Soil organic matter as a soil health indicator: Sampling, testing, and interpretation

D.M. Sullivan, A.D. Moore, and L.J. Brewer

Soil organic matter (SOM) includes a wide variety of compounds containing carbon, hydrogen and oxygen. These compounds vary in structure, age and resistance to decomposition. The half-life of SOM can range from weeks to centuries, depending on the types of compounds present and how strongly they are adsorbed onto soil particles.

Soil organic matter is an integral part of many processes that are critical to soil health and nutrient supply to crops, including:

- Response to tillage (e.g., ease of seedbed preparation).
- Resistance to wind and water erosion.
- Water-holding capacity, water infiltration, and water movement in soil.
- Capacity to retain and release nutrients for plant growth.
- Population and diversity of soil biota.

There is no laboratory test to directly quantify SOM. Estimation of SOM is usually accomplished through a measure of soil organic carbon (SOC), total soil carbon, or weight loss on ignition (Tabatabai, 1996). All laboratory methods have limitations and inherent sources of error.

Photo: Dan Sullivan, © Oregon State University

Summary

This publication provides guidance on soil organic matter (SOM) testing for the purpose of monitoring changes in soil health over time. Before using SOM test results for this purpose, it is important to understand that measurable improvements in SOM in response to soil management practices often take at least 3 to 5 years. Growers should not be overly concerned if SOM changes are not immediate.

Practices that increase SOM include increasing crop biomass production, retaining crop residues in the field, reducing or eliminating tillage and applying organic matter (OM) amendments.

Improper soil sampling methods can produce inconsistent and misleading SOM test results. This problem can be avoided by following consistent soil sampling practices. We recommend removing mulch from the soil surface prior to sampling. Soil sample depth must be consistent because SOM typically declines with depth.

SOM testing methods are based on the measurement of soil organic carbon (SOC), total soil carbon or weight loss upon ignition. These methods differ in cost, accuracy and reproducibility. Choose a soil testing laboratory and SOM testing method that can provide consistent data quality.

Dan M. Sullivan, professor and Extension soil scientist; Amber D. Moore, Extension soil fertility specialist; and Linda J. Brewer, senior faculty research assistant; all of Oregon State University

Oregon State University

Soil organic matter and nutrients

Although SOM is not itself a plant nutrient, it is an important source of nutrient supply to crops. Macronutrients such as nitrogen (N) and sulfur (S), along with micronutrients such as boron (B), are stored within OM and are released as OM decomposes. Soil organic matter is negatively charged and attracts and retains potassium (K), magnesium (Mg) and calcium (Ca), which are positively charged.

A soil with more OM contains more total N. However, total SOM percentage is *not* a quantitative indicator of the capacity of soil to supply plant-available nitrogen (PAN) for plant growth. The timing and amount of PAN released from SOM depend on its composition, soil temperature, soil moisture and other soil management factors.

Soil organic matter equilibrium

Soil properties affect SOM retention

Soil texture and drainage affect the capacity of soil to retain OM. Heavier-textured soils (e.g., clays and clay loams) are better able to protect OM from decomposition than are lighter-textured soils (e.g., sandy loams, loamy sands). SOM decomposition is less when soil pores are filled with water than when pores are filled with air. Therefore, under similar climate and management, poorly drained soils usually have greater SOM than well-drained soils.

Soil pH and other chemical properties also play a role in regulating the rate of OM decomposition. For example, decomposition of SOM via microbial activity is faster when soil pH is near neutral and slower when soil is strongly acidic (pH below 5).

Soil parent material also affects SOM retention in soils. For example, soils derived from volcanic ash bind very strongly with SOM, thereby protecting it from decomposition.

SOM will slowly reach equilibrium

Changes in SOM reflect the long-term balance between OM inputs and outputs (Figure 1). Management practices that increase OM inputs to the soil or reduce the rate of SOM decomposition can increase SOM concentration. Figure 1 shows the general pattern expected when improved soil management practices are implemented to increase OM inputs or decrease OM loss, resulting in net accumulation of SOM.

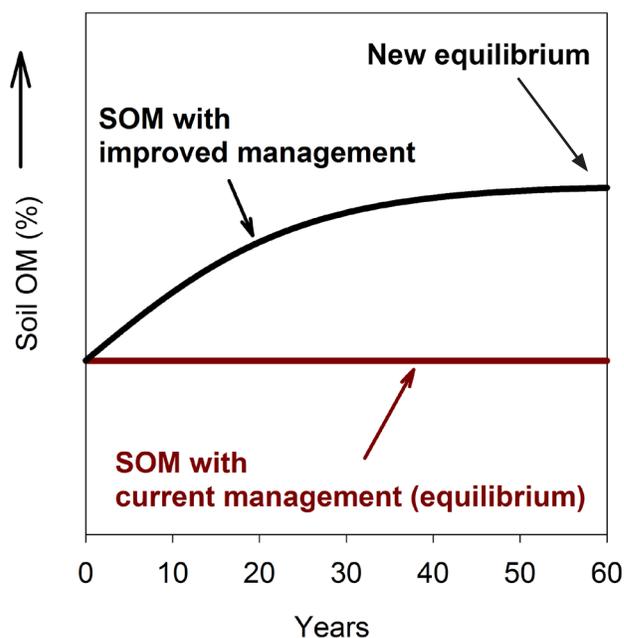The lower line in Figure 1, "SOM with current management (equilibrium)," shows a low concentration

