SOIL CARBON SOLUTIONS CENTER
COLORADO STATE UNIVERSITY

# Guiding methodologies for soil processing & analyses to support rigorous soil carbon accounting

*Authors: Rebecca J. Even, Megan B. Machmuller, Jocelyn M. Lavallee, Tamara J. Zelikova, and M. Francesca Cotrufo*

*White Paper by: Margaret Morgan*

*For a detailed version of the research methods and results described in this white paper, please see the final version of our peer reviewed paper in Soil:* ***Even et al. 2025***

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# Executive Summary

Precise quantification of Soil Organic Carbon (SOC) is an indicator of soil health, and is critical to build confidence in soil carbon crediting programs and carbon markets. Informative and meaningful comparisons across spatial and temporal time scales can only be made with reliable soil carbon measurements and estimates, which begin in the field and in soil testing facilities. We conducted a laboratory comparison across eight laboratories that are frequently involved in SOC quantification for C markets. We assessed the individual effect of several procedures: sieving, fine grinding, and drying as well as quantification methods on total (TC), inorganic (SIC), and organic (SOC) soil C concentration estimates. We analyzed agricultural soils using procedures that varied either in the sieving, fine grinding, drying, or quantification steps. We found that variations in laboratory procedures had a major impact on soil carbon quantification. Based on our findings, we recommend that labs prioritize methodological standardization to achieve reproducibility and improve trust in analyses outcomes. We also recommend that labs standardize methods that are associated with low variation and most accurate results. However, we recognize that there is often a trade-off between accuracy and cost. In those instances, we suggest that it is most critical to avoid directional bias across labs due to procedural variations and that consistency in how soils are processed should be prioritized to improve accuracy.

# THE WAY IN WHICH WE PROCESS SOILS MATTERS.

## There is no perfect way, but there are better ways.

Interest in agricultural soil carbon (C) and soil health is rapidly gaining traction with producers, corporate sustainability offices, policy makers, C market entities, civil society, and various companies interested in developing and scaling climate solutions. The efficacy of scaling soil C solutions as a climate mitigation strategy relies on the accuracy with which soil organic C (SOC) stock changes that result from an actionable change in land management can be quantified. This is especially important now given incentives to offset greenhouse gas emissions[1] through purchasing soil C credits[2].

Today, rigorous quantification approaches rely on physical soil sampling, either to quantify SOC directly or to calibrate and/or verify indirect measurements using modeling and remote sensing approaches.

[1] *Von Unger & Emmer, 2018*
[2] *Oldfield et al., 2022*

# Why focus on lab processing procedures

For reproducibility and comparability of SOC stocks across spatial and temporal scales, sample preparation is considered the first and one of the most important quantification steps.[3] The way soil samples are collected and processed can impact final SOC stock numbers, but there are currently no widely agreed upon guidelines to ensure consistency in how samples are collected in the field or processed in the lab. Today, soil pre-processing protocols and quantification of SOC stocks vary across labs, casting doubt on the quality of measurements they yield. For example, many commercial testing labs process soils initially using a mechanical grinder instead of hand sieving soil samples prior to running soil analyses, but for soil carbon and nitrogen stock quantification, it is deemed important to remove rocks and roots and account for them in calculations of bulk density (BD). A tiny amount of root in a soil sample can increase SOC stocks while grinding rocks with the bulk sample dilutes SOC. In addition, not considering their impacts on bulk soil mass can bias BD determinations. Even research laboratories that sieve soils use different approaches, both in terms of mesh sizes and how they break up soil aggregates.

In addition to pre-processing procedures, for most stakeholders and data users, a basic understanding of the different forms of carbon labs measure, such as total (TC), soil inorganic (SIC) or soil organic (SOC), is generally lacking. Labs implement different approaches to check for and quantify SIC in order to account for it in TC or remove it to directly measure SOC. These same data from laboratory analyses underpin the implementation of policy programs and the calibration and verification of soil biogeochemical models used to predict how changes in management affect SOC dynamics, making it more imperative that the best approaches are used to obtain accurate and precise SOC data across soil testing laboratories worldwide.

