A PRACTICAL GUIDE TO SOIL HEALTH INDICATORS FOR MONITORING SHIFTS IN SOIL ORGANIC MATTER

Abstract

Improving and maintaining soil health can have a wide range of economic benefits including reduced input costs and improved crop growth, quality, and yield. Soil organic matter (SOM) is a commonly used metric for assessing soil health but can be slow to respond to management changes, taking years or even a decade for measurable changes to occur. Soil health indicators that can detect shifts in microbial activity, carbon (C) cycling, and nutrient cycling are more responsive than SOM and can help producers see if they are moving in the right direction.

This publication provides an overview of soil health indicators that are related to shifts in SOM but can respond more rapidly to management changes. This practical guide will help producers navigate the names of tests, their availability in the Pacific Northwest, and the relevance of each test to production systems.

Dynamic Soil Health Indicators

Increasing soil organic matter (SOM) can address a host of production limitations in agricultural systems by improving soil nutrient supply, biological activity, structure, and water holding capacity. Levels of total SOM in agricultural soils typically range from 1 to 6% and are influenced by climate, soil texture and mineralogy, and management. Practices such as reducing tillage frequency and intensity, integrating cover crops into a rotation, and applying compost or manures can increase SOM levels over time.

The measurement of SOM is common in routine soil testing. Producers can monitor SOM to track long-term effects of changes in management practices. The SOM measurement represents the totality of organic matter in soil, which includes several fractions that play distinct roles in the soil environment. While multiple factors such as soil texture, disturbance intensity, and crop rotation can affect SOM levels, SOM levels are highly dependent on the quantity of organic material being added to the system. Even with high residue inputs in a fine-textured soil (meaning a soil dominated by clay, such as a clay loam, silty clay, or clay textured soil), an increase of only 0.1% SOM per year is to be expected (Magdoff and van Es 2021). It can often take 5–10 years to measure changes in SOM in response to management changes. However, by looking at individual chemical and biological pools that make up SOM we may be able to see changes much faster, sometimes in as few as 3 years. There are soil health indicators that can detect changes in microbial activity, carbon (C) cycling, and nutrient cycling faster than measuring SOM. Producers can use these indicators as a first look to determine if management changes are translating to measurable changes in soil health and function.

This publication provides an overview of soil health indicators that can be used to monitor shifts in SOM. Information on test cost and availability in the Pacific Northwest (PNW), synonyms for tests to look for when finding a lab, and additional resources that can help producers learn more about each test and developments in soil health research in the PNW is also provided.

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Steps for Testing a Sample

1**. Identify a test**: Using this publication and other soil health testing resources, determine which tests best meet your needs based on the relevance, cost, and availability of the tests detailed below and summarized in Table 1. Additional resources that may be useful for deciding on a test can be found in Table 2.

2. **Identify a lab**: Services offered by soil testing labs vary widely, especially for soil health indicators. In the sections below, we classify tests based on their availability in the PNW (common, somewhat, rare). Tests that are “common” are conducted by multiple labs in the PNW, whereas “rare” tests are not commonly performed by labs serving this region. Labs serving the PNW are described in Andrews et al. (2017) and Washington State Pest Management Resource Service (n.d.).

A wide range of names are used to refer to various soil health indicators. When searching a lab website for a specific indicator, be sure to look for names listed in the “also known as” sections below.

3**. Collect and submit a soil sample**: Collect a representative soil sample using principles outlined in *A Guide to Collecting Soil Samples for Farms and Gardens* (Fery et al. 2018) while keeping the following modifications in mind:

- Depth: It is most typical to test for soil health indicators in the top 6 in. of the soil profile, though deep soil health testing is an emerging area of research.
- Equipment: For most tests discussed here there is no standard sample collection equipment, such as a probe, auger, or shovel. The exception is for physical tests, such as aggregate stability, where it is a best practice to minimize disturbance during sampling and shipment. In this case, specific sampling and handling instructions will vary by test and lab.
- Shipping: Once sampled, it is a best practice to rush samples on ice to minimize shifts in biological and chemical composition during shipment, though individual labs may have more extensive instructions to follow.

As with any soil test, consult with your lab before taking a sample to discuss special sampling or handling instructions.

4. **Interpret results**: The interpretation of soil health test results for Washington State is rapidly evolving. Baselines for healthy soils in Washington State are currently being established. These baseline values can help you understand if your results are close to a desired range. For many of the tests discussed here, it is advised that you interpret changes in test results over time relative to your baseline, because baseline values for a healthy soil can vary by soil texture, climate, and management practices. When you compare subsequent tests to your baseline, you can determine (1) if you are seeing test results shift over time in response to a management change, and (2) if test results are shifting closer to or further from a desirable range.