Figure 1. Conceptual example of expected soil organic matter (SOM) increase over time in response to a management regime under which OM inputs exceed SOM loss. Improved management was implemented in Year 1 and continued thereafter. The rate of OM accumulation over time depends on how much the new management regime shifts the balance in favor of OM accumulation.

of SOM in equilibrium with consistent crop rotation, tillage, and erosion control practices. In the example, we assume that sufficient time has occurred for SOM to come to equilibrium (OM inputs = outputs).

The upper line, "SOM with improved management," shows the expected response in SOM percentage when a major change is made to alter the OM input/output balance in favor of OM accumulation. The rate of OM accumulation over time depends on how much the new management regime shifts the balance in favor of OM accumulation. In most cases, the maximum expected change in SOM is less than 2 percentage points (for example, from 2 percent to 4 percent SOM or from 4 percent to 6 percent SOM). Larger changes in SOM are possible over time with repeated application of manure or compost (see "Management actions to increase SOM," page 3).

Changes in SOM usually occur slowly and require at least three to five years to become measurable. The time required to achieve a measurable change in SOM depends on many site-specific factors. Soil organic matter near the soil surface changes most rapidly in response to typical soil management practices (Figure 2, page 4). High-rate applications of organic materials brought in from off-farm (e.g., compost or manure) can increase SOM more rapidly (see Appendix A, page 7).

Management actions to increase SOM

Table 1 shows categories of management actions that favor OM retention in soil. The overall balance between OM inputs and outputs over the years determines the net accumulation or loss of OM.

Soil erosion must be controlled as a prerequisite to increasing SOM. Soil organic matter concentration is highest at the soil surface (the source of eroded topsoil), and SOM is lighter than mineral soil particles, so soil eroded from fields is usually rich in OM. For example, when a topsoil contains 2 percent SOM, the water-eroded soil from the field may contain at least 3 percent OM (Sharpley, 1985; Schiettecatte, et al., 2008).

Often, the most effective ways to increase SOM are to reduce fallow periods and increase biomass production. For example, switching from wheat-fallow to annual direct seeding has been demonstrated to reverse declining SOM in the inland Pacific Northwest (Brown and Huggins, 2012). Winter annual cover crops have been shown to increase SOM in irrigated cropping systems (Mitchell, et al., 2015).

Crop residues are a critical contributor to SOM. When crop residues are routinely burned or baled, SOM often declines over time. Conversely, when crop residues are retained, the SOM input/output balance shifts in a positive direction.

Reducing tillage is also an important strategy to retain SOM, as tillage exposes OM to decomposition. When SOM is inside a soil aggregate, few soil organisms can access and consume it. When the soil aggregate is crushed by tillage, the OM becomes a readily accessible food source for soil organisms. As decomposition proceeds, soil carbon (C) is lost as CO_2 gas. The more frequent and intensive the tillage, the faster SOM decomposes and is lost.

Off-farm sources of OM (e.g., compost, animal manure, or municipal biosolids) can increase SOM, although the use of these materials is limited by location and cost. Some sources are more effective than others in increasing SOM. For example, composts are generally more effective than raw organic materials. Research in dryland wheat-fallow cropping systems in Oregon and Washington demonstrated that municipal biosolids were highly effective in increasing SOM (Cogger, et al., 2013; Wuest and Reardon, 2016; Sullivan, et al., 2018). However, repeated applications of manure, compost, or biosolids can lead to excessive nutrient accumulations in soil.

Forecasting changes in SOM over time is an inexact science because the interactions among soil management practices and soil processes are complex. A single soil management practice can alter the rate of both OM accumulation and loss. For example, a change from dryland to irrigated farming alters both OM inputs (irrigated crops produce more biomass) and the rate of OM decomposition (OM decomposition speeds up when soil is moist).

Monitoring changes in SOM in response to management

Periodic SOM testing, when properly done, can assist in understanding the cumulative impact of factors that can be controlled (soil management practices, Table 1), as well as natural factors (e.g., precipitation, temperature, soil texture). Figure 2 (page 4) illustrates measured SOM changes.

Both soil sampling methods and laboratory analysis methods must be consistent when comparing SOM percentages from the same field location over time. Large variations in reported SOM percentage can occur when soil sampling depth is inconsistent, when mulch from the soil surface is mixed with the soil sample, or when different laboratory methods are used. See the sidebar "Changes in SOM in a soil profile in response to management" (page 4) for more information about the importance of sampling at a consistent depth.

Even with optimal procedures, SOM test values are not perfectly reproducible. A SOM test result reflects variation in sample collection and variation

Table 1.—Management actions that can maintain or increase soil organic matter.