[3] *Theocharopoulos et al., 2007*

**MEASURING**

**MONITORING**

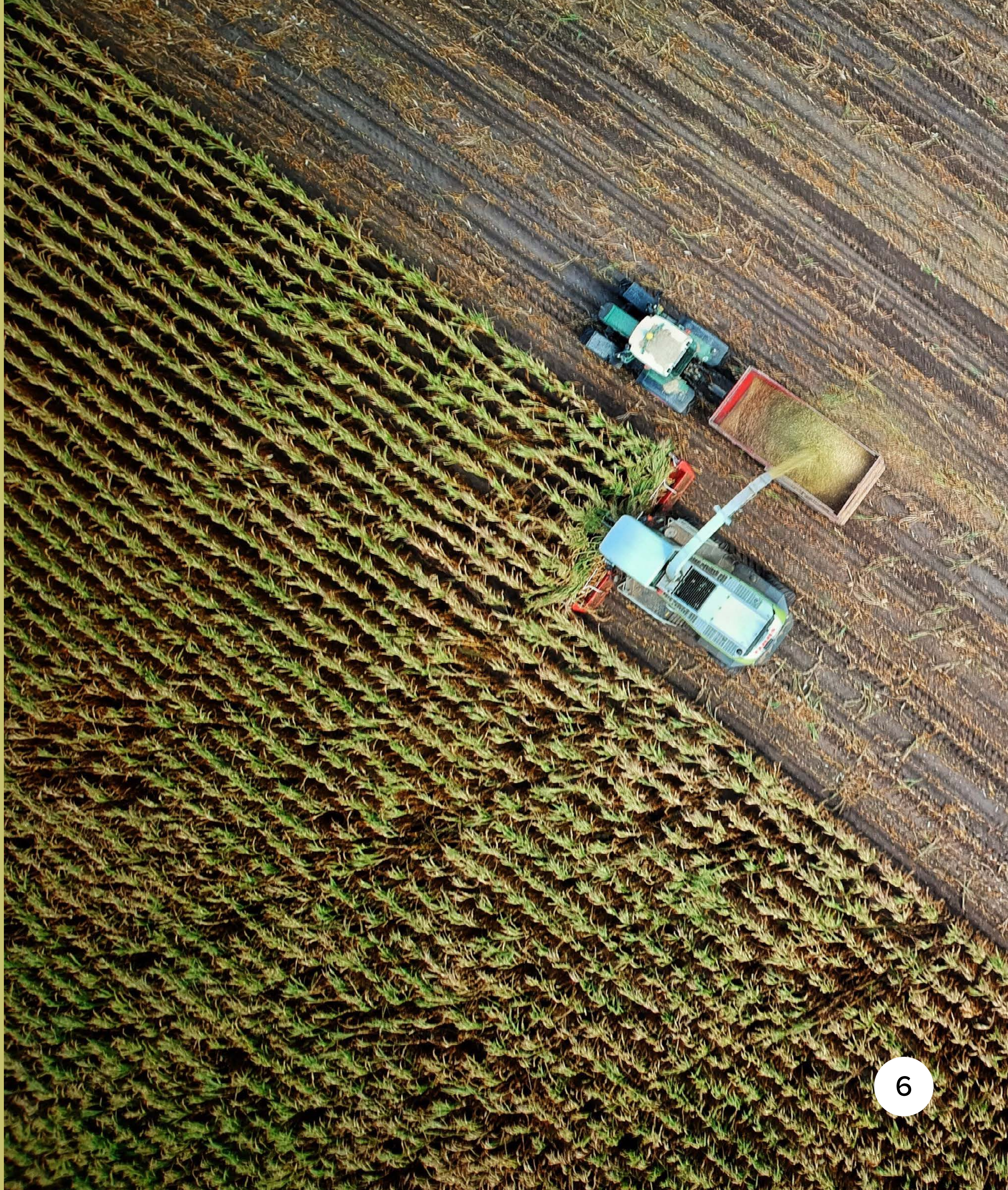
**REPORTING**

**VERIFICATION**

# The need for better soil carbon quantification

A range of stakeholders rely on accurate SOC assessments, from start-ups that need to test the accuracy of new tools against high quality lab data for commercialization to modeling platforms that need to benchmark against accurate datasets. Emerging markets need to be built on rigorous C accounting, and **discrepancies in C accounting may undermine climate benefits and goals**. Policy makers need to trust the quality of the data that underpin policies for climate change mitigation. Reducing variability and developing clear guidance on soil processing best practices can improve MMRV approaches and credibility of incentive programs, corporate sustainability efforts, and overall climate progress.

While research laboratories use relatively common protocols to process and analyze soils, there are variations of existing procedures that affect soil carbon quantification and **there is currently no agreed upon guidance for soil processing that helps ensure consistency.**



# Glossary & Common Terms

**Carbon (C)**
Chemical element

**Bulk density (BD)**
Bulk density of a material is defined as the ratio of the mass of solids to the bulk volume, reported as g/cm3 for soils.

**Total carbon (TC)**
Total carbon is composed of soil inorganic carbon (SIC) and organic carbon (SOC).

**Soil inorganic carbon (SIC)**
Soil inorganic carbon consists of mineral forms of carbon, primarily calcium carbonate.

**Soil organic carbon (SOC)**
Soil organic carbon is composed of decaying plant and microorganisms and various carbon compounds.

**Measurement, Monitoring, Reporting, and Verification (MMRV)**
MMRV is a multi-step framework used to account for the greenhouse gas (GHG) emissions and emissions intensity associated with specific sources.

**Elemental analyzer (EA)**
A specialized instrument used in analytical chemistry to determine the elemental makeup of a sample.

**Loss on ignition (LOI)**
Soil is burned in a muffle furnace and the organic matter is determined by the difference in sample weight pre and post ignition.[4]