Key

Availability in the PNW: ○○○ common ¦ ○○ somewhat ¦ ○ rare

Cost of analysis: $: $0–25 ¦ $$: $26–50 ¦ $$$: > $50

Based on estimates of individual analyses in 2022. Many labs offer package and volume discounts for testing.

Autoclaved Citrate-Extractable (ACE) Soil Protein

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Also known as: Soil Protein

Relevance: Nitrogen (N) within SOM is a building block of complex molecules, and the vast majority of organic N is contained within soil proteins. Two microbial transformations are required to mineralize N into a plant-available form: (1) **aminization**, which supplies the pool for (2) **ammonification**, producing ammonium-N. ACE soil protein measures the size of the pool being aminized, thus estimating how much N is available for **mineralization** (Roberts and Jones 2008; Hurisso et al. 2018). An increase in ACE soil protein is associated with increased aggregate stability and mineralizable N, though it is not as effective as potentially mineralizable N (see later section describing this indicator) at predicting N mineralization (Hurisso and Culman 2021). As with any measure of potential N mineralization, excessively high values may be of concern due to N losses to the environment.

Principle: Proteins are extracted using a citrate solution, and a protein-sensitive dye (Bradford reagent) is added to the protein extract. Detection of color intensity using a **spectrophotometer** allows the protein concentration to be calculated from absorbance values (Hurisso et al. 2016; Moebius-Clune 2016).

Aggregate Stability

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Relevance: Organic material and microbial activity act together in soils to bind smaller soil building blocks (**microaggregates**) into larger aggregates. Microbes can feed on larger pieces of organic matter (**particulate organic matter**) and leave simpler organic compounds behind that act as a glue stabilizing the soil aggregate. Management practices such as tillage that disrupt these processes can reduce aggregate stability and can thereby cause poor soil structure (Bongiorno et al. 2019). This can lead to soil crusting, formation of large clods, erosion, and compaction. Increased aggregate stability is associated with an increase in pore space and water infiltration and a reduction in soil erosion.

Principle: A variety of approaches can be used to measure soil aggregate stability. Most approaches involve measuring the size distribution of soil aggregates following a combination of wetting and mechanical disturbance, which can include simulated rainfall, dipping soil in water, or vibrating samples. Specialized sampling and handling methods may be needed to reduce aggregate disturbance during sampling and shipping. Be sure to consult your lab to understand the proper sampling technique for your specific aggregate stability test.

Permanganate Oxidizable Carbon (POXC)

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Also known as: Active Carbon, Reactive Carbon

Relevance: This test is used as an indicator of C accumulation and stabilization in soils (Hurisso et al. 2016; Morrow et al. 2016) and is correlated with **total SOM** (Bongiorno et al. 2019). Therefore, this test is most relevant for those who are interested in C sequestration and building SOM. Increases in POXC are associated with higher levels of C accumulation and stabilization in soil.

Principle: Potassium permanganate is a compound that oxidizes some portions of soil organic matter (Weil et al. 2003). The solution begins as a deep pink color and progressively turns clear as C is oxidized. The change in color indicates how much C was oxidized during the process, with the color intensity being inversely proportional to the amount of C that was oxidized.

Phospholipid Fatty Acid (PLFA) Analysis

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Relevance: This test gives a snapshot of the **microbial community composition** and abundance at the time of sampling. Because microorganisms respond rapidly to their environment, changes to the soil environment can be detected by quantifying the microbial response. While there is discussion about whether higher total microbial biomass, abundance of particular microbial groups, or a higher fungal-to-bacterial ratio indicates a favorable change in the soil environment, there is no known “ideal” soil microbial community at this time. Claims suggesting direct relationships between PLFAs and soil function and health should be viewed with caution as the state of this literature is evolving quickly.

Currently, PLFA analysis is most useful for assessing the rapid and short-term response of soil microorganisms to changes in the environment or management practices. Because microorganisms are so sensitive to the environment, it is best to make comparisons over time by sampling and assessing two management conditions simultaneously. When using PLFA analysis over multiple seasons, care should be taken to sample around the same time and in similar conditions each year.

Principle: **Phospholipid fatty acids** are molecules found in cell membranes of all microorganisms. The specific chemical makeup and quantities of these PLFA molecules can be used as chemical keys to determine what groups of microorganisms are present, the size of each of those groups, and total microbial lipids, a proxy for microbial biomass. Cell membranes and PLFAs degrade rapidly after microorganisms die, allowing PLFAs to serve as indicators of the living microorganisms (Willers et al. 2015).