Practice	Examples of management actions
Reduce soil erosion by wind and water	Maintain vegetative cover. Retain crop residue on the soil surface.
Increase crop biomass	Apply nutrients at agronomic rates. Maintain soil pH in the optimum range. Grow crops that produce greater amounts of above-ground and below-ground crop residue.
Increase duration of crop growth	When feasible, plant a cover crop between cash crops. Rotate to perennial grass. Consider relay (interseeded) crops.[1]
Retain crop residues	Leave crop residue in the field instead of burning or baling it.
Reduce tillage intensity, frequency, or depth	Use a less-intensive tillage implement. Substitute no-till or strip till for more intensive tillage (e.g., discing, plowing, rototilling). Use herbicides to replace tillage for weed control.
Add organic matter from off-farm sources	Apply compost, manure, or municipal biosolids.

[1]Relay cropping, or interseeding, is the practice of planting a cover crop or successive crop before the current crop is harvested.

associated with the laboratory test. In most cases, soil test SOM values within 0.5 percentage point (e.g., 2.0 and 2.5 percent) from the same location in a field are not different. Figure 7 (page 10) shows variation encountered when a well-mixed composite soil sample was analyzed by different testing laboratories.

Soil sampling and testing methods for OM determination

Soil sampling methods

The same general principles that apply to soil sampling for nutrient evaluation (Staben, et al., 2003) apply to soil sampling for determination of OM. A consistent soil sampling protocol is essential.

- Collect soil samples to consistent soil depth(s).
- Maintain consistency in the number of soil cores collected per composite sample.
- Always remove thatch or mulch from the soil surface prior to sampling.
- Inspect composite soil samples after collection and remove any obvious pieces of crop residue.
- Georeference soil sampling locations within the field when possible.

Frequency of sampling. Testing SOM levels once per crop rotation or every five years can be useful in measuring the impact of long-term soil management practices. Except for intensive long-term monitoring projects, testing soil for SOM more than once every three to five years is usually not useful, as random errors in sample collection and errors in laboratory measurement usually obscure small changes in SOM. More frequent soil sampling can be useful when manure or other organic amendments are applied.

Changes in SOM in a soil profile in response to management

Situation. The Crop Residue Long-Term Experiment was initiated in a winter wheat-summer fallow cropping system in 1931 at Pendleton, OR (Ghimire, et al., 2015).

Objective. This trial evaluates the effect of soil management practices on grain yield and soil properties, including SOM. We focus here on the effect of OM input history on SOM present in the top 24 inches of soil.

Methods. Table 2 shows annualized C and N input from three treatments as an average across alternating crop and fallow years. Each treatment included crop residues (retained straw and roots) plus a specific source of C and N, as indicated.

In 2010, soil samples were collected by depth (0–4, 4–8, 8–12, and 12–24 inches) from treatment plots. Soil C was determined by the combustion method (see Table 3, page 5). We estimated SOM using the reported soil C and an approximate conversion factor: SOM = soil C x 1.72.

Results. Treatment differences in SOM were more apparent near the soil surface than at greater depth (Figure 2). After 80 years of different management, SOM concentration at the 0- to 4-inch depth was about twice as much with the manure treatment (3.4 percent) than with the inorganic N fertilizer treatment (1.5 percent).

Conclusion. Most of the change in SOM in this example occurred in the top eightinches of soil. Maintaining a consistent soil sampling depth is essential when tracking changes in SOM over time.

Table 2.—Annualized C and N input to soil, Pendleton Crop Residue Long-Term Experiment.

Treatment ID[1]	C	N
	(lb/a)	(lb/a)
N fertilizer (NB45)	1,890	35
Manure (MN)	3,290	75
Pea vine (PV)	2,270	32

[1]Treatment IDs (NB45, MN, and PV) are those used in the published research. Source: Ghimire, et al., 2015.
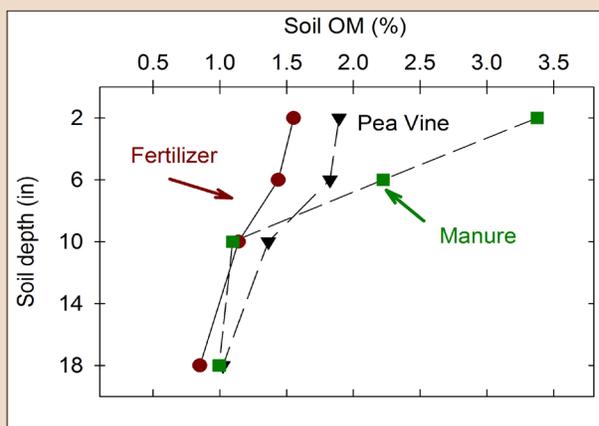

Figure 2. Soil organic matter with depth in a Walla Walla silt loam soil in a winter wheat-summer fallow cropping system under three OM input regimes initiated in 1931 and maintained thereafter (Crop Residue Long-Term Experiment, Pendleton, OR). Soil samples were collected in 2010. Adapted from Table 3 in Ghimire, et al. (2015).

Timing of soil sample collection. Plan to sample at a consistent time each year. Collect samples when the soil has not recently been disturbed by tillage and at least four to six months after a manure or compost application.