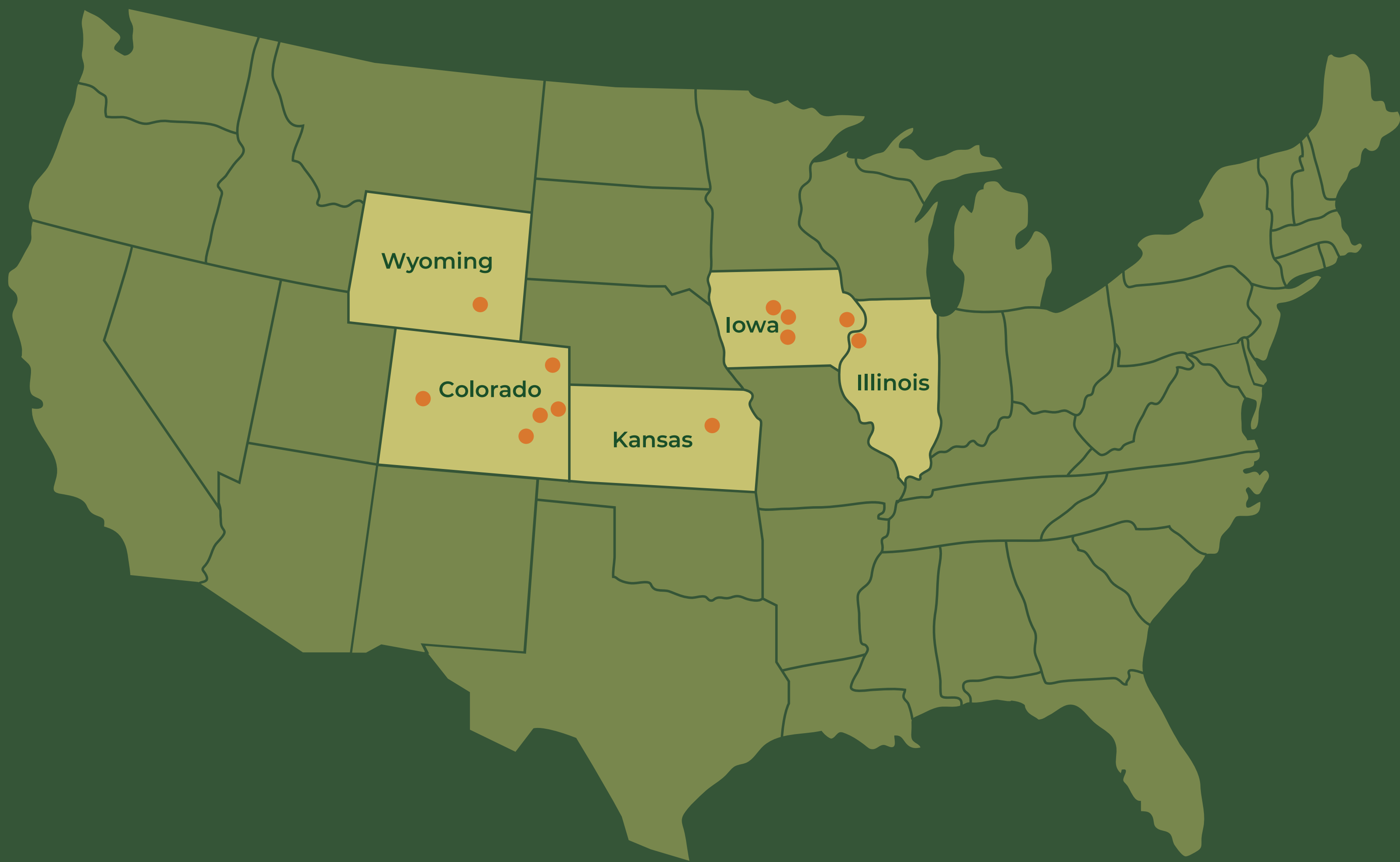
**Mechanical Grinder**
There are several types of mechanical grinders on the market (e.g., flail or disk grinders) which are used by most commercial labs because they significantly accelerate soil processing time, reducing total costs of analyses.[5]

**Coefficient of variation (CV%)**
We use a measure of variation to determine the precision of the procedure as it relates to quantification of SOC and define less variable #s as more precise.

[4] *Storer, 1984*
[5] *Garcia et al., 2022*

# Soil collection

Soils were collected from 12 agricultural sites that varied in management as well as soil textures, rock, root, and carbon content, including SIC:SOC ratios.



# Methods

We compared common variations in methodologies at each procedural step (i.e., sieving, grinding, drying, SIC determination, C analyses and calculation), varying one factor per step, while maintaining the remaining steps consistent. Specifically, we:

1. Reviewed the variety of soil sample processing approaches used in research, service and commercial laboratories to determine which procedures vary in ways that may influence final soil carbon concentration estimates. Based on the survey, we designed and carried out a series of lab tests to evaluate the influence of differential procedures on SOC and SIC quantification.

2. Quantified the degree to which different soil sampling processing procedures affect the precision, accuracy, cost and throughput of soil C measurements.

3. Carried out a comparison between our laboratory results and those from 8 external labs to assess the variability within and across labs.

**In this study, we focus on soil carbon concentrations, not stocks. In order to calculate soil carbon stocks, it is necessary to use a robust measure of soil bulk density, ideally on a per mass basis using the equivalent soil mass approach.[6] We address the variation in field procedures used to quantify bulk density in a separate study.*

[6] *Fowler et. al, 2023*

*Visual representation of 11 procedural variations, with reference procedures represented in gray and the remaining steps that are varied represented by different colors. We implemented these procedural variations across 12 contrasting soils (Table S1). Sieving variations are represented as S1-3, grinding variations as G1-2, drying variations as D1-2, and quantification steps as Q1-3. Note that the quantification steps were not singularly tested since each quantification step required a particular preparation step.*

| | | PROCESSING | | | QUANTIFICATION | | |
|---|---|---|---|---|---|---|---|
| | | Sieving | Grinding | Drying | Total C | SIC | SOC |
| REFERENCE | | 8mm + 2mm | roller table | 105°C | EA | Fizz + PT | EA - PT |
| Sieve 1 | S1 | mortar + pestle + 4 mm | roller table | 105°C | EA | Fizz + PT | EA - PT |
| Sieve 2 | S2 | rolling pin + 2mm | roller table | 105°C | EA | Fizz + PT | EA - PT |
| Sieve 3 | S3 | mechanical grinder | | 105°C | EA | Fizz + PT | EA - PT |
| Grind 1 | G1 | 8mm + 2mm | ball mill | 105°C | EA | Fizz + PT | EA - PT |
| Grind 2 | G2 | 8mm + 2mm | no grind | 105°C | EA | Fizz + PT | EA - PT |
| Dry 1 | D1 | 8mm + 2mm | roller table | 60°C | EA | Fizz + PT | EA - PT |
| Dry 2 | D2 | 8mm + 2mm | roller table | air dried | EA | Fizz + PT | EA - PT |
| Quant 1 | Q1 | 8mm + 2mm | roller table | 105°C | FTIR | | |
| Quant 2 | Q2 | 8mm + 2mm | roller table | 105°C | EA | TC - AF | AF |
| Quant 3 | Q3 | 8mm + 2mm | N/A | 105°C* | N/A | N/A | LOI |

