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Executive Summary

Soil carbon quantification has historically been implemented using direct measurement techniques: extracting soil cores from a field and analyzing SOC and bulk density in a laboratory setting. These methods are still widely used and are largely seen as the “gold standard” for comparison of alternative methods. In the last ten years, new methods to estimate SOC have evolved that include alternative methods of in-lab measurement, in-field measurement, and on-the-go measurement. The latter-two categories are referred to as proximal soil sensing (PSS). These alternative methods offer the possibility of more cost- and time-effective measurement of soil carbon and soil carbon stocks, but they generally do not possess the same depth of historical research to support their methods.

In this report, we review direct measurement and proximal sensing methods and their potential costs, accuracies, and commercial availability. We describe common methods of measuring SOC and BD in the lab, and then compare those with lab-based methods that use visNIR spectroscopy to estimate SOC. We also review proximal sensing methods that are focused on in-field analysis of soil cores, and methods that only require above-ground sensing. Finally, we compare all these approaches through the lens of utility for SOC stock change quantification over the immediate and longer-term time frames.

Direct Measurement

Overview

Rapid, inexpensive, and accurate measurements of SOC stocks are needed to determine carbon sequestration in agricultural soils. Standard methods for estimating SOC stocks require sampling and analysis of SOC, bulk density (BD), and rock fragments or coarse materials. Errors introduced when quantifying these soil attributes can propagate uncertainty in the estimates of SOC stocks, resulting in reduced accuracy. Direct measurement is widely regarded as the most reliable method for reducing such errors, however it also tends to be associated with high costs. In addition, the lab techniques used for direct measurement are inconsistent in how they account for the presence of inorganic carbonate and bicarbonate minerals¹, which may make measurement standardization difficult in some locations.

In this section, we describe sampling and analysis methods associated with direct ex-situ (laboratory) measurement. Specifically, we compare lab-based techniques for measuring SOC and BD, focusing on cost and accuracy as they relate to up-scaling measurement of SOC stocks. Our focus is at the field scale; at the landscape or regional scales other methodologies may be more appropriate.

Analysis Methods

SOC measurement is traditionally performed by using the loss-on-ignition (LOI) procedure, oxidation of SOC with an automated analyzer (dry combustion), or wet combustion, most commonly using the Walkley-Black method. Table 1 provides an overview of the important attributes of each method, including advantages and disadvantages, described in detail in the following sections.

Table 1. Analysis Features of C Determination Methods.

Method	Principal	CO ₂ Determination	Advantages / Disadvantages
Loss-on-ignition	Sample is heated to 430°C in a muffle furnace for 24 hours.	Gravimetric	Weight losses are due to moisture and volatile organic compounds. Overestimates the organic matter content. Conversion factor must be applied to convert from organic matter to organic carbon.
Automated Elemental Analyzer (Dry combustion)	Automated dry combustion analysis is typically done in gas chromatography-mass spectrometry analyzers (GCMS). Sample is mixed with catalysts or an accelerator and heated in a resistance or induction furnace in O ₂ stream to convert all C to CO ₂ . Resulting gas is typically separated from other gases via chromatography.	Thermal conductivity, gravimetric, IR absorption spectrometry.	Accurate and precise but expensive. With good equipment, highly scalable. Some consistency of methods and instrumentation across commercial labs. Slow release of contaminate CO ₂ from alkaline earth carbonate with resistance furnace. Analysis on bulk sample leads to combustion of inorganic C, appropriate methods must be applied to remove this sample component.
Walkey-Black (Wet combustion)	Sample is heated with K ₂ Cr ₂ O ₇ -H ₂ SO ₄ -H ₃ PO ₄ mixture. Excess dichromate is back titrated with ferrous ammonium sulfate.	Titrimetric	Oxidation factor is needed. Variable SOC recovery. Generate hazardous byproducts such as Cr.

Table adapted from Chatterjee *et al.*, 2009 in which different analysis features and their principal advantages and disadvantages are described.

The [North American Proficiency Testing Program](#) (NAPT) tests lab performance using standard soil analysis procedures and reports the mean absolute deviation (MAD) of the results on a quarterly basis. Table 2 summarizes the results from the Soil Science Society of America’s lab proficiency testing from 2011 - 2020, focused on SOC, total organic carbon, SOM via Walkley-Black and LOI, and CaCO₃. Results indicate that overall, combustion is the most consistent measurement technique across all labs, while sample analysis becomes less accurate with soils higher in CaCO₃.

Table 2. Summary of North American Proficiency Testing Program From 2011 - 2020

	MAD Soil Total C Combustion (%)	MAD SOM Walkley Black (%)	MAD SOM LOI (% Weight Loss)	MAD CaCO ₃ Content (%)	MAD Soil TOC Combustion (%)
Min	0.02	0.06	0.05	0.01	0.01
Q1	0.03	0.12	0.12	0.08	0.04
Median	0.05	0.16	0.16	0.12	0.07
Q3	0.08	0.27	0.22	0.26	0.11
Max	0.23	1.8	0.66	2.9	0.64
Mean	0.06	0.22	0.18	0.26	0.09

Results taken and summarized from the North American proficiency Testing Program lab proficiency testing with standard soil analysis procedures from 2011 - 2020. Reports are based on quarterly analysis from all participating labs. Where TOC = total organic carbon; MAD = mean absolute deviation. All values represented as percentages, with LOI represented as % weight loss.

Loss-on-ignition (LOI)

LOI methods consist of measuring the difference in soil mass before and after heating the sample in a muffle furnace. Use of this technique requires two assumptions: 1) mass loss during LOI is only attributable to the combustion of SOM and 2) the carbon content of SOM remains constant¹. Both assumptions can easily be violated. High temperatures and long ignition times can decompose inorganic compounds without burning the entire SOM pool within the sample¹, leading to loss of mass (and thus an inaccurate estimate of organic C). Additionally, a LOI sample is presumed to have no water at the start of analysis, but removing all water is very difficult in some clay-rich soils. During LOI this water is

¹ [Chatterjee et al., \(2009\)](#)

lost, further inflating the final mass loss estimate. C content within SOM has also been shown to vary within sampling depths and therefore cannot always be assumed constant².

The carbon content in SOM (i.e., SOC) can be calculated by multiplying by a factor of 0.58, with the assumption that the stoichiometric percentage of C in SOM is 58%. However, this assumption can lead to significant error, as the conversion factor can vary based on the types of organic compounds present^{3,2}.

