil Process	Importance to Soil Health
Soil Organic Matter (SOM) Cycling	• SOM is transformed as it is decomposed by soil biota and can be released to the atmosphere as CO_2 or sequestered in soil as more stable carbon compounds
	• SOM is an important factor in soil structure, water storage and drainage, nutrient cycling and availability, biological activity, and soil physical stability.
Soil Structural Stability	• Refers to the resistance of soil aggregates to breakdown which is necessary for carbon accumulation.
	• Soil structure is characterized by stable aggregates and a range of pore sizes that facilitates infiltration, drainage, and storage of water.
	• A good balance of pore space can facilitate water infiltration, aeration, enhance root growth and proliferation, and gas exchange.
	• Structural stability affects the resistance or susceptibility to the erosive forces of wind and water.
	• Structural stability can facilitate field operations through resistance to compaction and rill and gully formation.
Microbial Activity	• Active microbes promote SOM cycling, nutrient cycling and availability, and soil aggregate formation.
	• High microbial activity has been linked to pathogen/pest resistance and improved crop health.
Carbon Food Source for Soil Microorganisms	• The availability of carbon food sources are a limiting factor for microbial community size, diversity and activity.
Bioavailable Nitrogen (N)	• Bioavailable N refers to N held in inorganic and organic forms that have the potential to be mineralized, therefore readily accessible to plants and microbes.
	• Bioavailable N may impact microbial community size and activity, and subsequent N availability for plants.
Microbial diversity	• Diverse soil microbial communities *may* be related to improved C, nutrient cycling, and soil aggregation.
	• Microbial diversity has been linked to pathogen/pest resistance and improved crop health.

1.3 Importance of Monitoring Soil Health

Monitoring soil health is necessary to optimize management on agricultural and forested lands in support of soil health. Perhaps a farmer is implementing a new conservation practice such as no-till or cover crops. Soil health testing to monitor changes over time can be used to evaluate the effectiveness of improving identified soil health resource concerns. It is possible that maybe they have a low-production field they would like to improve, or they want to develop new goals for their operation and want to look at the status of the soil and the potential for improvement. In any of these cases, soil health testing would be a great option to assist in setting goals and evaluating if goals are met.

Figure 1. Reasons why a producer would choose to include soil health testing in their conservation efforts.

1.4 Rationale for Soil Tests Chosen by NRCS

NRCS with partners from the Agricultural Research Service, and land grant universities, evaluated many soil health tests that were established indicators of the chosen soil processes during a series of workshops organized and sponsored by the Samuel Roberts Nobles Foundation and the Farm Foundation at the onset of the 'Soil Renaissance' in 2013. Resources such as the Kellogg Soil Survey Laboratory Methods Manual (USDA-NRCS 2022), the Soil Science Society of America - Methods of Soil Analysis (1986), the more recent Soil Health Series: Volume 2 Laboratory Methods for Soil Health Analysis (Karlen et al. 2021b), as well as peer-review publications, were used to identify soil health methods. While many soil health test methods are available and established in literature, soil health tests were selected to best fit the needs of farmers including cost and availability at soil laboratories. The following criteria were used to compile a list of recommended soil health tests:

1. Sensitive to agricultural management
2. Suitable for high throughput laboratory processing
3. Measurement repeatability is within acceptable boundaries
4. Interpretable for agricultural management decisions

Although many other indicators of soil health are available, the recommended indicators meet the above criteria and represent the identified soil processes and characteristics (table 2).

Table 2. Description of the chosen NRCS soil processes/characteristics, soil health indicators, and recommended methods.

Soil Process and Characteristic	Soil Health Indicator	Method	Description
Soil Characteristic	Soil Texture	KSSL* Particle Size Distribution by pipette Hydrometer Method	Soil texture helps to understand soil health test results because it shows what the soil is naturally capable of. * Kellogg Soil Survey Laboratory
	Soil pH	1:1 water	Soil pH is used for context to interpret soil health results. If the pH is too high or low, it can impact microbial activity and plant growth. The 1:1 water pH is more common but also more variable.
		0.01M $CaCl_2$	Soil pH is used for context to interpret soil health results. If the pH is too high or low, it can impact microbial activity and plant growth. $CaCl_2$ pH is less variable measure of soil pH.
Soil Organic Matter Dynamics	Soil Organic C (SOC) content *SOM is not the same as SOC. SOC is a constituent of SOM.*	Dry Combustion	Measure of the amount of SOC in the soil. This method consists of a soil sample heated to 1200ºC and the evolved CO_2 is measured with infrared spectroscopy. *Sometimes SOC is reported as organic carbon, total organic carbon, or total carbon (TC) in soils pH ≤ 7.2. Soils with a pH ≥ 7.2 require a correction for the soil inorganic carbon to calculate SOC from TC.*
		Loss on Ignition	A rapid indirect method to estimate SOC by measuring the weight loss of a dried sample after combustion in a muffle furnace at high temperatures (typically 300-550 ºC). SOC calculated from SOM measured by loss on ignition.
Soil Aggregation	Wet Aggregate Stability	Wet Sieving	Measure of the amount and size of soil aggregates resistant to slaking in water.