Potentially Mineralizable Carbon (PMC)

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Also known as: Mineralizable Carbon, Microbial Respiration, Soil Respiration

Relevance: CO_2 is a byproduct of **aerobic respiration**. It can be used to measure microbial activity in soil and may be a good indicator of short-term nutrient release from organic matter decomposition (Hurisso et al. 2016). Higher levels of PMC indicate higher organic matter turnover and short-term nutrient supply from SOM stocks. PMC is best interpreted alongside POXC. An increase in PMC coupled with a decrease in POXC indicates that SOM is being lost over time, whereas when both test values are increasing you can expect SOM gains over time. The interpretation of PMC and POXC changes over time are summarized well in *Understanding and Measuring Organic Matter in Soil* (Collins and McGuire 2019).

Principle: Soils are moistened to activate microbes. Release of CO_2 is measured during a standard incubation period (e.g., one, three, and four days). Solvita CO_2 Burst is a commercial method of a one-day incubation.

Potentially Mineralizable Nitrogen (PMN)

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Relevance: Soil microbes regulate **mineralization**, the conversion of organic N into a plant-available or mineral form. Unlike ACE soil protein which measures a specific fraction of organic N, PMN is influenced by both the abundance of soil microbes and organic N. Higher levels of PMN indicate that more N will be supplied via biological N cycling. Higher PMN is desirable for those who would like to reduce N inputs but can be concerning when POXC is decreasing. This indicates that SOM losses are exceeding gains, and that SOM will decrease over time.

Principle: Moistened soils are incubated under controlled conditions, stimulating microbial activity. Change in mineral N is measured after incubating. Many labs report a value for mineralizable nitrogen that is estimated from SOM ("estimated N release"), which will only change as much as SOM does. A true PMN measurement through incubation will be more sensitive to recent management changes but will not exactly match the amount of mineralization under field conditions.

Local Developments in Soil Health

Learn more about the most up-to-date developments in soil health from the USDA, WSDA, and WSU in the resources below.

Websites

USDA NRCS Washington Soil Health: https://www.nrcs.usda.gov/conservation-basics/conservation-by-state/washington/soils

Washington Soil Health Initiative: https://soilhealth.wsu.edu/soil-health-initiative/

WSU CSANR Blog Posts

Perspectives on Sustainability: https://csanr.wsu.edu/blog/?taxonomies%5Bcategory%5D=blog&pf_author=&pf_page=2

Sustainability: https://csanr.wsu.edu/blog/?taxonomies%5Bcategory%5D=sustainability-blog&pf_author=

Sustainable Practices and Technology: https://csanr.wsu.edu/blog/?taxonomies%5Bcategory%5D=sustainable-practices&pf_author=

CSANR Research Library

Soil Health:
https://csanr.wsu.edu/publications-library/soils-fertility/soil-health/

Carbon Sequestration:
https://csanr.wsu.edu/publications-library/climate-change/carbon-sequestration/

Wheat Beat Podcast Episodes

All about Sustainable Farming Systems with Dave Huggins—Part 1:
https://smallgrains.wsu.edu/wsu-wheat-beat-episode-13/

All about Sustainable Farming Systems with Dave Huggins—Part 2:
https://smallgrains.wsu.edu/wsu-wheat-beat-episode-14/

Long-term Agroecosystems Research (LTAR) Discussion with Dr. Dave Huggins:
https://smallgrains.wsu.edu/wsu-wheat-beat-episode-30/

Soil Microbiology & Agricultural Sustainability with Tarah Sullivan:
https://smallgrains.wsu.edu/wsu-wheat-beat-episode-29/

Soils as an Instrument for Managing Climate Change with Dr. Rattan Lal, Ohio State University: https://smallgrains.wsu.edu/wsu-wheat-beat-episode-75/

The Northwest Sustainable Agro-Ecosystems Research Unit with Dr. Dave Huggins:
https://smallgrains.wsu.edu/wsu-wheat-beat-episode-108/

A Very Exciting Time for Soil Health with Dr. Tarah Sullivan:
https://smallgrains.wsu.edu/wsu-wheat-beat-episode-117/

The Soil Health Roadmap with Chris Benedict:
https://smallgrains.wsu.edu/wsu-wheat-beat-episode-121/

The Soil Health Initiative Is Born with Chad Kruger:
https://smallgrains.wsu.edu/wsu-wheat-beat-episode-120/

Table 1. Availability of testing for select soil health indicators at labs serving the Pacific Northwest: autoclaved citrate-extractable (ACE) soil protein, aggregate stability, permanganate oxidizable carbon (POXC), phospholipid fatty acid (PLFA) analysis, potentially mineralizable carbon (PMC), potentially mineralizable nitrogen (PMN).