The use of LOI for SOC measurement is relatively cheap and the necessary equipment is easy to obtain and maintain. But it may have lower accuracy than other methods, sometimes as high as +/- 20% error (NAPT). This results from the need for individual conversion factors or equations to obtain the SOC value from the weight difference. These factors or equations vary with the unique nature of the OM from each soil sample and are dependent on area, soil type, and soil horizons^{4,1}. As such, it is important to have detailed information on the soils before analysis so that the right correction factors are used.

Without this supporting information, temperature and duration of ignition can be difficult to determine, although both are critical to prevent the loss of CO₂⁴. Figure 1 details general global soil types and their corresponding temperature, duration of combustion, and correction factors. Figure 2 similarly displays temperature, duration of combustion, and SOC conversion equations but with a focus on locations in the US.

Table 5. Loss-on-ignition method			
	Temperature and time for OC removal	Equations or correction factors and comments	Refs.
Prairie north-west Canada soil	375°C for 16 h	$OC = -1.66 + 5.98LOI - 0.21 \text{ clay}$	[4]
Egyptian soils	600°C for 6 h	$OC = -1.923 + 0.567 \cdot LOI - 0.086 \cdot \text{clay}$	[10]
Sandy soil	550°C for 4 h	$OC = 0.624 \cdot LOI + 0.6$	[18]
New Zealand mineral soil	550°C	$OC = 0.232 + 0.581 \cdot LOI - 0.0851 \cdot \text{clay}$	[24]
Arid zone soils	400°C for 8 h	Soils containing 0.09–13.23% OM	[35]
Calcareous sediments and sedimentary rocks	550°C for 1 h	Also detects IC after removal at 1000°C for 1 h $OC = 0.47 \cdot LOI$	[51]
Sediments	475–500°C for 4–6 h	100% recovery	[53]
Mineral soil	450°C for 12 h	$OC = -0.0134 + (0.520 \cdot LOI)$	[54]
Forest floor	450°C for 12 h	$OC = -2.74 + (0.813 \cdot LOI) + (-0.00257 \cdot LOI^2)$	[54]
Different loams	450°C for 4 h	To evaluate SOM	[55]

The weight difference is determined; OC by dry combustion; LOI = weight loss.

Figure 1. Taken from Bisutti *et al.*, (2004)⁴, in which the temperatures, time for OC removal, and the specific correction factors are detailed for different types of soils.

² [Christensen and Malmros \(1982\)](#)

³ [Pribyl \(2008\)](#)

⁴ [Bisutti *et al.*, \(2004\)](#)

TABLE 4
Relationship between soil organic C (determined by wet oxidation and dry combustion) and weight loss-on-ignition (LOI)

Soil type	Temperature (°C)	Duration (h)	SOC = m*LOI + c			Reference
			m	c	(r ²)	
Forest soils, USA	300	2	0.4315	0.1603	0.69	Abella and Zimmer (2007)
Sierra Leone	375	2	-6.55	0.64	0.93	Kamara <i>et al.</i> (2007)
	550	3	0.5783	-1.2875	0.96	De Vos <i>et al.</i> (2005)
Nebraska sand hills, USA	360	2	1.414	-0.6791	0.94	Konen <i>et al.</i> (2002)
Central loess plains, USA	360	2	0.6717	-4.5359	0.94	Konen <i>et al.</i> (2002)
Southern Wisconsin & Minnesota till prairies, USA	360	2	0.5743	0.1025	0.98	Konen <i>et al.</i> (2002)
Central Iowa and Minnesota till prairies, USA	360	2	0.6824	-2.8696	0.97	Konen <i>et al.</i> (2002)
Illinois and Iowa deep loess and drift, USA	360	2	0.6094	0.1949	0.98	Konen <i>et al.</i> (2002)
Tasmanian acidic soils						
Non-basalt derived	375	17	0.726	-1.598	0.96	Wang <i>et al.</i> (1996)
Basalt derived	375	17	0.469	-0.941	0.95	Wang <i>et al.</i> (1996)
Canadian Prairie	375	16	-9.36	0.633	0.97	Soon and Abboud (1991)
	450	6	0.568	0	0.98	Donkin (1991)
	450	16	0.914	0	0.99	Lowther <i>et al.</i> (1990)
Various soils of U.K.	550	3	0.840	-1.68	0.98	Howard & Howard (1990)
	400	8	0.972	-0.37	0.97	Ben-Dor & Banin (1989)
	450	12	1.04	-0.03	0.92	David (1988)

Figure 2. Taken from Chatterjee *et al.*, (2009)¹, where soil type, temperature, duration of combustion, and the LOI is detailed for different soil types.

Another issue with LOI is that inorganic carbonates are burned off during the combustion process. Natural inorganic carbon and OC cannot be accurately separated because the combustion and decomposition temperatures overlap⁴.

Despite these drawbacks, some researchers and agronomists interested in quantifying SOC at the field scale prefer the LOI method due to its accessibility and affordability. While lacking in accuracy, especially compared to an automated elemental analyzer, a combustion system can be quickly built with easily accessible materials and LOI can be calculated on a landowner's property within a few hours, allowing producers to make quick and efficient management decisions.

Automated Elemental Analyzer

The use of an automated analyzer has become the standard for measuring SOC due to its high accuracy. The United States Department of Agriculture (USDA) currently considers use of an elemental analyzer as the most appropriate and accurate method for measuring SOC ([Recommended Soil Health Indicators and Associated Laboratory Procedures](#)). Benefits of an automated analyzer include: all forms of carbon are decomposed, only a small sample is required, and it requires only a short amount of time for analysis^{5,4} (NAPT program). Inorganic carbonates can be removed via a modified pressure calcimeter or through a HCL pre-treatment before analysis. However, it should be noted that one study found HCL

⁵ [Nayak et al., \(2019\)](#)

pre-treatment only removed 35% - 66% of inorganic carbonates compared to NaOCl treatment (63% - 91%) and therefore may not be the best pre-treatment procedure⁶.

A major drawback to automated analyzers are their expense, both for the initial purchase and for continued maintenance. [Costech](#) offers the [ECS 4010 CHNSO Analyzer](#) for \$52,000, which includes a micro balance. The micro balance retails around \$17,000 - \$19,000 if purchased separately. To lower costs, Costech offers maintenance agreements which are included in their warranty packages. Another option is [Shimadzu's SSM-5000A Solid Sample Combustion Unit](#). Additional consumable items necessary for use of an elemental analyzer further add to the expense, including reagents, custom glassware, replacement hardware, and helium gas, some of which require special chemical and occupational safety handling procedures.