Soil Process and Characteristic	Soil Health Indicator	Method	Description
		Cornell Sprinkler Infiltrometer	Evaluate the physical soil environment related water infiltration, carbon and nutrient storage, biological activity, and reduced erosion.
		Image Analysis	Image analysis is used to measure the ability of dry soil aggregates to resist dispersion once wetted. Weaker aggregates will slake (or break apart) more easily, while stronger aggregates will slake less, indicating better soil aggregation and healthier soil.
General Microbial Activity	Soil Respiration	Short-term C mineralization - CO_2 respired for 24-hours or 96-hours incubation	Measure how active and abundant the microbes are in the soil.
Carbon Food Source	Readily available C pool *Sometimes called the labile C pool*	Permanganate-oxidizable Carbon (POXC) *Sometimes called active carbon*	The amount of organic C is readily oxidizable (available) to support the metabolic activity of the soil microbial community.
		Water extractable organic carbon (WEOC)	Organic C that can be extracted from soil using water, assumed to be available to support the metabolic activity of soil organisms.
Bioavailable N	Available organic N	Autoclaved citrate-extractable (ACE) protein content	The amount of organic N is readily available to support the soil organisms.
		Water extractable organic carbon (WEON)	The amount of organic N is readily available that can be extracted from the soil using water assumed to be available the metabolic activity of soil organisms.
Microbial/ Functional Diversity	Community structure of microorganisms	Phospholipid fatty acid (PLFA)	A molecular measure of the size and broad categorization of the living microbial community.

Soil Process and Characteristic	Soil Health Indicator	Method	Description
	Enzyme Activity	β -Glucosidase	A catalyst excreted by microorganisms to promote organic C breakdown.
		N-acetyl-β-D-glycosaminidase	A catalyst excreted by microorganisms to promote organic C and N breakdown.
		Protease	A catalyst excreted by microorganisms to promote organic N breakdown.
		Phosphatase (Acid or Alkaline)	A catalyst excreted by plants and microorganisms to promote organic P breakdown.
		Arylsulfatase	A catalyst excreted by plants and microorganisms to promote organic S breakdown.

1.5 Soil Health and Fertility Testing

Soil health tests are a relatively new tool to use for crop management. Land managers may be more familiar with soil fertility tests as a management tool. While soil fertility is an important part of soil health, there are some important differences between the two types of testing (table 3). Ideally, both soil health and fertility testing will be used to manage the cropping system. Both types of tests provide key information that influences crop and soil management. Many laboratories will offer soil health packages that include both soil health and fertility tests. While these packages offer a comprehensive snapshot of the soil health, it is important to note that the fertility results should not be used for nutrient management planning due to potential differences in how and when the soil is sampled.

Table 3. Differences between soil health and soil fertility tests. Each group focuses on different aspects of the farm management system and together provides a holistic picture of system health.

Common Groups of Indicators	Measurement Type	Description
Soil Health Tests	Biological, Physical, and Chemical (related to soil biology and carbon)	• Measures biological, physical, and chemical status of the soil. • Focus is on ecological status and soil function. • Are sensitive to management and disturbance. • Values are generally "directionally understood," i.e. higher is better. • Established in research and have been effective at detecting differences in management in laboratory and field experiments. • Values may not be well defined regionally, making comparison difficult. • Need more work to be widely correlated to regional production outcomes. • Methods are not always standardized or comparable. • Many indicators can be highly variable within a given region due to differences in soil sample collection, season, temperature, moisture levels, crop, and biological activity "hotspots."
Soil Fertility Tests	Chemical	• Used by producers and planners to calculate nutrient application rates for crop production. • Evaluates the chemical status of the soil, such as available nutrient content, cation exchange capacity (CEC), and pH – all considered important components of soil health. • Methods are standardized within a given region and calibrated to an expected yield response determined by research at land grant universities. • Results from the same methodology are generally comparable within that region. • Most give little or no information on soil physical or biological status.

2. Conducting Soil Health Testing

2.1 Planning Soil Health Testing

The following questions can be used to plan monitoring activities:

- Producer goals
  - Do they want to address resource concerns such as SOM depletion, aggregate instability, compaction, or soil organism habitat?
  - Are they making a change to their management and want to measure the effect?
  - Are they trying to diagnose a poor yielding area or discover the potential of their soil?
  - Are they trying to develop soil health goals for their land?
- Information needs
  - How will the data be interpreted and used after analysis?
  - Do you need to track the changes over time?
  - At what point in their cropping system does it make the most sense to test? Often testing is done just before planting the cash crop.
  - What soils or management do you want to compare?
- Choosing indicators that provide the most useful information
  - Indicators should be related to the producer's goals. Are they interested in microbial activity? Nitrogen cycling? Soil aggregation? All of the above?

The answers to these questions will help you plan the soil sampling, select the soil health tests, and determine how the test results will be interpreted after analysis. Additional information on potential comparisons is in Section 4.