Equipment. The goal is to obtain a sample that contains an equal volume throughout the sampled depth. A shovel will not achieve this goal. Standard soil probes ensure uniform soil volume throughout the sampled depth.

Area sampled (sampling unit). For long-term monitoring of trends in SOM, we recommend using a sampling approach that will reduce variability due to soil type, landscape position, crop residue management, and organic inputs (e.g., manure). Rather than collecting a "whole field" sample, consider monitoring SOM in a reference area (a few acres) that represents a single NRCS soil mapping unit and a uniform cropping history. In fields that have received manure inputs, choose a reference area that has uniform soil test P and K levels, as levels of these nutrients are indicators of historical manure applications. Consider collecting replicate soil samples at the first sampling date to assess inherent variability in SOM.

Laboratory testing methods for SOM and C

The following three methods are commonly used to estimate SOM or soil C:

Loss on Ignition (LOI). Soil organic matter is estimated indirectly by measuring sample weight loss on ignition at 360°C. At this temperature, OM compounds in the soil are converted to carbon dioxide gas, thus lowering the weight of the soil sample.

Walkley-Black. Soil C is estimated via a wet chemical method, using potassium dichromate as an oxidizing agent. The dichromate (Cr_2O_7) ion remaining after reaction with the soil sample is quantified by titration with $FeSO_4$. Alternatively, the Cr^{3+} generated by the reaction of dichromate with organic C can be quantified by colorimetry (Sims and Haby, 1971).

Combustion. Soil C is determined after combustion of the sample at temperatures above 1,000°C. An infrared or conductivity detector is used to determine the amount of C present in the exhaust gas (CO_2).

These testing methods differ in cost, accuracy and reproducibility, as well as in suitability for alkaline soils that contain carbonates (Table 3). Appendices B, C and D discuss additional aspects of these testing methods.

Photo: Dan Sullivan, **© Oregon State University**

Figure 3. Organic mulch present on the soil surface can contaminate a soil sample. Scrape away organic mulch from the soil surface before collecting a soil core. Also remove any organic matter adhering to the outside of the soil core.

Table 3.—Advantages and limitations of test methods for determining SOM or soil C.

Method	Test cost and availability	Suitability for soil with carbonate	Comments
Loss-on-Ignition (LOI)	Low cost; often included in routine soil test "package"	Carbonates can be lost from the sample at very high oven temperatures, causing OM to be over-estimated. To avoid carbonate volatilization, use an oven temperature of 360°C.	SOM values determined by LOI are usually higher than those obtained with the Walkley-Black method. The LOI method is most inaccurate when SOM is low (less than 2 percent). The oven temperature and duration of the test may vary among laboratories.
Walkley-Black[1]	Moderate to high cost; some labs are phasing out this test because it generates toxic chromium waste.	Suitable	Some laboratories use a modified Walkley-Black method (Sims and Haby, 1971).
Combustion[2]	Moderate to high cost; available as an additional test upon request at many labs	Not suitable for soils with carbonates, unless inorganic C concentration is also measured or carbonates are removed. See Appendix C.	Sample size (grams of soil analyzed) varies among combustion instruments. To improve test reproducibility, an instrument using a large sample size is preferred.

[1]The traditional Walkley-Black method measures C concentration by redox titration of the remaining dichromate, while the modified method (Sims and Haby, 1971) determines the chromate ion (Cr^{3+}) in extract by colorimetry. See Appendix B for additional information.

[2]SOM is estimated as C multiplied by a conversion factor. The most common conversion equation is SOM = C x 1.72. Some laboratories employ other C-to-OM conversion factors based on proprietary data.

Organic matter as a soil health indicator: Total SOM vs. "active" SOM

Soil health is defined as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran and Parkin, 1994). Soil organic matter is considered a critical Tier 1 indicator of soil health (Soil Health Institute, 2018).

This publication addresses total SOM, which responds slowly to soil management changes.

Conceptually, total SOM can be divided into passive and active pools based on its stability, or resistance to decomposition (Weil and Magdoff, 2004). The half-life of the passive pool ranges from decades to centuries. This portion of OM is responsible for soil characteristics such as color and cation exchange capacity. The active pool has a half-life of a few years and therefore is more sensitive to short-term changes in soil management practices.

Ongoing research is evaluating the sensitivity and applicability of direct and indirect indicators of active OM (Soil Health Institute, 2018), including the following:

- Short-term C and N mineralization rate

- Permanganate oxidizable carbon

- Soil Protein Index

- Soil enzymes: B-glucosidase, B-glucosaminidase, phosphatase, arylsulfatase

- Microbial community characterization: phospholipid fatty acid (PLFA), ester-linked fatty acid methyl ester (EL-FAME)

- Genomics

- Diffuse reflectance spectroscopy

Photo: Ed Peachey

Figure 4. Adding a winter cover crop to a rotation won't immediately produce a measurable increase in total SOM, but it likely will increase the active SOM fraction.

Appendix A. Soil organic matter response to repeated dairy manure applications

Situation

Dairy manure is a common organic matter amendment for cropping systems in the Snake River Valley of southern Idaho. A long-term study is being conducted to evaluate the impact of repeated dairy manure applications on soil properties and crop production.