If purchasing an elemental analyzer is not possible, soil samples can be submitted to an independent lab for analysis. [Ward Labs](#), using a [Leco TruMac analyzer](#), charges \$16/ sample for a bundled package analysis of NPK, OM, CEC, and S, or \$5.50 for a single OM analysis using the LOI method. [Atlantic Microlabs](#) also offers CHNS analysis, using an ECS 4010 elemental analyzer (from Costech) for \$26/sample, with an average turnaround time of 1-3 days.

When using an elemental analyzer, sample size is an important consideration. Due to the relatively small sample size and weight needed for analysis, errors can be introduced if the sample is not representative of the soil volume of interest. Therefore, sample preparation techniques must include sufficient attention to homogenization and sub-sampling techniques.

Walkley-Black (WB)

Walkley-Black (WB) is the most commonly used wet combustion method for measuring SOC. The WB method is easy, cheap, and involves minimal equipment, making it a preferred methodology in developing countries⁵. However, because of the costs and personal safety hazards of handling chromium waste and acidic reagents, many labs have started to move away from the method. Additionally, there are multiple accuracy drawbacks to using WB: the process only oxidizes the active SOC in the sample, errors are frequent due to manual titration, and site-specific correction factors are needed to accurately estimate SOC^{5,4,1} (as detailed in Figure 3). Recovery is possible, but it is variable due to soil type and properties of SOC. *De Vos et al., (2007)*⁷ found that there is a strong correlation between recovery percentage and the soil texture and pedogenetic horizons within the soil sample. Some researchers have estimated that the oxidation process may vary between 59% - 88%⁴ or 60% - 86%⁵ in efficacy. Depending on the correction factors used, SOC may also be over or underestimated.

⁶ [Zimmermann et al., \(2007\)](#)

⁷ [De Vos et al., \(2007\)](#)

TABLE 3
Correction factors for soil organic C not recovered by the Walkley-Black (Walkley and Black, 1934) method

Sampling location	Recovery%	Average Correction Correction factor	Reference
Forest soils, Belgium	63	1.58	De Vos <i>et al.</i> (2007)
Calcareous soil, Italy	77	1.30	Santi <i>et al.</i> (2006)
Sierra Leone	83	1.20	Kamara <i>et al.</i> (2007)
Native Prairie, Arkansas,USA	66	1.51	Bryre and Slaton (2003)
Agricultural soil, Arkansas,USA	63	1.59	
Russian Chernozem	61	1.63	Mikhailova <i>et al.</i> (2003)
Graminean pasture, Argentina	59	1.69	Díaz-Zorita, (1999)
Mineral soils, New Zealand	80	1.25	Grewal <i>et al.</i> (1991)
Canadian Prairie	71	1.40	Soon and Abboud (1991)
Australia	88	1.14	Lowther <i>et al.</i> (1990)

Figure 3. Taken from Chatterjee *et al.*, (2009), where sampling locations and their corresponding recovery percentage and average correction factor is detailed for the Walkley-Black method.

Bulk Density

Accounting for BD is crucial for SOC stock calculations, as inaccuracies can lead to error propagation, especially for soils high in rock fragments or coarse fragments. Bulk density of surface horizons is also more variable due to root and stubble biomass, especially in agricultural soils where management decisions can change the soil structure^{8,9}. Furthermore, BD can change over time as soils become more or less compacted. Therefore, it is important that appropriate sampling techniques are used so that SOC stocks are not over or underestimated due to errors in BD measurements. Indirect and direct methods have previously been used to measure BD. At broader spatial scales, and of particular interest in the absence of historical data, BD can be retroactively calculated through regression methods, such as pedo-transfer functions, but the accuracy of the results are dependent on the calculation method used¹⁰. At the field scale, the three main techniques for BD measurement are soil cores, soil pits, and clod sampling.

The most common and most frequently recommended soil sampling technique for BD is the use of an auger or hydraulic soil cores, whereby a probe or solid ring is used to capture an exact volume of soil,

⁸ [Czyz and Dexter \(2009\)](#)

⁹ [Zolfaghari et al., \(2020\)](#)

¹⁰ [Boschi et al., \(2018\)](#)

including roots and rock fragments, to a fixed depth^{11,12,13}. Samples are dried for 2 -3 days, depending on soil moisture and the core size, and the mass of the dried sample is calculated.

Core sampling of BD is easy and inexpensive, yet choices must be made about probe size and sampling depth, especially in agricultural soils where BD is highly variable. If the sampling probe is too small (<1 in), the soil sample will become compacted and shatter, thus inflating the BD number¹⁴. Soil probes can also underestimate the presence of roots and rock content because they are not large enough to include rock fragments, which are generally used to correct BD estimates. As such, soil probes should have a diameter of 38mm to account for rock and root content. Additionally, inconsistent sampling depths can lead to error magnification in BD and SOC stock calculations. It is therefore recommended to separate soil samples into consistent sampling increments. The thicker the sampling depth increment, the more variance across the sample. The standard is to use 30cm depth increments, with many studies using 10 or 15cm depth increments^{10,15}. Finally, accuracy is further impacted by soil type, especially for soils with high sand content or low levels of organic matter, as soil samples can fall out of the probe or holes created by the probe collapse^{10,16}. It is recommended that the core used should be dependent on soil type: for soils high in soil organic matter and low in sand, a push or hammer probe will work best, whereas augers are better suited for sandy and low soil organic matter soils.

Soil pits include digging trenches into the soil for diagnostic / descriptive soil science, where researchers sample horizontally or dig a more comprehensive (0.5 - 1m) soil pit for quantitative assessment. Some suggest that due to the thoroughness and accessibility to soil layers, soil pits are a more accurate sampling technique for BD¹⁰. However, while soil pits may provide more accuracy and pedological site descriptions, they are often deemed too laborious, obtrusive to landowners, and are impractical to implement in multiple locations at a single site.

Sampling via the clod method is a complicated process. Samples must be dried and calculating their mass and volume involves using paraffin wax and is dependent on the equilibrium water potential⁹. It is no longer considered an up-to-date method, is difficult to scale, and has similar drawbacks to soil pits in terms of soil disturbance. The accuracy of clod sampling is additionally dependent on the size of the sample, soil pore size, soil texture, experience of the operator, and calibration of the equipment^{10,17}.