2.2 Soil Sampling Considerations

The soil ecosystem is an extremely dynamic system that can vary greatly over time and space. Well-planned, careful, consistent, and documented soil sampling is critical to the accurate monitoring and interpretation of soil health. Repeating the sampling plan over time can minimize variability. Detailed guidance for sampling can be found in Technical Note No. 470-07 Soil Health - Guidance on Field Grab Sampling for Soil Health Testing (USDA-NRCS 2024). At a minimum, the following items should be considered when planning soil collection for testing:

1. It is imperative that the chosen soil sampling plan be used consistently over time.
2. Soil should be sampled at the same depth (0-6 inches (0-15 cm)) at each collection.
3. Avoid edge of field, high traffic, or abnormal areas.
4. Timing: sampling should be conducted at the same time of year to ensure that sampling conditions are as consistent as possible.

   a. Preferably before seasonal management activities. Spring is generally recommended but depends on the site and crop.
   b. Moderate soil moisture facilitates soil collection: avoid excessively wet or dry soil.
5. Laboratories often have different instruments or protocols that will affect the results. The same laboratory should be used over time to ensure results can be compared over sampling years.
6. Once a trend has been established (more frequent sampling may be needed to establish a trend at the outset), subsequent soil monitoring should proceed based on the goals of the producer.
7. Communicate with the selected laboratory prior to the sampling event. Depending on the tests selected, considerations may include equipment type, storage containers, and proper timing to shipment. For example, samples that will be used for biological analysis such as PLFA or soil enzymes should be kept as cold as possible; spade or sharp-shooter should be cleaned between samples and samples should be shipped as soon as possible.

2.3 Lab Selection

Any lab that offers soil health testing can be chosen, provided it maintains a current certification from one of the following:

a) The Performance Assessment Program from The North American Proficiency Testing Program under the auspices of the Soil Science Society of America, or

b) The American National Standards Institute, National Accreditation Board, or

c) The International Organization for Standardization (ISO/IEC 17043:2010) for ISO 10694:1995, or

d) State-approved certification program that considers laboratory performance and proficiency to assure accuracy of soil test results.

Laboratories may offer soil health packages that include multiple tests. These packages are an excellent option as they offer measurements that provide information on multiple aspects of soil health. Ensure that the chosen package offers the desired indicators and methods, as there may be several methods available.

Labs may change their available tests or procedures over time, which may not be noted on their website. Additionally, they may have specific guidance on the amount of soil to collect, soil storage, and shipping. **Labs should be contacted by email or phone before soil samples are collected to ensure current and complete information.** Detailed guidance can be found in Technical Note No. 470-01 Soil Health Division: Choosing a Laboratory for Soil Health Testing (USDA-NRCS 2023).

3. Soil Health Indicators

Soil indicators are most useful when they are measured in a suite of tests. Monitoring several indicators at once gives us a much better picture of overall health. A soil health indicator may have several different testing methods that are associated with it. NRCS chose the most appropriate method based on the criteria outlined in Section 1.4. Following are descriptions of soil health indicators and their recommended preferred or alternate methods. While each method may have unique benefits and challenges, selecting multiple indicators allows us to capture different aspects of soil health, provide more context for soil health interpretation, and mitigate some of these challenges.

3.1 Soil Organic Matter Dynamics

Soil Organic Carbon Content

Description
SOM is the organic component of the soil, such as a residue of a once-living organism or a byproduct of a living thing. SOC is the carbon fraction of SOM; generally, 45-60% of the SOM total weight. Soil organic carbon is a very well-established indicator and method, however, the amount of SOC in the soil sample can be slow to change, making it difficult to use as a sole indicator. It is possible to infer SOC effects on physical, chemical, and biological aspects of the soil ecosystem due to its importance for soil structure, biological activity, and both nutrient and water holding capacity.
Importance
SOC is one of the most important and most studied soil health indicators because it is connected to many aspects of soil health, including soil structure; ability to accept, filter, and retain moisture; sustain microbial and invertebrate life; supply nutrients; and resist erosion, among others.
Methods
• **Dry Combustion** - A soil sample heated to 900-1200ºC and the evolved CO_2 is measured with infrared spectroscopy (USDA-NRCS 2022). Sometimes SOC is reported as organic carbon, total organic carbon, or total carbon (TC) in soils pH ≤ 7.2. Soils with a pH ≥ 7.2 require a correction for the soil inorganic carbon to calculate SOC from TC. • **Loss on Ignition** - A rapid indirect method to estimate SOC by measuring the weight loss of a dried sample after combustion in a muffle furnace at high temperatures (typically 300-550 ºC). SOC calculated from SOM measured by loss on ignition.
Interpretation
"More is better." It is generally understood that increasing SOC in a soil is considered an improvement in soil health. Most soils have an inherent upper limit for SOC, which can be found using USDA-NRCS Web Soil Survey-https://websoilsurvey.nrcs.usda.gov.