Method

Stockpiled dairy manure was applied each fall from 2012 to 2017 to a Portneuf silt loam in two adjacent irrigated fields near Kimberly, Idaho. Prior to initiation of the study, chemical fertilizers were routinely applied to these fields to supply nutrients for crop production. Beginning in 2013, a wheat-potato-barley-sugar beet crop rotation was established. The experimental design was a randomized complete block design with four replications.

Each fall, manure was applied at 15.5 ton/acre (dry weight basis). Manure contained 48 percent OM and 52 percent ash on a dry matter basis, so 7.4 ton/acre of OM was applied each year. Manure was tilled into the soil within one to two days after application. The control nutrient application was a commercial inorganic fertilizer treatment, based on University of Idaho recommendations. Aside from manure or fertilizer application, all plots in the experiment were managed with the same tillage, irrigation and other management practices.

Soils were sampled (0- to 12-inch depth) in March or early April from 2013 to 2018. Composite samples were created from 10 soil cores collected from each treatment plot. Soil organic matter was determined by the Sims and Haby (1971) method, a variation of the Walkley-Black method (Table 3 and Appendix B). Soil OM percentage presented in Figure 5 is averaged across soil samples collected from each treatment.

Results

While soil organic matter increased with the manure treatment, it remained relatively constant (1.3 percent to 1.5 percent) with the chemical fertilizer treatment (Figure 5). With manure application, SOM increased from 1.6 percent at the start of the trial (2012) to 2.6 percent in 2016, an average increase of 0.25 percent per year. Soil organic matter did not increase in 2017 and 2018, despite continued annual manure applications at the same rates.

Conclusion

This trial demonstrates that SOM tends toward equilibrium in response to OM inputs and outputs. In this example, SOM concentration stabilized after five years of manure application, despite additional annual applications. In the fertilizer treatment plots, SOM percentage remained constant over the entire study period, as would be expected when OM inputs (crop residues) and outputs (CO_2 lost via respiration) remain relatively constant over time.

This study had very high OM inputs (7.4 ton OM/acre/year as dairy manure) compared to most cropping systems that do not include manure or compost input. Therefore, the change in SOM over time in this example is much greater than that expected for systems that modify tillage practices or increase crop biomass inputs.
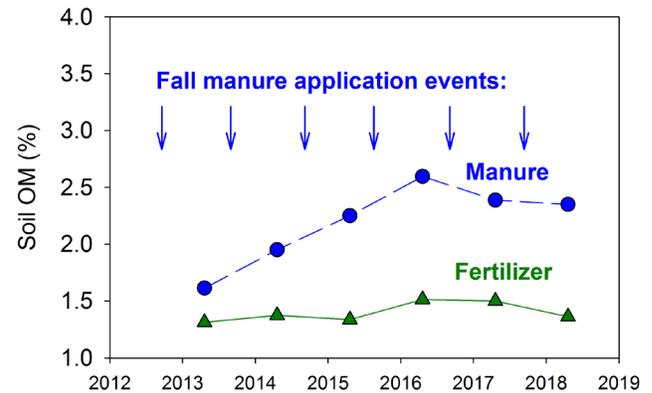

Figure 5. Soil organic matter concentration in response to manure or inorganic fertilizer application, Kimberly, Idaho. Manure was applied annually (15.5 ton/acre/year on a dry weight basis). Inorganic fertilizer was applied at agronomic rates, based on university recommendations. Manure was applied in the fall, and soil samples were collected in the spring. Source: Amber Moore and April Leytem, unpublished data.

Photo: Amber Moore, © Oregon State University
Figure 6. Field application of stockpiled dairy manure to manure treatment plots, Kimberly, Idaho.

Appendix B. Laboratory methods for SOM determination

Except as noted, this Appendix is derived from *Soil, Plant, and Water Reference Methods for the Western Region* (Gavlak, et al., 2005).

Walkley-Black (Western Region Method S 9.10)

This method quantifies oxidizable soil C by reacting soil with dichromate and sulfuric acid. The dichromate remaining after reaction with the soil sample is quantified by titration with $FeSO_4$. Because dichromate does not oxidize all soil C, raw lab data is adjusted with a correction factor to estimate soil C. The method detection limit is approximately 0.1 percent C and is generally reproducible to within ± 8 percent (Gavlak, et al., 2005). Soil organic matter is estimated by multiplying soil C by 1.72 (Walkley-Black C x 1.72 = OM).

Large amounts of manganese or carbonates in soils may interfere with C results from this method. Pretreatment of soil with 0.1N HCl can remove carbonates and manganese.

Dichromate is a hazardous waste and must be disposed of properly by the laboratory. For this reason, the Walkley-Black method is being phased out of general use.

The Sims and Haby (1971) method is the same as the Walkley-Black method except that it quantifies soil organic C via colorimetry and measures the Cr^{3+} generated by the reaction of organic C with dichromate.