# Detailed description of each procedural variation: processing

## Sieving

| | | |
|---|---|---|
| R | 8 mm + 2 mm | Hand sieving fresh (i.e., field moist) soil using an 8 mm sieve and then 2 mm sieving once air-dried[7] using a mortar and pestle to break soil aggregates. |
| S1 | Mortar and pestle + 4 mm | Use of mortar and pestle on air-dried soil to initially break soil aggregates until the entire sample passes through a 4 mm sieve.[8] |
| S2 | Rolling pin + 2 mm | Use of a rolling pin to break soil aggregates until the entire sample passes through a 2 mm sieve.[9] |
| S3 | Mechanical grinder | Air-dried bulk soil is poured into a mechanical grinder cavity powered by electricity to break soil aggregates to pass through a screen immediately underneath the grinding apparatus. Multiple passes may be required to pass the entire sample through the screen but the procedure is not consistent. The mess screen used is usually 2 mm but can also vary.[10] Commercial labs that use mechanical grinders use them as both a sieving and grinding method. |

## Grinding

| | | |
|---|---|---|
| R | Roller table | Soil samples are placed in glass jars with 3 metal bars and rolled for 18 hours to achieve a grind finer than 250 µm.[11] |
| G1 | Ball mill | Soil samples are pulverized using 20 metal balls in a small metal chamber for 2 minutes to achieve a grind finer than 125 µm. |
| G2 | No grinding | Soil samples are left unground after 2 mm sieving (<2000 µm). |

## Drying

| | | |
|---|---|---|
| R | 105°C | Finely ground soil samples in glass vials are placed with the caps off in a 105°C oven overnight prior to elemental analysis |
| D1 | 60°C | Finely ground soil samples in glass vials are placed with the caps off in a 60°C oven overnight prior to elemental analysis. |
| D2 | Air dry | Soils are not dried beyond the air-drying step for 2 mm sieving but are finely ground prior to elemental analysis. |

7 *Mosier et al., 2021*
8 *Syswerda et al., 2011*
9 *Soil Survey Staff, 2022*
10 *Gilson example grinder*
11 *Arnold and Schepers, 2004*

# Detailed description of each procedural variation: quantification

## Total Carbon Quantification

| | | |
|---|---|---|
| R | Elemental analyzer | The soil sample is combusted under a flow of $O_2$ at a temperature of 950-1100°C, converting all C in the soil to $CO_2$ that is then quantified by a Thermoconductivity detector.[12] |
| Q1 | FTIR | Samples are scanned in the mid-infrared region. The produced spectra are then coupled with predictive models that must be well trained to produce accurate soil C estimates. [13, 14] |

## Soil Inorganic Carbon Quantification

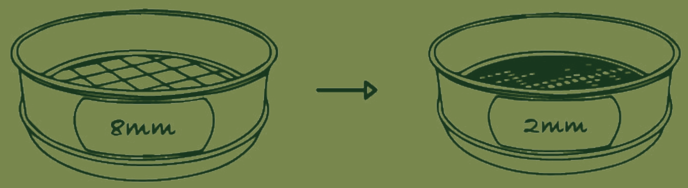
| | | |
|---|---|---|
| R | Pressure transducer | An acid solution is applied and left to react with the calcium carbonate present in the soil sample. The pressure of the $CO_2$ released from the reaction is measured after two hours adapted from a common protocol. [15] |
| Q1 | FTIR | *Same as above in TC Q1.* |
| Q2 | Acid fumigation | SIC is calculated by TC - SOC after acid fumigation. |

## Soil Organic Carbon Quantification

| | | |
|---|---|---|
| R | Elemental analyzer for TC - SIC quantified by pressure transducer | SOC is calculated by TC - SIC after pressure transducer. |
| Q1 | FTIR | *Same as TC Q1.* |
| Q2 | Acid fumigation | SOC is quantified by fumigating soils with acid to remove the SIC and running samples on the EA for the estimation of % SOC. [16] |
| Q3 | Loss on ignition | Soil is heated to 360°C for 2 hours in a muffle furnace to oxidize organic matter. The soil organic matter content is calculated by comparing the weight of a sample before and after it has been subjected to the high temperatures during ignition.[17] SOC is then calculated using a conversion factor of 0.58.[18] |

[12] *Bisutti et al., 2004*
[13] *Reeves, 2010*
[14] *Goydaragh et al., 2021*
[15] *Sherrod et al., 2002*
[16] *Harris et al., 2001*
[17] *Hoogsteen et al., 2015*
[18] *Pribyl, 2010*

# Recommendations

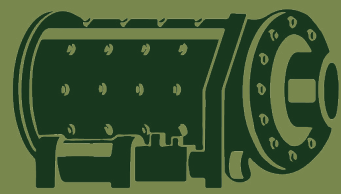



## Sieving

We recommend manually sieving soils to <2 mm. Fresh soils can either be sieved using a 8 mm sieve, followed by 2 mm or air-drying the bulk sample and using a rolling pin to break aggregates to move through a 2 mm sieve. Although the 4 mm manual sieving procedure did produce similar C measurements to the 8 + 2 mm sieving and 2 mm sieving with a rolling pin procedures;

We **do not solely recommend using the 4 mm sieve** because it does not remove rocks from soils and there is potential impact of not removing rocks between 2-4 mm in size that we did not adequately test with our range of agricultural soils.