Effect of Rock Fragments on BD Calculations

Another factor impacting BD and SOC estimates is the presence of rock fragments. At larger scales (regional, country, etc.), rock fragments are often ignored when calculating BD. BD and rock fragment measurements are most common at the plot-scale due to their more intensive sampling requirements.

¹¹ Robertson, P.G., Coleman, D.C., Bledsoe, C.S., & Sollins, P. 1999. Standard Soil Methods For Long Term Ecological Research Oxford University Press, United States.

¹² Carter, M.R. & Gregorich, E.G. 2008. Soil Sampling and Methods of Analysis. CRC Press, Boca Raton, FL.

¹³ [Walter et al., \(2016\)](#)

¹⁴ [Al-Shammary et al., \(2018\)](#)

¹⁵ [Jandl et al., \(2014\)](#)

¹⁶ [Gross and Harrison, \(2018\)](#)

¹⁷ [Rossi et al., \(2008\)](#)

In studies estimating SOC at the regional, national, or country scale, BD estimates are typically calculated using pedotransfer functions while rock fragment estimates are ignored¹⁸.

Inclusion of rock fragments can drastically change SOC stock estimates and should therefore be considered. Poeplau *et al.* (2017)¹⁹ estimate that soils containing >30% rock fragments can overestimate SOC as much as 100% and that 68% - 87% of SOC stock-focused studies overestimated SOC stocks (assuming a rock fragment fraction >0) or did not account for rock fragments at all (which was common for studies looking at agricultural soils). The authors' suggested equation to account for rock fragments in SOC stock calculations is detailed in Appendix A, Equation 3.

Hobley *et al.* (2017)²⁰ disagreed with this method of accounting for rock fragments and claimed it is prone to error propagation due to the assumption of uniform rock density and extra calculation steps. According to Hobley *et al.* (2017)²⁰, mass-balance derived equations are simpler because including the mass of fine fractions introduces a greater potential for error than using mass proportion of rocks; rocks are always conserved during sieving, unlike fine soil mass, which can be lost as dust. Additionally, Poeplau, Vos, and Don *et al.* (2017)¹⁹ use rock density to calculate BD, which is dependent on the soil's parent material and can increase error if assumed. The equation used by Hobley *et al.* (2017)²⁰ is listed in Appendix A, Equation 4.

Fixed Depth Versus Equivalent Soil Mass for Accounting for BD

Some sampling methodologies adjust SOC stock estimates to account for BD variability within soil layers and BD response to soil management change, but none have been adequately evaluated⁴. In many studies, BD is assumed to be constant over time, which is not always the case, especially in agricultural soils. In particular, some practices like conservation crop rotation, cover crop, deep tillage, prescribed grazing, and residue and tillage management have demonstrated significant effects on soil bulk density.

In most studies, fixed depth (FD) sampling methods are applied. Caution should be employed when sampling to a fixed depth, especially when comparing between two treatments where BD is assumed to be constant. The fixed depth method can produce large errors when BD significantly differs between treatments being compared (such as agricultural management systems and land use changes) and is not accounted for, or when BD has changed over a monitoring period¹⁶. If BD differs between treatments, then soil masses will also differ. If BD is assumed constant, then the soil samples will be unequally compared, ultimately resulting in significant SOC stock estimation errors.

To mitigate against the differences in soil mass, Wendt and Hauser (2013)²² suggested using soil mass layers (such as 1-1000, 1000-2000, 2000-3000 Mg ha⁻¹) which are insensitive to changes in BD, rather than soil depth layers, which are fixed. Equations for estimating soil mass layers and OC mass can be found in Appendix A, Equations 1 and 2.

Under scenarios where soil bulk density varies drastically due to management, the equivalent soil mass (ESM), or the reference soil mass per unit area in a chosen layer, can correct for changes in BD over time and thus improve SOC stock estimates²². Despite its ability to overcome estimation errors, measuring

¹⁸ [Don et al., \(2007\)](#)

¹⁹ [Poeplau et al. \(2017\)](#)

²⁰ [Hobley, et al. \(2017\)](#)

ESM is challenging. It cannot detect SOC change in an individual layer, requires increased sampling at multiple depths for a meaningful comparison at deeper soil layers, and is prone to error magnification²¹.

Equivalent soil mass can be calculated via 1) sample adjustment or 2) interpolation. Calculating equivalent soil mass by sample adjustment is most commonly done using soil rings with a volume between 100 - 500 cm² or soil probes to a fixed depth with multiple increment depths, which can introduce substantial errors and will be discussed below^{11,22}. Sample adjustment is most appropriate when analyzing a single sample corresponding to one depth at each location. Soil from a lower depth must also be collected, weighed, and homogenized with the upper layer, but only one sample per location undergoes lab analysis. The method is relatively easy and cheaper than interpolation methods. However, sample adjustment is not without its disadvantages. The process involves physical redistribution of soil samples from different soil layer depths, creating additional risks for error propagation¹⁶.

The second ESM calculation technique is to use interpolation, which requires sampling of multiple layers, from which a more comprehensive picture of soil changes can be obtained. Interpolation allows researchers to quantify soil parameters for any soil mass, and physical readjustment of soil samples is not necessary. However, because each soil sampling increment must be analyzed, laboratory costs can increase dramatically, even if only two depth layers are considered (2x the cost of single-depth analysis)¹⁵.

Despite increased recognition of the importance of the equivalent soil mass (ESM) compared to the fixed depth (FD) approach, in terms of SOC stock evaluation, the ESM approach focuses on the direct impact of bulk density but ignores the potential indirect effect on SOC concentration (Xiao et al (2020)²³. Whether the increased cost and complexity of applying the ESM approach is justified for the estimation of SOC stock changes at the field level likely depends on the variability of the bulk density of each site in time and also the depth of sampling.

Xiao *et al.*, (2020)²³ found that overestimation of the soil carbon stocks from the fixed depth method as compared to ESM may be minimized by increasing the sampling depth. Their results suggest that the traditional FD method overestimates carbon stocks within the 5–10 cm deep surface layer as compared with the ESM method in cropping systems that had recently transitioned to no-tillage. However, the FD method also underestimates SOC stocks within the 30–70 cm deep soil layer. Combined, this resulted in no significant differences between the carbon stocks estimated by the FD and the ESM methods for entire soil profiles. Consequently, the overestimation of SOC stocks, based on the FD approach may not be as high as previously assumed, even in managed systems with high variability in bulk density. Further research is needed in order to define the criteria to choose between either of the methods.