Loss on Ignition (Western Region Method S 9.20)

This method estimates SOM by measuring sample weight loss following burning in a high-temperature muffle furnace (360°C). Organic matter burns at this temperature, and mineral soil particles do not. LOI organic matter is estimated by the difference in sample weight at 360 and 105°C. Some laboratories further adjust raw LOI data via a regression equation between LOI and another established method (e.g., Walkley-Black). The method is generally reproducible within ± 20 percent (Gavlak, et al., 2005).

Combustion (Western Region Method S 9.30)

This method determines total C released from a soil sample by combustion in a furnace at a temperature of at least 1,000°C using a proprietary instrument. Carbon present as carbon dioxide (CO_2) gas after combustion is determined by an infrared or conductivity detector. Prior to CO_2 determination, combustion gas is treated to remove moisture and to ensure complete conversion of soil C to CO_2. For acid soils, total soil C as determined by the instrument equals soil organic C because acid soils do not contain significant quantities of carbonates (inorganic C).

When soil pH is greater than 7.4, carbonates typically are present. When a soil sample contains carbonates, two approaches can be used to estimate soil organic C. See Appendix C (page 9), "Using the Combustion Method for SOM Determination in Soils Containing Carbonates," for details.

Soil sample weight and fineness required for test reproducibility vary among combustion instrument manufacturers and models. Some instruments require that soils be pulverized to pass 60-mesh sieve.

The detection limit for this method is instrument-dependent, and is approximately 0.02 percent C. It is generally reproducible to within ± 5 percent (Gavlak, et al., 2005).

Appendix C. Using the combustion method for soil organic C determination in soils containing carbonates

Analytical problem

Soils with pH above 7.4 may contain "free lime" or carbonates (XCO_3, where X = Ca, Mg, or Na). For these soils, test results for soil C via the combustion method are unreliable because measured C is the sum of organic C in SOM plus inorganic C in carbonates.

Soils that contain carbonates can be identified by a qualitative test (the "fizz test" with acid).

Solutions

Here we describe two approaches to avoid interference by carbonates:

1. Estimate organic C by difference

Description:
- Determine soil total C (organic + inorganic) in a subsample via combustion.
- Quantitatively determine inorganic C in another subsample.
- Estimate organic C as the difference: soil organic C = (total C – inorganic C).

Advantages:
- Precise and accurate methods for quantitative determination of carbonates exist.
- A soil analysis for carbonate percentage has other useful applications. For example, it can be an indicator of exposed subsoil and may provide useful information to guide P fertilization rates.

Disadvantages:
- Two separate analyses are required (combustion method for total C and inorganic C determination). Each analysis can have associated error.
- This method assumes that the distribution of carbonates is identical in the two samples. Identical distribution may be difficult to achieve in some situations, especially when the soil contains carbonate "chunks." Grinding soil to fine mesh size is required to achieve sample homogeneity.

2. Pretreat the soil with acid to remove carbonates

Description:
- Measure soil C via combustion after carbonate removal with acid.

Advantages:
- Only one analysis is required. The combustion method directly measures soil organic C remaining after carbonate removal.
- Acid pretreatment can be done on a relatively large soil sample, reducing error due to nonuniform distribution of carbonate in the sample.

Disadvantages:
- The acid pretreatment may also remove some of the organic C present in the soil.
- The acid pretreatment procedure is often not standardized for time and acid molarity, making the results less reproducible.
- When carbonate is removed, soil sample weight decreases. Results for C via the combustion method must be corrected for this weight loss.

Appendix D. Comparison of methods for organic matter testing

Situation

More than 100 soil testing laboratories participate in the North American Proficiency Testing (NAPT) program. Participating laboratories receive a common set of soil samples each quarter and report analyses to a centralized database (NAPT, 2019).

Method

We used the NAPT sample analysis database for 2018 from Quarters 1, 3, and 4 to compare test results for the combustion method, the Walkley-Black method, and the LOI method. For the combustion method data, we used reported values for total C (n = 30 laboratories) because only a few of the participating laboratories reported both total C and total organic C (n = 10). Two soil samples contained significant inorganic C (carbonate) and were excluded from the dataset for the combustion method. Variability reported here represents only laboratory error and does not include errors that may have occurred during soil sampling and sample preparation.

Results

Figure 7 shows the SOM test results for the Walkley-Black and the LOI methods. Averaged over all soil samples, SOM was 2.7 percent for the Walkley-Black method and 3.3 percent for the LOI method. The higher SOM values measured using LOI are likely associated with "bound water" present in SOM and hydrated clays, which is lost at high temperature.

The NAPT data also show how much variability is expected when different laboratories analyze the same soil sample. For a single sample, the typical range for $\pm$ 1 standard deviation across participating laboratories was 0.2 to 0.4 percent SOM for both the Walkley-Black and LOI methods. For a soil sample containing 4 percent SOM, the expected measured value was approximately 3.7 to 4.3 percent SOM (4.0 $\pm$ 1 standard deviation) across laboratories.