Drivers
SOC is more likely to accumulate in cold, wet environments than hot or dry environments. This is because biological activity resulting in oxidation of SOM and release of SOC as CO_2 is greater under warm and oxygen-filled environments. Soil organisms process soil organic matter as "food." Some carbon in SOM is respired as CO_2 gas, while some is stabilized into long-term SOM. Whether SOC is more likely to end up respired or stabilized depends on factors such as SOM inputs, microbial carbon use efficiency, disturbance, and climate.
- Living roots increase SOC by releasing sugars from their roots to recruit microbial symbionts at the root surface. High soil bulk density may curb root growth and proliferation, thereby resulting in limits to SOC accrual.   - High disturbance can reduce SOC. For example, tillage can aerate the soil and temporarily increase C mineralization and microbial respiration, while decreasing the establishment of beneficial fungi and reducing aggregate stability.   - Erosion typically results in the translocation or loss of surface soils, which can be SOC-rich.   - Topography drives SOM formation; SOM tends to be greater and permeates deeper in lowland soils, toe slopes, and coves, due to gravity that collects SOM-rich eroded topsoil and water as well as physical protection. These low, wet areas may also be difficult to farm and therefore may be less subject to disturbance.

Management
- Management practices, such as tillage, that disturb the soil and change soil biological and physical properties, have the potential to alter total SOM in the long-term.   - Cover crops or perennial crops may increase SOM through multiple routes. They keep living roots in the ground, thereby exuding SOM and supporting microbial activity; they protect the soil surface from compaction by raindrops; they prevent erosion; and their biomass can be incorporated to add SOM formed through the process of photosynthesis.   - Organic inputs such as biochar, compost, plant residues, cover crop biomass, or manure can replenish SOM lost due to management-related disturbance and harvest (removal of SOM from the landscape).   - Reducing tillage can support SOM accrual by keeping SOM protected in soil aggregates and allowing SOM to percolate deeper into the soil.

3.2 Soil Structural Stability

Wet Aggregate Stability

Description

Soil aggregation is an important indicator of soil organism habitat, water infiltration, resistance to erosion, and SOC storage. It is measured by a soil sample's ability to resist slaking (breaking apart in water) when subject to disturbance. This indicator can be powerful for producers as improved aggregation can be detected by the naked eye and observed during farm operations.

Importance

Aggregate stability is an important contributor to soil structure and indicator of resistance to disturbances that may ultimately lead to collapse of structure or erosion. Unstable aggregates have been shown to be more susceptible to surface crusting, interrill erosion, and runoff. Stable aggregates support gas exchange through pore spaces to facilitate root and soil organism growth.

Methods

Common methods include:

Wet sieve with pre-wetting (Rieke et al. 2022, USDA-NRCS 2022)

Sprinkle Infiltrometer (Mobius-Clune et al. 2016, Rieke et al. 2022)

Image Analysis (Rieke et al. 2022)

Interpretation

"More is better." Aggregate stability can be measured in percent stable aggregates or in a somewhat abstract value called Mean Weight Diameter (MWD) that takes into account various aggregate sizes. In both cases, higher percentage stable aggregates or a larger MWD value is considered better.

Drivers

- In general, micro-aggregation (53-250 μm) is an inherent soil property influenced by mineralogy and texture, while the degree of macro-aggregation (> 250 μm) is highly influenced by management.
- Clays and Al- and Fe-(hydr)oxides help form organo-mineral associations found within microaggregates, and are glued together by carbonates, SOM, and short range ordered phases of Al, Mn, and Fe.
- SOM, microbes (especially fungal hyphae), and roots all secrete organic compounds that act as "glue" to bind microaggregates into macroaggregates.
- Pores conduct water down into the soil profile and serve as an important location for gas exchange. Both water and air sustain plant and microbial activity in the soil, which contributes to aggregation.

Management
• No-till and reduced tillage protects aggregates from the physical disturbance of plowing implements slicing into the ground and breaking them apart. • Transitioning from high to lower disturbance systems can help preserve aggregates; for example, switching from tilled annual row crops to perennial systems. • Cover cropping and continuous roots contribute to aggregation by protecting surface aggregates from the repeated pressure of raindrops and support sub-surface aggregation through root exudates that help glue soil particles together. • Organic amendments such as compost, biochar, and plant biomass act as "food" to support soil organisms populations that support macro aggregation.

3.3 General Microbial Activity

Soil Respiration – Short-term C mineralization

Description
Microorganisms serve many critical functions in the soil such as decomposing organic residues and improving soil structure. While they are conducting these important tasks, they are respiring and exuding different compounds. These compounds include enzymes that act as catalysts to break down organic molecules. To monitor their activity, laboratories can measure different products from their activity.
Importance
The amount of the CO_2 that is respired by microorganisms (soil respiration) can be used as an indirect measure of microbial activity.
Methods
Short term C mineralization 24 hour or 96-hour incubation (Franzluebbers 2016).
Interpretation
Higher respiration is associated with higher microbial activity and N mineralization. Disturbance can lead to a temporary increase in microbial respiration. For example, tillage can increase aeration in the soil and spike respiration. Interpreting this indicator should be done in the context of field operations.
Drivers
• Microbial biomass is highly correlated to soil respiration, where more microbial biomass typically results in higher respiration levels. High respiration and high microbial biomass are indicative of nutrient cycling and mineralization to support healthy plants. • Aerobic conditions support microbial gas exchange and proliferation, resulting in higher basal respiration. • Soil organic matter supports microbial life by acting as "food" – soils with higher SOM tend to have higher microbial activity and respiration.