We also **do not recommend sieving using a mechanical grinder** as this method resulted in significantly lower C measurements and higher variability, particularly in soils with medium to high rock content. We attribute this to the mechanical grinder grinding large rocks into the sample.



## Grinding

We recommend **finely grinding the samples beyond 2 mm** (either using a ball mill or roller table) to reduce variation among heterogeneous replicates due to sample heterogeneity. Either a ball mill or roller table is preferable to no fine grind. The ball mill method resulted in significantly lower variability in soil carbon TC and SOC measurements. The roller table method

# Recommendations

## Drying

We recommend drying soils at 105°C. However, in soils with a high proportion of organic matter, a soil moisture correction may be preferable prior to elemental analysis.
We note that none of the service labs we spoke with mentioned implementing a soil-specific moisture correction for mass to account for incomplete drying at lower temperatures but several labs noted using a standard 1-2% correction.

## Quantification

Accurate estimates of soil C using FTIR depend on the spectral libraries available and consistency following sample preparation and instrumentation protocols.

We also recommend the pressure transducer for direct measurements of SIC.

Despite finding a relatively low CV% in SOC, we do not recommend LOI. In our study, the low CV% using LOI was most likely a result of the rigorous sample preparation, ignition temperature, and time of exposure all being consistent across the samples. The range of LOI values are generally larger between labs when they use their own protocols instead of a rigorous standardized protocol.[19]

[19] *Heri et al., 2001*

# Discussion of Results

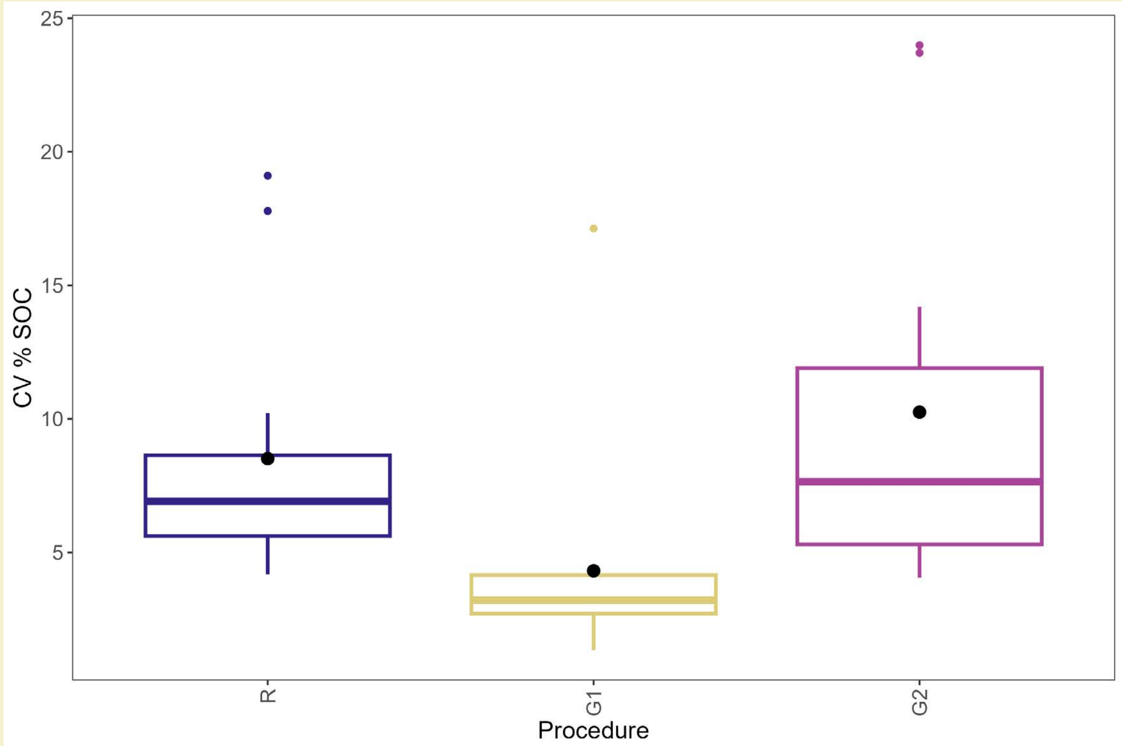
## Impacts of Sieving

- The amount of rocks and plant material removed from samples varied between the four sieving procedures in soils with medium or high rocks or plant material but not for soils with low rocks or plant material.
- The sieving procedure mattered more for soils with high rock and/or root content.
- Leaving more coarse materials in soil samples resulted in higher variability in total and organic carbon estimates.
- Rocks left in the sample have no organic matter and add mass. Large rocks that were not adequately removed significantly reduced % TC and SOC.

# Discussion of Results

## Impacts of Grinding

- Finely ground soils had lower variability in soil carbon.
- Fine grinding helps homogenize heterogeneous samples to minimize between-sample variation.
- If service laboratories are using elemental analyzers that accommodate larger sample masses, sample grind size and homogeneity may be less important.