Analyses for the three methods were linearly related, with R^2 values > 0.95 (Figures 8 and 9). The data points used in the regression equations are the means of 30 laboratory analyses for the Walkley-Black and combustion methods and the mean of 70 laboratory analyses for LOI. These data should *not* be used to justify measuring SOM with one analytical method and then estimating the SOM for another analytical method using a regression equation.
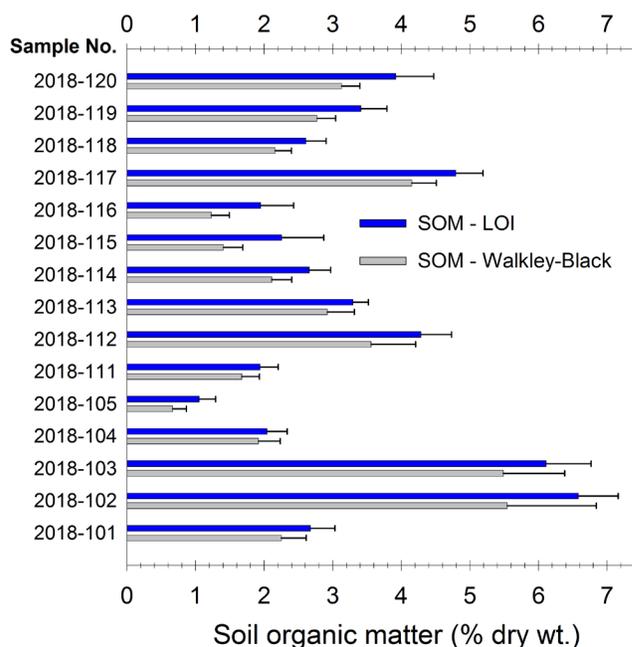

Figure 7. Soil organic matter as determined by the LOI and Walkley-Black methods. Each group of bars represents a single composite soil sample analyzed by laboratories participating in the North American Proficiency Testing (NAPT) program in 2018. The error bar is the standard deviation across approximately 30 laboratories for the Walkley-Black method and across 70 laboratories for the LOI method.
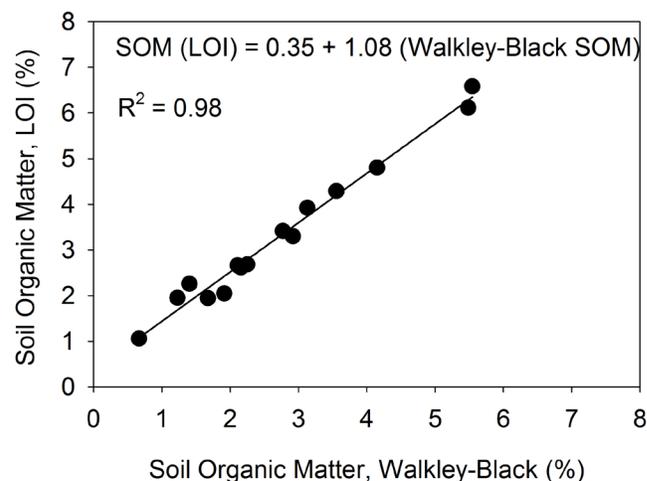

Figure 8. Relationship between SOM determined by the Walkley-Black method and SOM determined by the LOI method. Each data point represents one soil sample—the mean of approximately 30 analyses for the Walkley-Black method and 70 analyses for the LOI method. Analyses were performed by laboratories participating in the North American Proficiency Testing (NAPT) program in 2018.

Conclusions

The NAPT dataset illustrates the variability and bias associated with laboratory methods employed for determination of SOM or soil C. Soil organic matter measurements using the LOI method were consistently higher than those resulting from the Walkley-Black method. SOM estimated by the Walkley-Black method was approximately 1.5 times the soil C value determined by the combustion method. SOM determined by the LOI method was approximately 1.7 times the soil C value determined by the combustion method. When SOM values were less than 2 percent, all tests had greater variability, expressed as a percentage of the mean.

To track meaningful trends in SOM or soil C over time, we recommend using one test method consistently.