Nevertheless, given the simplicity and smaller cost of the FD method, it may be preferred under the following conditions:

²¹ [Lee et al. \(2009\)](#)

²² [Wendt and Hauser, \(2013\)](#)

²³ [Xiao et al., \(2020\)](#)

- Management practices or changes in land use in the area of interest are not expected to create drastic changes in BD
- When sampling to at least 30 cm depths
- If treatments are being compared and BD is consistent between both

Proximal Sensing

Proximal soil sensing (PSS) describes the use of in-field and lab-based sensors for quantifying the soil properties at the sub-field scale, when a sensor is in contact with or close (<2 m) to the soil. Over the last 20 years, PSS has increased in prominence as a potential alternative to traditional lab-based soil analyses, which can be expensive and time consuming, especially when implemented at high spatial resolutions.

In this section, we provide a brief overview of PSS technologies that are relevant for quantifying SOC stocks and provide references to resources describing each technology in more detail. We focus our analysis on the practical implementation and opportunities provided by PSS technologies, relying equally on available academic literature and information gathered from commercial tool vendors. The end product of this section is a discussion of the relative merits of each technology, including recommendations on the most promising tools with regards to availability, cost, and accuracy.

Viscarra Rossel *et al.* (2011)²⁴ describe proximal sensing technologies in terms of four primary categories. These include measurement (invasive or noninvasive/above the soil surface), the source of energy (passive or active), whether the sensor is stationary or mobile, and whether inference of the target soil property is direct or indirect (figure 1). The authors describe a wide array of techniques within this categorization, but for the purposes of detecting SOC, only four are relevant: inelastic neutron scattering (INS), X-Ray fluorescence (XRF), visible, near-infrared, and mid-infrared spectroscopy (vis-NIR; MIR), and laser-induced breakdown spectroscopy (LIBS) (Table 3). These techniques are summarized below; more detail is available in Viscarra Rossel *et al.* (2011)²⁴, Kavetskiy *et al.* (2019)²⁵, Bellon-Maurel and Mcbratney (2011)²⁶, and Cremers *et al.* (2001)²⁷. A recent in-depth comparison of many of these technologies was also published by England and Viscarra Rossel (2018)²⁸. Other technologies that are useful for characterizing soil but not soil carbon, such as electrical resistivity and gamma radiometrics, are briefly described at the end of this section.

²⁴ [Viscarra Rossel *et al.*, \(2011\)](#)

²⁵ [Kavetskiy *et al.*, \(2019\)](#)

²⁶ [Bellon-Maurel and Mcbratney, \(2011\)](#)

²⁷ [Cremers *et al.*, \(2001\)](#)

²⁸ [England and Viscarra Rossel, \(2018\)](#)

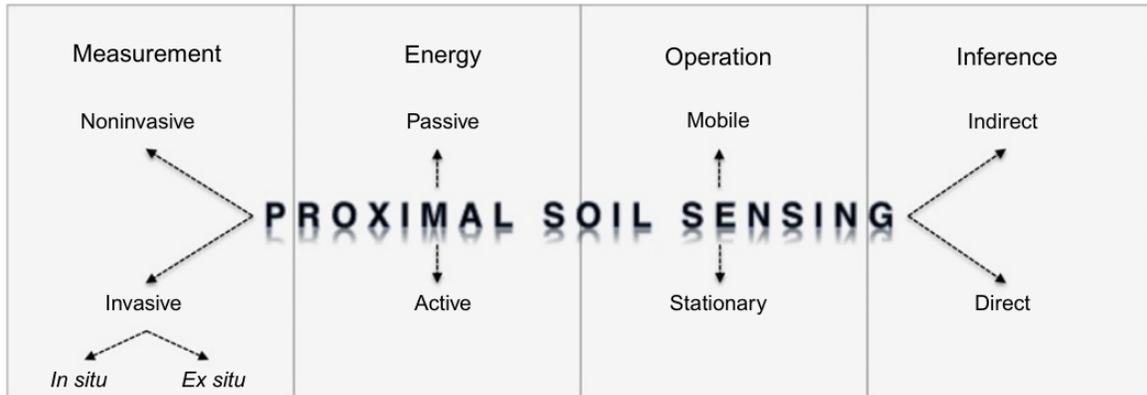


Figure 4. Categories of proximal soil sensing instruments, from Viscarra Rossel *et al.* (2011)²⁴.

Table 3. PSS techniques for measuring SOC; table adapted from Viscarra Rossel *et al.* (2011).

		Measurement	Energy	Operation	Inference
EM Range Wavelength	Technique	Invasive/ noninvasive	Active/passive	Stationary/mobile	Direct/indirect
γ -Rays (10^{-12})	INS	N	A	S/M	D
X-Rays (10^{-12})	PXRF	N	A	S	D
Vis - MIR (10^{-8} to 10^{-4})	visNIR/MIR	I (in/ex situ)	A/P	S/M	D/I
	LIBS	IN	A	S	D

Inelastic Neutron Scattering (INS)

INS is an active PSS technique whereby neutrons are emitted by a pulsed neutron generator and collide with nuclei of soil atoms (pulse fast neutron thermal analysis; PFTNA; Wielopolski *et al.*, 2011²⁹). The resulting interactions result in re-emission of fast neutrons along with gamma rays, the latter of which are specific to the atomic composition of the soil. Emitted gamma rays can be detected with spectrometers and that signal is then used to characterize the soil sample. Differences between the gamma-ray signature during the pulse events and the between-pulse events is proportional to the soil carbon content, therefore can be used to estimate SOC³⁰.

²⁹ [Wielopolski *et al.*, \(2011\)](#)

³⁰ [Yakubova *et al.*, \(2014\)](#)

The INS system is typically calibrated against a synthetic soil that is composed of sand and different percentages of granular C. The synthetic soil is of a known volume and mass; therefore, the INS signal can be calibrated against the C density. For non-synthetic and therefore un-homogeneous soils, the signal instead represents the total C under the footprint of the INS system (g C m^{-2} ; system footprint is 1.0 m^2), which must then be scaled to soil volume. Based on Beer's law, which determines the exponential attenuation of the gamma rays, 90% of the signal is derived from the top 30 cm of soil, which is referred to as the effective soil volume (Wielopolski *et al.*, 2010³¹). It is unclear how changes in bulk density would affect the volume of soil interrogated by the system; this may be a limitation of INS.