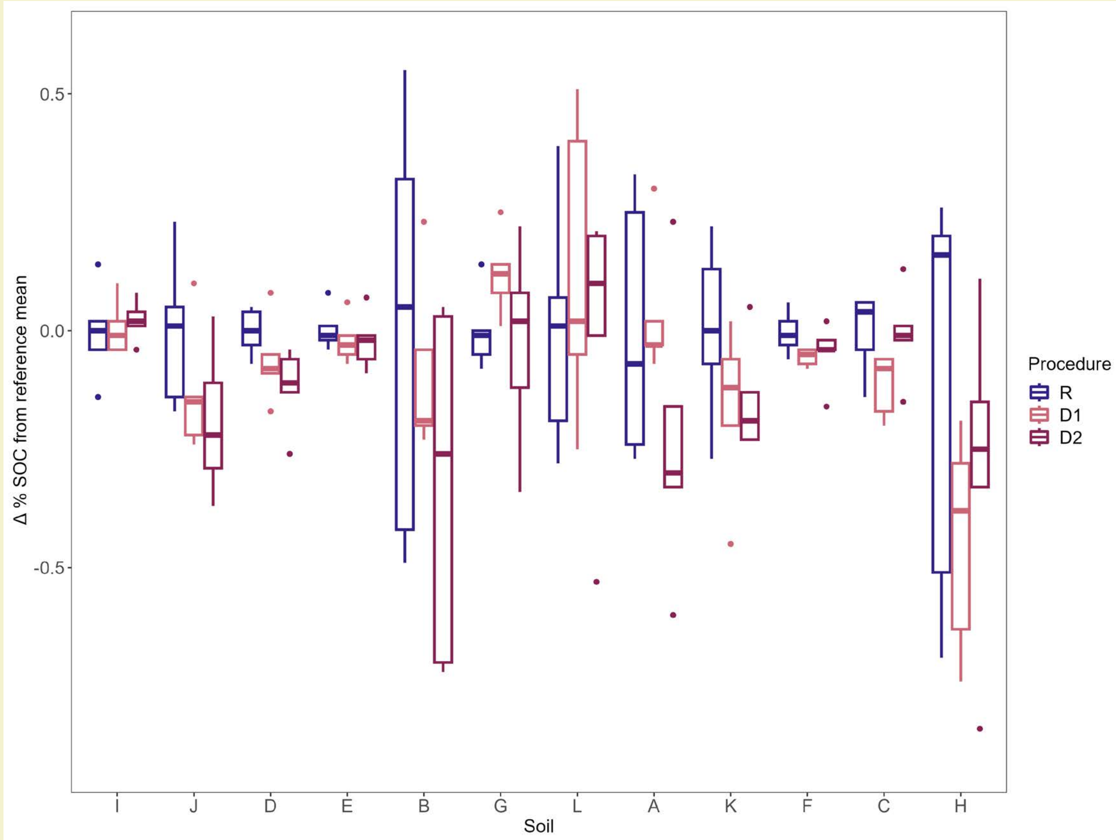



*The distribution of the coefficient of variance (CV) across all soils (n=12) for each of the three grinding procedures tested, as described in Figure 1. Box plots report the median, first and third quartiles. Whiskers extend to the upper and lower data point that are within 1.5 times the interquartile range. Black dots represent the mean CV % SOC.*

# Discussion of Results

## Impacts of Drying Temperature

- We found lower SOC in air-dried soils, likely due to some moisture remaining in the sample and impacting the sample mass.
- Different drying temperatures had no effect on the variability of the final carbon numbers, indicating that drying at any temperature is more effective than air-drying.

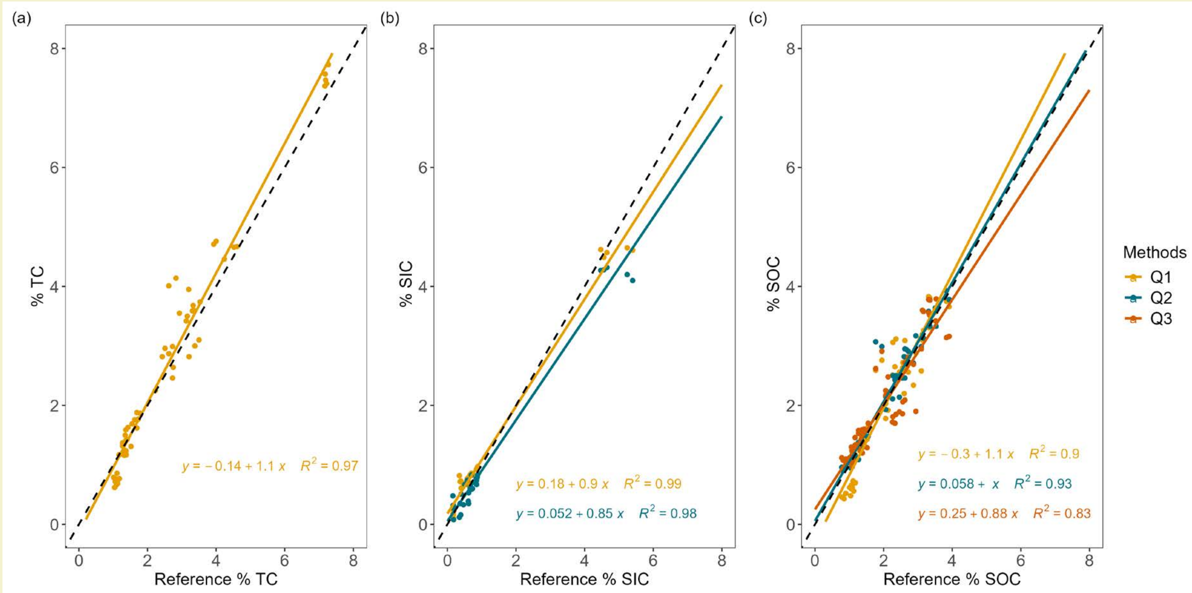



*The difference (Δ) in % soil organic carbon (SOC) compared to the reference (R) mean for all drying procedures, including R. Box plots report the median, first and third quartiles. Whiskers extend to the upper and lower data points that are within 1.5 times the interquartile range. Letters indicate the different soils, as described in Table 1, which are arranged on the x-axis by proportion of rock material removed from the R sieving procedure.*