Management

- Cover cropping and perennialization provide continuous roots to support soil respiration by supplying microbes with "food" in the form of plant biomass and sugary root exudates.
- Reduced and no-till can support microbial growth and activity by reducing soil habitat disturbance.
- Fresh organic amendments (manure, compost, etc.) typically result in a flush of microbial soil respiration and enzyme production.
- The C/N ratio of amendments is important to consider when managing to support microbes, because N is needed to break down the organic compounds. Low C/N ratio amendments, such as legume biomass, tend to support more short-term microbial activity.

3.4 Enzyme Activity – Carbon, Nitrogen, Phosphorus, and Sulfur Cycling Enzymes

Description

Similar to soil respiration.

Importance

The activity of enzymes that are exuded by microorganisms (potential enzyme activity) can be used as an indirect measure of microbial activity.

Methods

Potential Enzyme Activity (Dick 2011) – Individual enzymes are chosen for their role in nutrient's cycling:

β -Glucosidase (carbon)
N-acetyl-β-D-glucosaminidase (carbon and nitrogen)
Protease (nitrogen)
Phosphatase (acid or alkaline) (phosphorus)
Arylsulfatase (sulfur)

Interpretation

In general, more is better. Higher activity can be in response to substrate demand or availability (Nevins et al. 2020, Starr et al. 2024).

Drivers

- More microbial biomass can result in higher nutrient demand and increased enzyme activity. High respiration and high microbial biomass are indicative of nutrient cycling and mineralization to support healthy plants.
- The application of excess inorganic nutrients has been shown to suppress some enzyme activity.
- Soil organic matter supports microbial life by acting as “food” – soils with higher SOM tend to have higher microbial activity and nutrient demand. This can result in higher enzyme activity.
- Enzymes are excreted in response to higher nutrient demand.
- Higher enzyme activity can indicate higher microbial activity and higher nutrient cycling potential.

Management

- Cover cropping and perennialization provide continuous roots to support soil respiration by supplying microbes with “food” in the form of plant biomass and sugary root exudates.
- Reduced and no-till can support microbial growth and activity by reducing soil habitat disturbance.
- Fresh organic amendments (manure, compost, etc.) typically result in a flush of microbial soil respiration and enzyme production.
- The C/N ratio of amendments is important to consider when managing to support microbes, because N is needed to break down the organic compounds. Low C/N ratio amendments, such as legume biomass, tend to support more short-term microbial activity.

3.5 Carbon Food Source

Readily Available Carbon Pool

Description

The readily available carbon pool is an important source of food for microorganisms. Common substances that are measured as part of the available carbon pool include root exudates, easily mineralized carbon compounds from plant and animal residues, and water-soluble organic compounds. The available carbon can either be respired as CO_2, incorporated into the living organism biomass, or be stored in a more stable carbon pool.

Importance

The readily available carbon pool is part of the larger soil organic carbon content but adds more information about the quality and availability of the carbon in the soil, and the ability of the soil to support the microbial community. For example, a soil that was amended with wood chips may have high SOC but low available carbon; a soil that had a history of cover crops would likely have high SOC in addition to a large available carbon pool.

Methods
• POXC (sometimes called Active Carbon) - Potassium permanganate is theoretically "mimicking" the oxidative activity of microbes on organic matter. This provides a measure of carbon that is readily available to microorganisms (Schindellbeck et al. 2016, USDA-NRCS 2022, Weil et al. 2003. The amount of organic C that can be extracted from the soil using water, assumed to be available to support the metabolic activity of the soil organisms. This is considered as a labile fraction of the total soil carbon pool (Ghani et al. 2003). • WEOC – Water Extractable Organic Carbon – The active soil carbon pool that is easily mineralizable and therefore a direct driver of microbial activity and responsible for providing N and P mineralization in soil (Haney et al. 2012) (Haney et al. 2018).

Interpretation
"More is better". This indicator can be very sensitive to growing roots and seasonal variation.
Drivers
• Living roots may increase POXC or WEOC
Management
• Use of cover crops, reduced fallow periods, reduced tillage, diversified crop rotations, and amendments (for example, manure or compost) have all been shown to increase readily available carbon.