Indicator	**Related Functions**[a]			**Availability in PNW**[b]			**Cost**[c]
	Nutrient cycling	Biodiversity and habitat	Physical stability and support	Common	Somewhat	Rare	
ACE Soil Protein	●		●		●		$
Aggregate Stability		●	●		●		$
PLFA		●				●	$$$
PMC	●		●	●			$–$$
PMN	●				●		$
POXC	●				●		$

[a] See http://soilquality.org/ for more information.

[b] Common = available at a majority of labs offering soil health testing services in the Pacific Northwest (PNW). Somewhat = available at more than one lab serving the PNW. Rare = offered at one or fewer labs in the PNW.

[c] $: $0–25 ; $$: $26–50 ; $$$: > $50. Based on estimates of individual analyses in 2022. Many labs offer package and volume discounts for testing.

Table 2. Summary of additional resources describing the principles and methodologies for indicators described in this publication: autoclaved citrate-extractable (ACE) soil protein, aggregate stability, permanganate oxidizable carbon (POXC), phospholipid fatty acid (PLFA), potentially mineralizable carbon (PMC), and potentially mineralizable nitrogen (PMN).

Indicator	**Additional Information**
ACE Soil Protein	Collins and McGuire (2019); Schindelbeck et al. (2017d)
Aggregate Stability	Schindelbeck et al. (2017e); USDA NRCS (n.d.)
POXC	Collins and McGuire (2019); Schindelbeck et al. (2017a); USDA NRCS (n.d.)
PMC	Collins and McGuire (2019); Schindelbeck et al. (2017c); USDA NRCS (n.d.)
PLFA	Kaminsky et al. (2021); Zuber and Kladivko (2018)
PMN	Schindelbeck et al. (2017b); Sullivan et al. (2020); USDA NRCS (n.d.)

Glossary

aerobic respiration: Process where organisms use oxygen to make energy to power cell functions from carbohydrates (fats, sugars).

aminization: The decomposition of complex proteins into simpler N-containing molecules, such as amines, amino acids, and amides.

ammonification: The conversion of the products of aminization into ammonium.

microaggregate: The smallest building block of soil structure (< 250 µm).

microbial community composition: The description of the microbial groups present, and the number of individuals in each group.

mineralization: The conversion of a nutrient from an organic form into an inorganic, plant-available form.

particulate organic matter: The largest fraction of organic matter in soils (0.05–2 mm).

phospholipid fatty acids: Molecules that make up the cell membranes of organisms.

spectrophotometer: An instrument that passes light through a substance and measures the concentration of a color in the substance.

total soil organic matter: The entirety of organic matter in soil, which includes several fractions that play distinct roles in the soil environment.

References

Andrews, S., D. Walenta, C. Sullivan, L. Henderson, and L. Brewer. 2017. Analytical Laboratories Serving Oregon. *Oregon State University Extension Publication* EM8677. Oregon State University.

Bongiorno, G., E.K. Bünemann, C.U. Oguejiofor, J. Meier, G. Gort, R. Comans, P. Mäder, L. Brussaard, and R. de Goede. 2019. Sensitivity of Labile Carbon Fractions to Tillage and Organic Matter Management and Their Potential as Comprehensive Soil Quality Indicators across Pedoclimatic Conditions in Europe. *Ecological Indicators* 99: 38–50. DOI: 10.1016/j.ecolind.2018.12.008.

Collins, D., and A.M. McGuire. 2019. Understanding and Measuring Organic Matter in Soil. *Washington State University Extension Publication* EM118E. Washington State University.

Fery, M., J. Choate, and E. Murphy. 2018. A Guide to Collecting Soil Samples for Farms and Gardens. *Oregon State University Extension Publication* EC628. Oregon State University.

Hurisso, T.T., and S.W. Culman. 2021. Is Autoclaved Citrate-Extractable (ACE) Protein a Viable Indicator of Soil Nitrogen Availability? In *Soil Health Series: Volume 2 Laboratory Methods for Soil Health Analysis*, edited by D.L. Karlen, D.E. Stott, and M.M. Mikha, 176–193. Soil Science Society of America, Inc. DOI: 10.1002/9780891189831.

Hurisso, T.T., S.W. Culman, W.R. Horwath, J. Wade, D. Cass, J.W. Beniston, T.M. Bowles, et al. 2016. Comparison of Permanganate-Oxidizable Carbon and Mineralizable Carbon for Assessment of Organic Matter Stabilization and Mineralization. *Soil & Water Management & Conservation* 80(5): 1352–1364. DOI: 10.2136/sssaj2016.04.0106.