$$SOM\ (WB) = 0.28 + 1.47\ (Combustion\ C)$$
$$R^2 = 0.98$$

$$SOM\ (LOI) = 0.49 + 1.65\ (Combustion\ C)$$
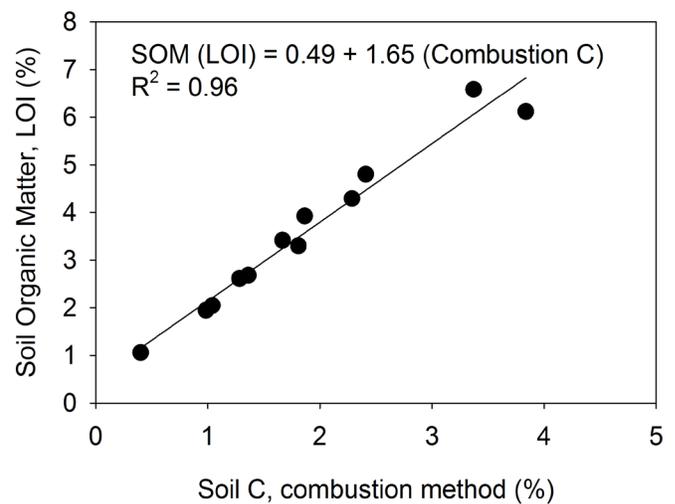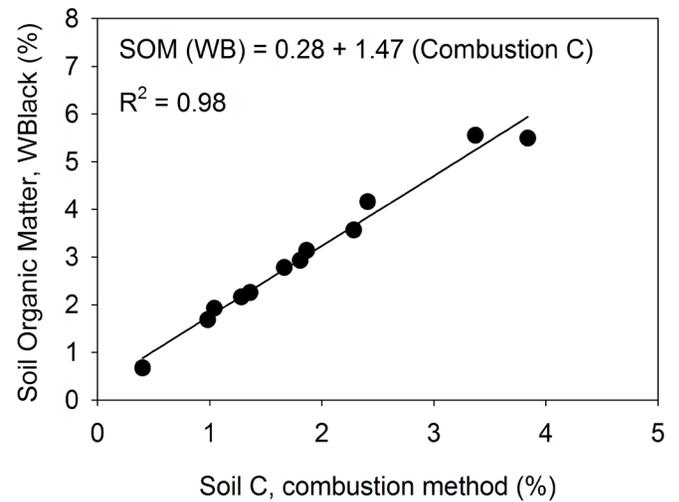$$R^2 = 0.96$$

Figure 9. Relationship between soil C determined by the combustion method vs. SOM determined by the Walkley-Black method (top) or LOI method (bottom). None of the soil samples in this dataset contained significant quantities of carbonates. Each data point represents one soil sample—the mean of approximately 30 analyses for the Walkley-Black method and the combustion method and 70 analyses for the LOI method. Analyses were performed by laboratories participating in the North American Proficiency Testing (NAPT) program in 2018.

For more information

Brown, T.T. and D.R. Huggins. 2012. Soil carbon sequestration in the dryland cropping region of the Pacific Northwest. Journal of Soil and Water Conservation 67:406–415.

Cogger, C.G., A.I. Bary, E.A. Myhre, and A. Fortuna. 2013. Long-term crop and soil response to biosolids applications in dryland wheat. Journal of Environmental Quality 42:1872–1880.

Doran, J.W. and T.B. Parkin. 1994. Defining and assessing soil quality. In *Defining Soil Quality for a Sustainable Environment* (pp. 1–21). Special Publication 35, Soil Science Society of America.

Gavlak, R.G., D.A. Horneck, and R.O. Miller. 2005. *Soil, Plant and Water Reference Methods for the Western Region* (3rd ed.). WREP-125, WERA-103 Technical Committee. http://www.naptprogram .org/files/napt/western-states-method -manual-2005.pdf

Ghimire, R., S. Machado, and K. Rhinhart. 2015. Long-term crop residue and nitrogen management effects on soil profile carbon and nitrogen in wheat-fallow systems. Agronomy Journal 107:2230–2240.

Mitchell, J.P., A. Shrestha, W.R. Horwath, R.J. Southard, N. Madden, J. Veenstra, and D.S. Munk. 2015. Tillage and cover cropping affect crop yields and soil carbon in the San Joaquin Valley, California. Agronomy Journal 107:588–596.

North America Proficiency Testing Program (NAPT). 2019. https://www.naptprogram.org/

Schiettecatte, W., D. Gabriels, W.M. Cornelis, and G. Hofman. 2008. Enrichment of organic carbon in sediment transport by interrill and rill erosion processes. Soil Science Society of America Journal 72:50–55.

Sharpley, A.N. 1985. The selective erosion of plant nutrients in runoff. Soil Science Society of America Journal 49:1527–1534.

Sims, J.R. and V.A. Haby. 1971. Simplified colorimetric determination of soil organic matter. Soil Science 112:137–141.

Soil Health Institute. 2018. North American Project to Evaluate Soil Health Measurements. https://soilhealthinstitute.org/

Staben, M.L., J.W. Ellsworth, D.M. Sullivan, D.A. Horneck, B.D. Brown, and R.G. Stevens. 2003. *Monitoring Soil Nutrients Using a Management Unit Approach*. PNW 570, Oregon State University Extension Service. https://catalog.extension .oregonstate.edu/pnw570

Sullivan, D.M., C.G. Cogger, A.I. Bary, and L.J. Brewer. 2018. *Biosolids in Dryland Cropping Systems*. PNW 716, Oregon State University Extension Service. https://catalog.extension.oregonstate .edu/pnw716

Tabatabai, M.A. 1996. Soil organic matter testing: An overview. In *Soil Organic Matter: Analysis and Interpretation* (pp. 1–9). F.R. Magdoff, M.A. Tabatabai, and E.A. Hanlon, Jr. (eds.). Special Publication 46, Soil Science Society of America.

Weil, R.R. and F. Magdoff. 2004. Significance of soil organic matter to soil quality and health. In *Soil Organic Matter in Sustainable Agriculture* (pp. 1–43). CRC Press.

Wuest, S.B. and C.L. Reardon. 2016. Surface and root inputs produce different carbon/nitrogen ratios in soil. Soil Science Society of America Journal 80:463–471.