3.6 Bioavailable Nitrogen

Available Organic N - ACE Protein

Description
Measure of the organically bound nitrogen that is available to microorganisms. This pool of N can be mineralized and made available to plants and other organisms.
Importance
Similar to organic C, available organic N is an important source of nutrition of the soil ecosystem. Nitrogen availability is highly correlated with microbial activity. Protein is the largest pool of organically bound N in the soil and can influence soil function by simultaneously storing and releasing N.
Methods
• ACE Protein is the quantity of protein extracted in a soil through the use of an autoclave and dilute citrate solution (Hurrisso et al. 2018, Naasko et al. 2024, Schindelbeck et al. 2016). • WEON is the amount of organic N readily available that can be extracted from the soil (using water assumed to be available) for the metabolic activity of soil organisms (Haney et al. 2012) (Haney et al. 2018).
Interpretation
"More is better". This indicator can be sensitive to soil conditions and N management.

Drivers
• Carbon management and soil fertility can influence the amount and storage of organic nitrogen. • Low soil moisture can accelerate the loss of ACE protein due to management (Graham et al. 2021). • High clay and high pH may negatively impact ACE protein levels. The mechanism behind this is unknown.
Management
• A combination of soil health practices that focus on increasing organic matter, maximizing biomass, and balance soil fertility. • Because available organic N is a fraction of SOM, management practices that enhance SOM such as reduced and no-till management, diversifying crop rotations, and adding leguminous cover crops may improve ACE protein.

3.7 Microbial Diversity

Community Structure of Microorganisms - PLFA Analysis

Description
Many different groups of microorganisms live in the soil ecosystem, performing many different critical functions. Laboratory methods allow managers to take a snapshot of the microbial biomass and broad community structure in the soil.
Importance
Soil microorganisms provide a litany of benefits to the agricultural systems and the environment. Fostering a large and diverse microbial community is an important consideration when addressing cropping system sustainability.
Methods
PLFA is a method that identifies and measures indicator biomolecules from cell membranes to determine the size of the microbial biomass and offers an estimate of some broad community groups such as bacteria, fungi, arbuscular mycorrhizal fungi, and actinomycetes (Fanin et al. 2019, and Frostegård et al. 2011).
Interpretation
Interpretation is challenging and not well understood. In general, a larger total microbial biomass is preferred. Ranges of values relative to soil function are not well defined. PLFA has been shown to be sensitive to short-term management changes.
Drivers
• Microbial abundance and diversity can be affected by disturbance, soil amendments, soil fertility management, pH management, soil cover, compaction, and plant diversity. • This test is very sensitive to sampling conditions such as soil moisture and temperature. There is high seasonal variability.

Management
• Following the principles of soil health by increasing diversity, root growth, and soil cover, and minimizing disturbance can increase microbial abundance and diversity. Balanced soil fertility and pH management can increase microbial diversity.

4. Soil Health Indicator Interpretation

4.1 Importance of Site Characteristics

It is important to recognize that the potential for soil health varies between sites, cropping systems, and land uses. Putting soil health results in context is a critical part of soil health testing. For instance, soil health test results from an orchard in Hawaii will differ from those in a corn field in Iowa. The soil conditions such as pH and texture provide important context when conducting soil health testing. These conditions can impact the soil health potential of a given soil (table 4). For example, a sandy silt loam or a soil with very low pH may have lower soil health test numbers than a soil with less sand or a more neutral pH.

Table 4. Rules of thumb related to common soil characteristics and their potential impact on soil health.

Soil Characteristic	Favorable	Unfavorable
High Sand Content	Well drained Resists compaction Good resistance to erosion (unless sand is fine).	Slow to increase organic matter due to decreased ability to hold water. Low inherent fertility Low CEC
High Silt Content	Good drainage and water holding capacity. Medium CEC	High erosion potential
High Clay Content*	High water holding capacity High fertility High CEC Good resistance to erosion if aggregated.	Can hold water so tightly that it is not available to organisms. Poorly drained – can become waterlogged, reducing microbial activity and plant growth. Can become compacted more easily High resistance to pH change
Organic Matter	Good drainage and water holding capacity. High fertility High CEC Helps the soil resist erosion and compaction. Reduces bulk density	Can be difficult to accumulate in dry areas. Can be lost to erosion when accumulated on soil surface. Possible for highly amended soils to have too much organic matter – can become a nutrient loss risk

Soil Characteristic	Favorable	Unfavorable
	(Especially important in surface layers of Oxisols and other low fertility soils.)	
Very low or high pH	Certain plants thrive in low or high pH environments.	Reduces nutrient availability for plants and soil organisms. Can increase the availability of undesirable elements.
Iron and Aluminum Oxides (found in high concentrations in Oxisols)	Well aggregated Resist compaction and erosion Reduced stickiness when soil is wet.	Low ability to hold nutrients High ability to fix P so that it is not available to plants. Can reduce the CEC of silicate clays by masking their charge sites. In acidic conditions, Fe and Al become more soluble & toxic to plants.

*Clay minerology can impart many different properties to the soil. Knowledge of common clay properties is an important consideration.

4.2 Monitoring Objectives and Soil Sampling

As discussed in Section 2, using farmer goals and desired comparisons will help in the planning for sampling and also how we can use those comparisons once we get our results from the lab. The following table provides some examples of different comparisons that can be made using soil health tests.

Table 5. Types of comparisons that can be made using soil health testing.