Hurisso, T.T., D.J. Moebius-Clune, S.W. Culman, B.N. Moebius-Clune, J.E. Thies, and H.M. van Es. 2018. Soil Protein as a Rapid Soil Health Indicator of Potentially Available Organic Nitrogen. *Agricultural & Environmental Letters* 3(1): 1–5. DOI: 10.2134/ael2018.02.0006.

Kaminsky, L., M. Cloutier, S. Fleishman, S. Isbell, K. Borrelli, and T. Bell. 2021. Soil Microbes in Organic Cropping Systems 101. *EOrganic*.

Magdoff, F., and H.M. van Es. 2021. Building Soils for Better Crops: Ecological Management for Health Soils. 4th ed. College Park, MD: Sustainable Agriculture Research and Education (SARE).

Moebius-Clune, D.J. 2016. Autoclaved-Citrate Extractable (ACE) Soil Protein. In *Cornell University Comprehensive Assessment of Soil Health Laboratory Standard Operating Procedures*, edited by B. Schindelbeck, K. Kurtz, and J. Amsili, 55–69. Cornell University.

Morrow, J.G., D.R. Huggins, L.A. Carpenter-Boggs, and J.P. Reganold. 2016. Evaluating Measures to Assess Soil Health in Long-Term Agroecosystem Trials. *Soil Science Society of America Journal* 80(2): 450–462. DOI: 10.2136/sssaj2015.08.0308.

Roberts, P., and D.L. Jones. 2008. Critical Evaluation of Methods for Determining Total Protein in Soil Solution. *Soil Biology and Biochemistry* 40(6): 1485–1495. DOI: 10.1016/j.soilbio.2008.01.001.

Schindelbeck, R.R., A.J. Ristow, K.S. Kurtz, L.F. Fennell, and H.M. van Es. 2017a. Active Carbon. Cornell University Comprehensive Assessment of Soil Health Laboratory Soil Health Manual Series. Geneva, NY: Cornell University.

Schindelbeck, R.R., A.J. Ristow, K.S. Kurtz, L.F. Fennell, and H.M. van Es. 2017b. Add-on Test: Potentially Mineralizable Nitrogen. Cornell University Comprehensive Assessment of Soil Health Laboratory Soil Health Manual Series. Geneva, NY: Cornell University.

Schindelbeck, R.R., A.J. Ristow, K.S. Kurtz, L.F. Fennell, and H.M. van Es. 2017c. Soil Respiration. Cornell University Comprehensive Assessment of Soil Health Laboratory Soil Health Manual Series. Geneva, NY: Cornell University.

Schindelbeck, R.R., A.J. Ristow, K.S. Kurtz, L.F. Fennell, and H.M. van Es. 2017d. Soil Protein. Cornell University Comprehensive Assessment of Soil Health Laboratory Soil Health Manual Series. Geneva, NY: Cornell University.

Schindelbeck, R.R., A.J. Ristow, K.S. Kurtz, L.F. Fennell, and H.M. van Es. 2017e. Wet Aggregate Stability. Cornell University Comprehensive Assessment of Soil Health Laboratory Soil Health Manual Series. Geneva, NY: Cornell University.

Sullivan, D.M, A.D. Moore, E. Verhoeven, and L.J. Brewer. 2020. Baseline Soil Nitrogen Mineralization: Measurement and Interpretation. *Oregon State University Extension Publication* EM9281. Oregon State University.

USDA NRCS (Natural Resources Conservation Service). n.d. Soil Quality Indicators.

Washington State Pest Management Resource Service. n.d. Analytical Laboratories and Consultants Serving Agriculture in the Pacific Northwest.

Weil, R.R., K.R. Islam, M.A. Stine, J.B. Gruver, and S.E. Samson-Liebig. 2003. Estimating Active Carbon for Soil Quality Assessment: A Simplified Method for Laboratory and Field Use. *American Journal of Alternative Agriculture* 18(1): 3–17. DOI: 10.1079/AJAA2003003.

Willers, C., P.J. Jansen van Rensburg, and S. Claassens. 2015. Phospholipid Fatty Acid Profiling of Microbial Communities—A Review of Interpretations and Recent Applications. *Journal of Applied Microbiology* 119(5): 1207–1218. DOI: 10.1111/jam.12902.

Zuber, S., and E. Kladivko. 2018. How to Understand and Interpret Soil Health Tests. *Purdue University Extension Publication* AY-366-W. Purdue University.

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