# Discussion of Results

## Different Approaches to Quantifying Soil Carbon

- We found a strong correlation between the FTIR-predicted % TC and directly measured % TC using the elemental analyzer (EA).
- The FTIR spectroscopy method may thus be a good alternative to EA as it is both reliable and more time and cost efficient.
- Getting accurate FTIR-predicted soil C measurements relies on developing or accessing rigorous spectral libraries and consistently following sample preparation and instrumentation protocols. [20]
- Calculating % SIC as % TC - % SOC is not as precise as quantifying % SIC directly using FTIR or the pressure transducer method.



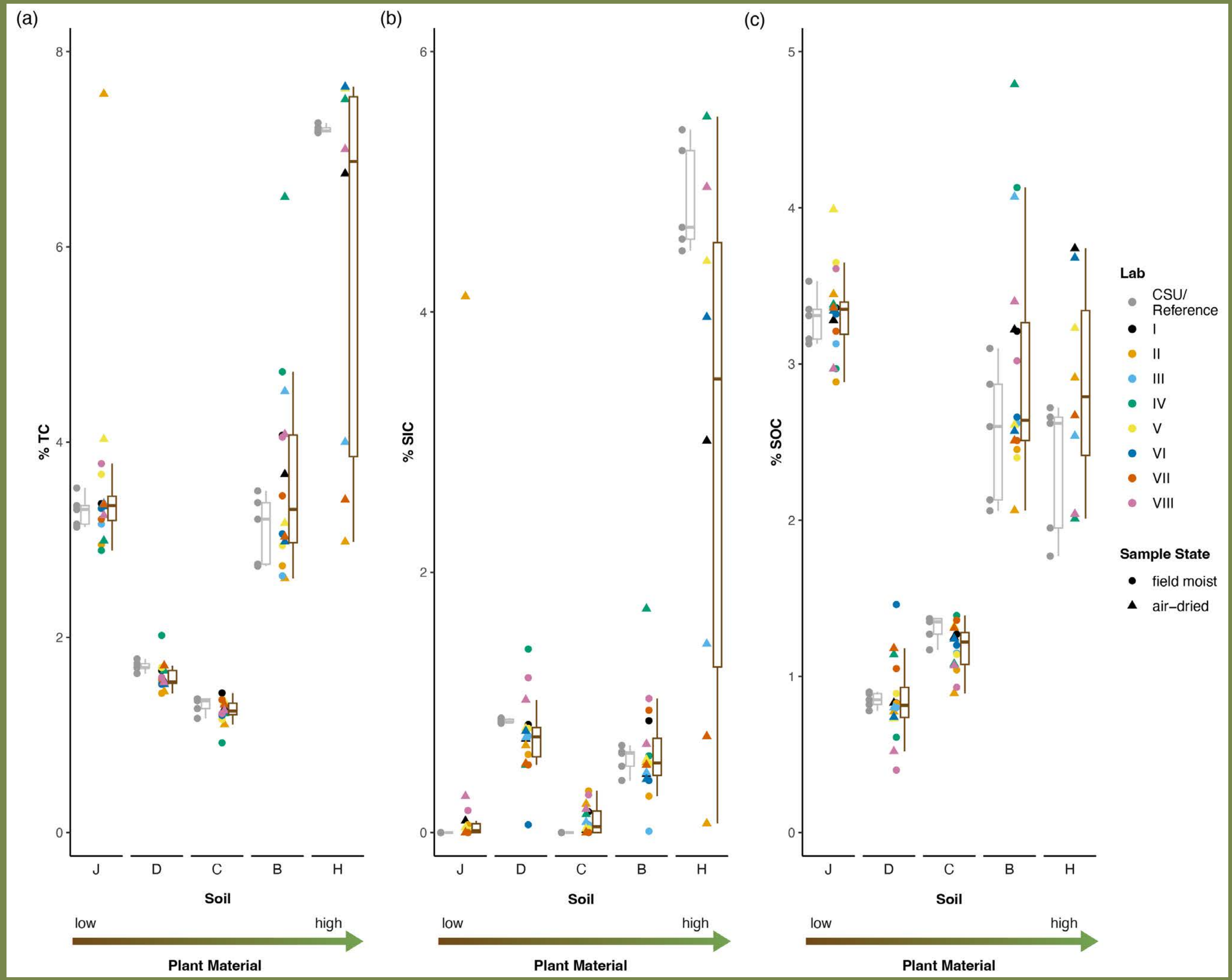

*All quantification methods for % soil total carbon (TC), % soil inorganic carbon (SIC), and % soil organic carbon (SOC) plotted against the reference method where Q1 is predictions using Fourier transformed infrared spectroscopy (FTIR), Q2 is acid fumigation, and Q3 is loss on ignition. The dashed line represents a 1:1 relationship.*

[20] *Sanfanelli et al., 2023*

# External Lab Comparison

We focused our external lab comparisons on variation among labs since we sent homogenized subsamples of the same soils, which would hypothetically yield similar results regardless of lab. These subsamples were also analyzed at CSU using rigorous and consistent methods and serve as a point of comparison. Variation among external labs was notable across several metrics.