Despite possibly being sensitive to changes in bulk density, INS possesses many other advantages. Most notably, since it is non-invasive it may be used as a mobile sensor that can detect SOC stocks at high resolution over large areas²⁵. This is in contrast to invasive sampling, where only a small volume of soil is analyzed and is assumed to be representative of a much larger area. INS can also be used to measure other elements via thermal neutron capture (TNC), including K, total P, and Si (Allen, personal communication³²). Like many other PSS technologies, INS cannot distinguish between organic and inorganic carbon, therefore it may not perform as well in locations where significant amounts of carbonates are present. However, this may be irrelevant when the intention is to detect changes in SOC stocks, because inorganic carbon would not be subject to appreciable change over time.

As of this report, no systems for using INS are commercially available. However, Carbon Assets Solutions, based in Australia, has currently licensed the technology (developed by the USDA), and is required to have a commercially available product by the end of 2021. Based on a very rough estimate (Torbert, personal communication³²), at the top end the system would cost ~\$75,000.

(Portable) X-Ray Fluorescence (XRF)

XRF has only received limited attention for estimation of SOC (Morona *et al.*, 2017³³). The technology is based on detecting x-ray fluorescence of atoms as they are irradiated with x-rays. XRF is typically used to quantify soil mineral content or environmental contaminants such as heavy metals, and lighter elements such as C are typically treated as noise (and are only measured indirectly). In our review, only one organization (X-Centric) was found that is seeking to commercialize PXRF via a hand-held sensor. Typical instruments cost approximately \$50,000, whereas the instrument developed by X-Centric is expected to cost significantly less money (\$100 for a prototype; Roozbeh, personal communication³⁴). X-Centric claims that the device, which operates in the z-plane rather than laterally, can perform as well as vis-NIR technology.

Vis-NIR and MIR Sensors

The use of the visible to infrared wavelengths of the electromagnetic spectrum for measuring SOC has received significant attention from researchers over the last 20 years (Angelopoulou *et al.*, 2020³⁵).

³¹ [Wielopolski *et al.*, \(2010\)](#)

³² Conversation with Dr. Allen Torbert (USDA), September 2020.

³³ [Morona *et al.*, \(2017\)](#)

³⁴ Conversation with Roozbeh Ravansari (owner of X-Centric), September 2020.

³⁵ [Angelopoulou *et al.*, \(2020\)](#)

Visible wavelengths are well attuned to SOC and iron-oxides via changes in soil color, whereas NIR absorptions are associated with overtones from the MIR portion of the spectrum and are subject to overlapping signals from multiple soil components (Brown *et al.*, 2006³⁶). However, when both are combined, the visible and NIR portion of the spectrum improve overall SOC prediction abilities.

MIR has also demonstrated success in predicting SOC, but it requires air- or oven-dry, and ground samples, and is typically measured in the lab (Soriano-Disla *et al.*, 2014³⁷). Similar to MIR spectroscopy, vis-NIR techniques achieve superior performance in the lab. In the field, vis-NIR achieves varying levels of accuracy, which can be improved if soil water is accounted for using direct standardization (DS) or external parameter orthogonalization (EPO; Minasny *et al.*, 2011³⁸) adjustment techniques. Angelopoulou *et al.* (2020)³⁵ provide an exhaustive list of prior research on vis-NIR SOC quantification studies. They provide detail on accuracy metrics and calibration details, which demonstrate that results range from unacceptable (e.g., $r^2 < 0.6$, RPD < 1.5) to excellent ($r^2 > 0.8$, RPD > 2.5), although, as with the remote sensing section, these metrics are highly dependent on the study characteristics and validation methodology. This diversity of accuracy metrics highlights the lack of consensus on best practices for calibration, validation, and use of training libraries in addition to discrepancies in data quality across instrumentation and labs. Given the recent publication date of this review, we omit a detailed discussion of these nuances and the extensive literature, and instead focus on the commercialization potential of vis-NIR or MIR spectroscopy.

In the last five to ten years, vis-NIR sensors have been increasingly tested ex-situ but in-field, typically using expensive spectrometers such as those available from Panalytical, Inc. (formerly ASD). Ex-situ sampling typically involves collecting a soil core, homogenization or compositing of the sample for the horizon of interest, and then measurement of the soil spectral signature. Low-cost sensors have been developed by organizations such as Our-Sci that attempt to reduce the expense of sampling, yet accuracy may depend highly on context and the availability of local calibration data (Dan Kane, personal communication). A vis-NIR sensor is also available from Agrocures/soilcures, which uses their own proprietary soil spectral library (SSL) for calibration (sensor cost: \$3,500 including \$1900/yr for calibration database access; van Beek and Mournetas, personal communication³⁹). Other vis-NIR spectrometers may also be available that have not received extensive testing for estimating SOC (Tang *et al.*, 2020⁴⁰). An alternative ex-situ approach has been developed via the SCANS system, which pulls a soil core within-field then uses vis-NIR sensors to determine SOC, and gamma-radiometrics to estimate bulk density with a calibration accuracy of $R^2 = 0.9$ (Viscarra Rossel *et al.*, 2017⁴¹). The SCANS system is not available commercially and may be subject to regulatory restrictions (Lobsey, personal communication⁴²).

³⁶ [Brown *et al.*, \(2006\)](#)

³⁷ [Soriano-Disla *et al.*, \(2014\)](#)

³⁸ [Minasny *et al.*, \(2011\)](#)

³⁹ Conversation with Christy van Beek and Florent Mournetas (Agrocures), September 2020.

⁴⁰ [Tang *et al.*, \(2020\)](#)

⁴¹ [Viscarra Rossel *et al.*, \(2017\)](#)

⁴² Conversation with Craig Lobsey (Professor at University of Southern Queensland and researcher on SCANS system), September 2020.

In-situ sensors have also been developed in the last ten years, most notably penetrometers that are inserted into the soil to measure vis-NIR spectra. These instruments have been available for some time from Veris, Inc. (Christy, 2008⁴³), and are under continual development by researchers at Texas A&M, UNL, and other universities (Widjewardane, 2020⁴⁴). In their current form, these sensors are unable to quantify bulk density, therefore adjacent soil cores must also be collected. However, it may be possible with extensive calibration to use the insertion force of the penetrometer to estimate bulk density.