Type of comparison	Description and Example
Management comparison	Comparison of one area to another that has a conservation practice. Example: A silvopasture system is established and compared to traditional pasture.
Best versus troubled areas	Comparison of a high to a low producing area. Example: A winter wheat field has a low producing spot compared to the rest of the field.
Comparison to nearby reference	A sample is taken from a crop field and compared to one from the fence line to compare the soil health of the field to the potential for that soil. Example: A sample from vegetable beds is compared to an undisturbed soil sample from under the fence.

Type of comparison	Description and Example
Soil health models	The results from a soil health test are compared to a database of other soil health results that have been used to develop the model. The model will often correct for climate and soil type to determine if the results are high or low compared to the expected range. A valuable assessment requires sufficient data from your region and cropping system. Example: The Cornell Soil Health Lab provides an assessment report of test results to provide a rating based on their model and the expected values.
Trends over time	Soil samples are collected and analyzed over several years. The results are compared to see if the numbers are trending in the desired direction. This approach can be challenging because some years are influenced by weather, affecting the outcome and subsequent comparisons. Example: A farmer took a sample from their field as a baseline and then collected samples over multiple years. They observed that soil organic matter and soil respiration were decreasing incrementally over time while compaction was increasing.

4.3 Soil Health Models

If a soil health model or assessment framework is available and calibrated to your region, the value can be interpreted as being poor to excellent for the area. Until more data is collected, evaluated by region and soil type, and connected to desired production outcomes, single time-point evaluations of soil health have limited interpretation value.

While some research has shown that some models and soil health assessment frameworks can distinguish differences between agronomic management practices, research connecting soil health assessment frameworks to specific production outcomes, such as yield, increased nutrient efficiency, water quality, minimized labor, or minimized inputs, is limited (Baldwin-Kordick et al. 2022, Moebius-Clune et al. 2016, USDA-NRCS Tech Note 450-03 2019; van Es and Karlen 2019). The Natural Resources Conservation Service and the Agricultural Research Service are working to collect soil health data from across the country to calibrate the USDA SHAPE model to improve assessment and predictive capabilities to provide producers with the most useful management information. Future versions of SHAPE are under development to expand the dataset for better representation (more labs are producing data for soil health initiatives) and to provide multiple layers of interpretation.

Soil Health Assessment Planning and Evaluation (SHAPE)

Most recent soil health modeling tool developed by USDA ARS –for use by NRCS to interpret soil health test results.

Based on concepts found in previous soil health frameworks such as the Comprehensive Assessment of Soil Health and Soil Management Assessment Framework.

Calibrates regionally specific scoring curves to interpret soil health indicators for cropping systems (Nunes et al. 2021).

Based on a large dataset (almost 15,000 soil samples) from across the US, from a wide range of site conditions and values.

Creates soil "peer groups" that reflect soil texture and soil suborder groupings that are adjusted for regional climate conditions (mean annual temperature and precipitation).

The soil peer groups provide context for scoring data for new soil samples, and the SHAPE score tells you where in the peer group distribution your sample fits. For example, a SHAPE score of 62% means there is likely room for improvement; whereas a score of 96% means the soil may be near its expected potential.

4.4 Recommended Steps to Read a Soil Health Report

1. Refer to description of the individual indicators in this guide to refresh understanding of the metric, soil process it represents, and ensure the methods were the same (if needed).
2. Look for local research or other sources (neighbors, university extension) to determine an estimated value range for your area and land use.
    a. Values entered into the SHAPE model or other frameworks will provide this context.
    b. If that information is not available, don't fret! You may be a pioneer and the first to document these values in your area.
3. If that format is not provided from the lab, enter values in a spreadsheet.
4. Enter the range of values for each indicator for all the samples.
    a. Is there a large spread among the values or are they relatively similar?
    b. Are there any outliers (values that are very different from the others)?
    c. If your values are outside the expected range, call the lab to discuss the results to see if they are within a reasonable range.
5. Calculate the percent difference between the sample values from the same sampling period for each indicator.
    a. Do any of the fields begin to stand out?
    b. Don't be concerned if some indicators conflict, it is the overall picture that is most important.

6. Compare the results from the same field at different time periods if you have the data available.
    a. What is the change from year to year?
    b. Are some values moving up or down by an amount that seems noteworthy?
7. Compile the soil health indicator values with other available data from the same field such as soil fertility reports, yield, and field observations, and organize by cropping year (begins at the end of one harvest and ends when the next crop is harvested).
8. Note any trends, observations, field notes, and historical information for each field site to build a picture of system health, changes, desired outcomes (measured or not), and challenges to adjust the planning process.
9. Look for local research to determine an estimated range of results.

Soil health indicators are used to take the figurative "temperature" or general health of the soil. As previously discussed, they can be highly variable and change in response to soil temperature and moisture, crop, field history, pH and nutrient management, among other things. These indicators are most valuable when interpreted with other farm measures and used to monitor health change.

4.5 Example Soil Health Lab Report

Figure 2. An example soil health lab report from the Soil Health Lab at Oregon State University and some potential observations.