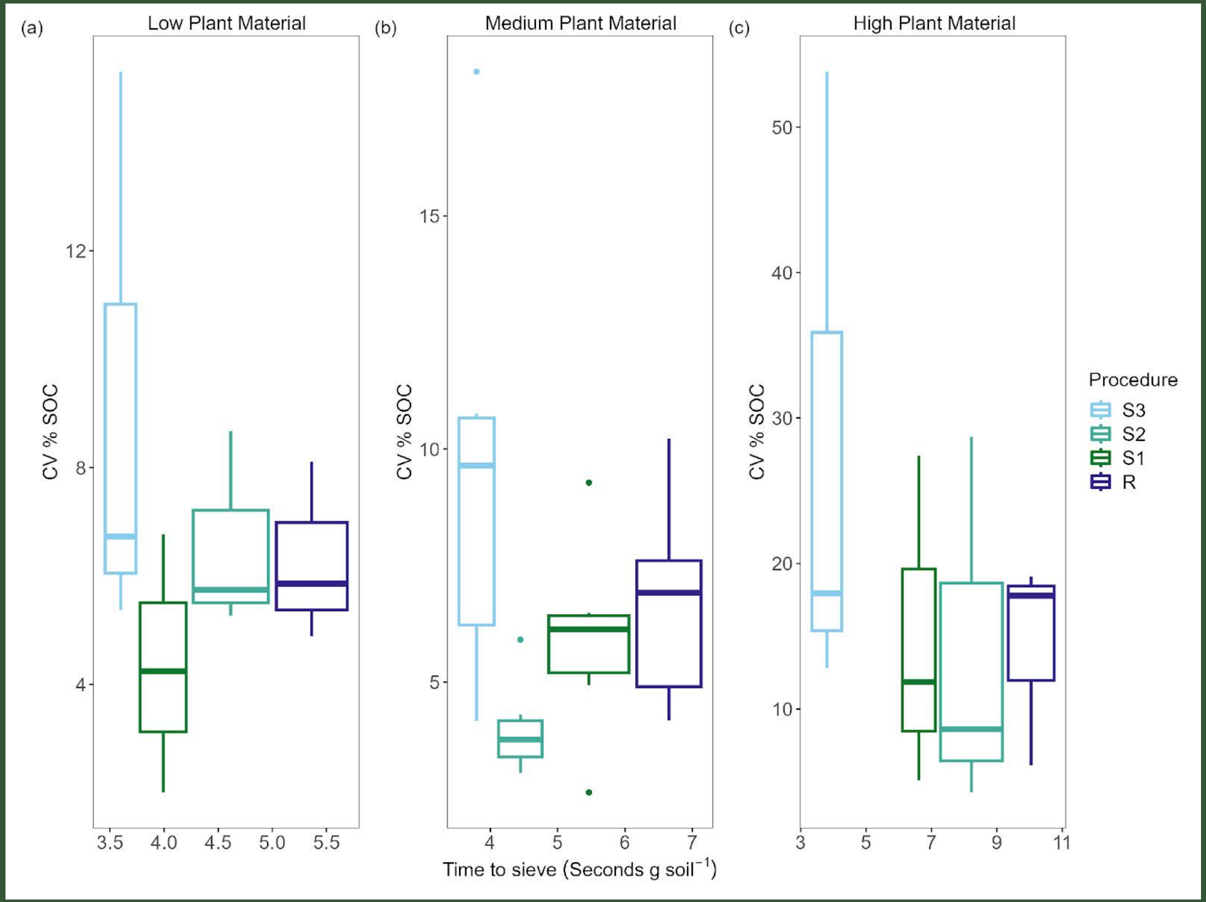
- For subsamples from the same soils, variation across labs was higher for soils with more plant material and higher presence of SIC.
- Variability across labs was also higher for soils with higher SIC content. We attribute this to the challenges associated with accurately measuring % SIC, which also impacts SOC if it is quantified using TC - SIC.
- This trend is also true looking across labs. Service labs reported a spread of 0.07 - 5.5 % SIC for soil H, which had the highest % SIC, as quantified by CSU using the reference methodology.
- Variation across external labs is notable given the fact that the soils were homogenized to the extent possible without sieving before subsamples were sent for analysis or used at CSU for the reference method. Subsampling was performed in the same way for all samples, so the difference in variation between the CSU/Reference method and the commercial labs is more likely due to differences in processing than to soil sample heterogeneity.




*Variation within and across labs in total carbon TC (panel a), soil inorganic carbon SIC (panel b), and soil organic carbon (panel C), with sites on the x-axis ordered from low to high in plant material. Circles represent field moist samples, triangles represent air-dried samples. The box plots represent the median, first, and third quartiles for subsamples analyzed across external labs, with gray box plots representing variability across replicates analyzed at CSU.*

# COST EVALUATION

- The most rigorous sieving procedure (8mm -> 2mm) took the most time in every instance, regardless of the total carbon content, but also increased with carbon content.
- The 4 mm sieve and the mechanical grinder were generally faster than the other two sieving procedures.
- There is a trade-off between processing time and soil carbon quantification precision. Soils with higher carbon content were also generally soils with more plant material and the sieving procedures that removed less plant material were associated with more variability in total carbon.




*The coefficient of variance (CV) of % soil organic carbon (SOC) distributed across soils categorized as having low (panel a), medium (panel b), or high (panel c) plant material for each sieving procedure. Box plots report the median, first and third quartiles. Whiskers extend to the upper and lower data points that are within 1.5 times the interquartile range. Time to sieve is represented as seconds per gram of soil on the x-axis.*

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