Regardless of the method of obtaining the soil sample and the location in which it is analyzed, vis-NIR techniques (as with all PSS) must be calibrated to local, regional, or global SSLs (Angelopoulou et al., 2020³⁵). As suggested by their name, global SSLs tend to cover a wide area but at lower resolution than regional or local SSLs. Local SSLs tend to achieve superior performance but are impractical to create unless they cover the area where a cluster of SOC quantification projects will be implemented. Alternatively, a joint local-global approach may be used, such as the RS-LOCAL method developed by Lobsey *et al.* (2017)⁴⁵, which uses 10-20 locally collected samples to select a broader set of representative calibration samples from a regional SSL.

Laser Induced Breakdown Spectroscopy (LIBS)

LIBS involves the use of fast-pulsed lasers to generate a plasma on the surface of the soil sample which subsequently emits radiation which can be measured by a spectrometer operating from 190 to 1000 nm (Izarraulde *et al.*, 2013⁴⁶). It is a technique that can achieve high accuracy ($R^2 = 0.86$ for calibration data) but is subject to the constraints of many lab-based methods, namely that it requires dried, ground, and sieved samples that are pressed into pellets prior to analysis. The throughput of LIBS sensors is very high (~ 1 minute per sample), but cost is expected to be in the \$400,000 range, making it accessible only to high-volume soil analytical labs (Nault, personal communication⁴⁷).

Other Soil Characterization Technologies

During our review of this section, we also considered commercial offerings from SoilOptix, SmartCloudFarming, and Teralytic. SoilOptix uses a mobile, passive gamma-ray spectrometer that indirectly estimates parent material and clays in the topsoil, both of which are correlated to SOC to varying degrees. It is unable to estimate SOC, therefore the generated spatial surface is typically used as an input layer for stratification algorithms; subsequent soil sampling is still required. Purchase costs for the unit are \$35,000, but it may be leased for as low as \$3.75 per acre excluding laboratory costs (Harmer, personal communication⁴⁸).

SmartCloudFarming aims to provide software similar to other remote sensing companies and intends to launch some time in 2021. They appear to only be in the prototype stage and therefore are not of primary interest.

⁴³ [Christy, \(2008\)](#)

⁴⁴ [Wijewardane et al., \(2020\)](#), and personal communication with Nuwan Wijewardane (UNL), September, 2020.

⁴⁵ [Lobsey et al., \(2017\)](#)

⁴⁶ [Izarraulde et al., \(2013\)](#)

⁴⁷ Conversation with Jacques Nault (LaserAg), September 2020.

⁴⁸ Conversation with Zach Harmer (SoilOptix), September 2020.

Teralytic offers probes which will measure N₂O emissions rather than soil carbon levels. Their approach is currently under development and is expected to be commercially available by the end of 2023.

Comparison of Technologies

Currently Available Tools

In addition to traditional direct measurement methods, three commercial PSS offerings are currently available for purchase: the Agro/soilcares scanner, the Our-Sci reflectometer, and the Veris penetrometer (Table 4). The Veris penetrometer has the longest track record of use and testing, however its accuracy is highly dependent on the number of local soil cores collected for calibration (it does not use a regional SSL) and it still requires BD samples to be collected for estimating SOC stocks. As a result, it is unlikely to provide substantial benefits over traditional DC and BD calculation methods. The Texas A&M penetrometer achieves greater accuracy but is not commercially available and is similarly limited with respect to BD (and rock fragments, if present).

Based on communications with Dan Kane, the Our-Sci reflectometer offers the potential for moderate-accuracy and low-cost in-field measurements of SOC, but extensive data have not been collected in a sufficiently wide variety of agricultural contexts to be confident in its ability to consistently achieve acceptable accuracy. This tool may merit testing in ESMC pilots in order to accelerate development of accuracy metrics that are tool-specific, but for broader use it may not be reliable until these metrics are more robust. In addition, as with other vis-NIR methods, BD measurements are still required.

The Agro/soilcares scanner is the most well-developed solution that is currently available and is not overly expensive. It provides a complete cloud-based solution for quantifying SOC and does not require manual statistical analysis or other data handling in order to produce results. Primary drawbacks include the lack of a widespread, robust calibration SSL in the US and the still-present need to collect soil cores for quantifying BD and rock fragments.

Table 4. Comparison of commercial tool offerings for quantifying SOC and SOC stocks.

Tool	Underlying Tech	Field Method	BD	Analysis location	Date Commercially Ready	Accuracy Rating (1=low,5=high)	Cost (E = estimated, A = actual)
Agro/soilcares	vis-NIR	In-field soil cores	No	in-field	Now	3	\$3500 + \$1900/yr (A)
Our-Sci reflectometer	vis-NIR	In-field soil cores	No	in-field	Now	2	~\$400 (A)
Veris penetrometer	vis-NIR	penetration	No, possible	in-field	Now	2	\$45,000 (A)
Texas A&M penetrometer	vis-NIR	penetration	No, possible	in-field	Unknown - maybe 2021	3	\$63,000 (E)
X-Centric	PXRF	In-field soil cores	No	in-field	End of 2021	2	~\$100-200 (E)
LaserAg	LIBS	In-field soil cores	No	lab	2021	4	\$400,000 (E)
INS	INS	On-the-go sensor	Yes	in-field	End of 2021	3-4	<\$75,000 (E) or \$10/ha
SCANS	vis-NIR, gamma-ray	In-field soil cores	Yes	in-field	Unknown	3-4	\$100,000 - \$130,000 (E)
Agricarbon	DC, BD	In-field soil cores	Yes	in-field	2021	5	1 GBP/sample (E)

Near-term Tools

In 2021, several more tools may become available, although projected availability is subject to numerous potential roadblocks including delays in building manufacturing capacity and time required for field testing, among other possible issues. Most notable of the near-term tools are LaserAg, INS and Agricarbon, each of which relies on a different quantification technology. The PXRF sensor available from X-Centric is also slated to be available in 2021, but the lack of supporting academic literature and its limited funding suggests that it warrants monitoring but not near-term adoption.

LaserAg may be closest to commercial availability, but its high price tag (\$400k) makes it unlikely to be practical for use outside of large soil testing labs. At scale, it may be able to reduce the cost of laboratory SOC tests, but it still requires samples to be pulled in the field, dried, ground, and sieved. In

addition, traditional BD measurements are still required. Given these constraints, we estimate that LIBS technologies may only be available for per-sample lab-based processing beginning in 2022.