Name:	Petunia Pug Farms
Organization:	
Contact for results:	Lady Evelyn Pigglesworth
Date submitted:	04/20/2025
Date delivered:	05/22/2025
Group number:	

Sample ID		**%**				**µg CO2-C/g dry soil/day**		**ppm**
Customer ID	**Lab ID**	**Moisture**	**C**	**N**	**OM**	**CO2 Respiration 24 hr**	**CO2 Respiration 96 hr**	**Active Carbon (POXC)**
Conventional	1	28	1.84	0.15	3.68	46	23	315
No Till w/ Cover Crops	2	24	2.10	0.16	4.40	62	33	394
Fence Row	3	24	2.26	0.10	4.52	79	41	356

Sample ID		**%**				**pH Units**	**mg protein/g dry soil**
Customer ID	**Lab ID**	**Water Stable Aggregates**	**Sand**	**Silt**	**Clay**	**pH**	**ACE Protein**
Conventional	1	32	24	54	22	6.49	2.55
No Till w/ Cover Crops	2	46	18	60	22	6.34	3.57
Fence Row	3	52	18	60	22	6.51	4.15

Potential Observations

1. Sample 3 has higher SOC, SOM, aggregate stability, ACE protein, and microbial respiration. This provides a good general measure of the soil's potential because it has not been disturbed (dark green).
2. Sample 2 has higher SOC, SOM, microbial respiration, and POXC than sample 1, indicating an improvement from the no-till and cover crop (light green).
3. Sample 2 may have higher POXC than sample 3 due to the cover crop that was growing just before soil sampling (pink).
4. Sample 1 has more sand than sample 2 and 3, which can reduce the aggregate stability, and SOC. This difference may reduce the soil health potential compared to samples 2 and 3 (light orange).
5. The ACE protein was higher in sample 3. If we include a leguminous cover crop next season, we may be able to increase the ACE protein in sample 2 (blue).
6. Soil pH was relatively similar across the samples. If they were lower or higher than desired, pH management would be a good step towards better soil health.

4.6 Challenges to Interpreting Soil Health Indicators

Interpreting soil health indicators is often a subject of debate and confusion. While soil fertility tests are often related to local calibrations from crop response experiments and yield goals based on many decades of data, soil health indicators have not yet been validated in the same way. There are several reasons for this:

1) **Most soil health indicators – by nature – are not direct measurements.** An example of a direct measurement might include a biochemical analysis of the prevalence of different chemical bonds present in a soil's organic matter. Instead, indicators are tests that we use as proxies, or stand-ins, because direct measurements are too expensive, time-consuming, or difficult to measure. Therefore, soil health indicators can tell us about soil health because they are theoretically related to concepts of soil health and sensitive to changes in management, but they do not directly measure outcomes.

2) **Soil health looks different depending on the soil type (Zuber et al. 2020).** The potential capacity of a soil to perform a certain function is governed by factors we cannot typically change through management, for example: soil texture, mineralogy, topography, hydrology, and climate. For example, we wouldn't expect a sandy soil in a warm, dry climate to exhibit the same range of soil health values as a silt loam soil in a cold, wet climate. Therefore, much of the way we interpret soil health is relative to what is possible in the region, or relative to the same location at a different time, and some regions are studied more than others. Similarly, some indicators might be more significant in one soil type than another.

3) **Concepts of soil health may be value-driven and dependent on land use.** That is, landowners manage soils for different purposes (for example: annual commodity crop production, forestry, rangeland, etc.) and may prioritize different aspects of soil functions, such as nutrient management, carbon storage, or water movement. Further, the prioritization of different aspects of soil health may be driven by personal interests, values, and pressures.

4) **We do not know everything yet.** Soils are complex matrices of solids, liquids, and gasses, with both biotic (living and dead) and abiotic (non-living) components. Defining and evaluating soil health in the Western scientific tradition has occurred primarily over the past thirty years, and the tools that we use to evaluate soil health are changing rapidly. When it comes to many of the soil health indicators discussed in this document, the knowledge of what an indicator is physically measuring has yet to be understood. Without this knowledge, it becomes difficult to connect soil health indicators to management outcomes.

5. Key Take Aways

1. Using soil health tests can be a useful tool to make comparisons, set goals, and monitor progress for producers.
2. Use multiple soil health indicators to get the most information about the health of your soil.
3. Changes to the soil ecosystem can be slow in some regions. Allow 3-5 years (up to 10 years in dry regions) to observe consistent soil health improvements.
4. Careful planning should be conducted before sampling the soil.
5. Sample in the same way, using the same lab over time if possible.
6. Soil health testing is complex. Find references and request help early and often. NRCS, land grant university extension, and technical service providers are excellent sources of information.
7. A soil health test is a snapshot in time. Consider production outcomes such as ease of field operations, yield, and off-farm inputs, and site history put your results into context. Use comparisons, soil health models, and monitor overtime to interpret your results.
8. Monitoring soil health can be challenging and must be evaluated based on the soil type, regions, and production system.

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