INS is one of the more intriguing technologies, especially for its ability to interrogate SOC over large areas, which will minimize accuracy issues that typically arise for traditional sampling; namely, the size of sample support (whether soil cores are representative of large areas), and sub-sampling heterogeneity. Two primary issues with this technology remain: whether it can consistently delineate a depth-based or ESM-based boundary for detecting changes in SOC stocks, and whether regulatory issues that arise from using active radiation can be overcome. The former issue may be resolved with more extensive knowledge about the technology, and the latter may be resolved as the technology moves towards commercialization. Finally, it is unknown exactly when Carbon Assets Solutions will be able to produce the technology for commercial purchase.

Agricarbon, which has not yet been mentioned, is an organization based out of the UK focused on rapid in-field analysis of soil cores using DC and traditional BD methods. Such an approach would eliminate many of the accuracy issues associated with the other technologies, with the exception of errors due to small sample supports. According to its founder, Stewart Arbuckle⁴⁹, the estimated cost when commercially ready will be no more than 1 GBP per sample (plus a small license fee). The technology is currently in prototype phase and is expected to be commercially ready in summer 2021.

Longer-term Tools (Beyond 2021)

Beyond 2021, the SCANS system described by Viscarra Rossel et al. (2017) may offer a viable whole-package approach to SOC stock quantification. Its integrated use of vis-NIR sensors for SOC quantification (which also accounts for soil water), gamma radiometrics for estimating bulk density, and sophisticated calibration algorithms, provide a moderate to high-accuracy solution that has been tested extensively in academic settings and in published literature (Viscarra Rossel et al., 2018). If this system was commercially available, it would likely be recommended for near-term use. Like INS, it may be subject to regulatory constraints. According to Craig Lobsey³⁶ (personal communication), one of the developers of the system, it may be under license to a company named Carbon Link in Australia. Nevertheless, it is not available today.

Conclusions and Recommendations

Based on the maturity of available direct measurement and PSS technologies, we recommend a phased approach towards technology adoption over the next one to three years.

In the immediate term to two years, traditional lab analysis methods used for direct measurement will be required due to their widespread availability and the robust foundation of research that underpins their application. For measuring SOC, LOI or WB methods may be sufficient where cost is a significant constraint and only directional changes in SOC stocks need to be measured. For Scope 1 and Scope 3 quantification, the use of an elemental analyzer (dry combustion) is recommended despite its greater expense. To measure BD, hydraulic coring using appropriate equipment (non-slotted probes with

⁴⁹ Conversation and e-mail communication with Stewart Arbuckle, August 2020.

recessed tips) is advised in most settings. Rock fragments also need to be measured during the sieving process and factored into BD calculations. Finally, sampling and analysis procedures that ensure high levels of accuracy should be prioritized including exclusion of coarse SOC fractions, thorough homogenization of samples, testing of analytical variability, and potential use of equivalent soil mass approaches (depending on the emerging consensus on ESM vs FD approaches).

For upcoming ESMC pilot projects, we also recommend testing of the Agro/soilcares scanner and Our-Sci reflectometer in tandem with traditional direct measurement procedures. Although neither of these tools has demonstrated consistently moderate to high accuracy in the US or has a fully developed SSL for any regions in the US, the incremental amount of additional time required to collect the measurements is relatively minor. In addition, by gathering data with these instruments, the SSLs can be expanded and calibrated/validated on a broader scale, which may improve future applicability (note: soil samples would also need to be sent to the Agro/soilcares lab for analysis since they only use one location to achieve maximum standardization). Where possible, any efforts to improve SSLs also merit coordination with existing standardization efforts (e.g. [GLOSOLAN](#)).

Over the next year, the INS and Agricarbon systems are most promising for achieving significant improvement over current measurement options. In the case of INS, the ability to measure SOC stocks at a high resolution, over large areas, and without needing to extrapolate from low-volume cores to high-volume areas, would be a notable step forward. For Agricarbon, the very low price point and ability to use well-established traditional direct-measurement technologies would offer a feasible way to perform high-density sampling and avoid relying on relatively unproven technologies. Both INS and Agricarbon have obstacles to overcome before their technologies are commercially available, and it is entirely possible that neither will be available in the near future. However, their potential advantages make the technologies worth tracking closely and adopting or testing where possible.

The other technologies, including penetrometers, the SCANS system, and the X-Centric PXR sensor are also worth following, although due to less extensive testing, regulatory constraints, or longer commercialization time frames, merit less attention than the aforementioned tools. This conclusion has the potential to change rapidly as ESMC learns about new developments, so maintaining communication with the tool developers is advised.

Appendix A: Equations

Equivalent Soil Mass Equations

Wendt and Hauser (2013) suggest using soil mass layer and depth layer equations for accounting for the equivalent soil mass of a soil sample. Soil mass layers ($M_{SOIL(DL)}$, $Mg\ ha^{-1}$) can be calculated via:

$$M_{SOIL(DL)} = \frac{mass}{area} = \frac{M_{SAMPLE(DL)}}{\pi\left(\frac{D}{2}\right)^2 \times N} \times 10000 \quad (1)$$

Where, DL is the depth layer, $M_{sample(DL)}$ is the dry sample mass in g, and $\pi(D/2)^2$ is the cross-sectional area of the diameter inside the probe in mm. If multiple cores are combined, then N is equal to the number of soil cores that were sampled. From there, organic carbon mass can be calculated by:

$$M_{OC(DL)} = M_{SOIL(DL)} \times C_{OC(DL)} \quad (2)$$

Where $M_{OC(DL)}$ is the OC mass in the depth layer ($kg\ ha^{-1}$) and $C_{OC(DL)}$ is the OC concentration. The two above equations can be used at any soil depth, and cumulative soil and OC masses are calculated by summing the depth layer masses. By doing the above calculations, no BD samples have to be taken (i.e., exact, consistent sampled volumes are not required), thus mitigating the compaction or core fracturing problems associated with BD sampling.

Rock Fragment Equations

According to Poeplau, Vos, and Don (2017)¹⁸, to account for rock fragments, and avoid overestimation of SOC, they suggest using soil probes and the following equation:

$$FSS_i = \frac{mass_{fine\ soil}}{surface_{sample}} \quad (3)$$

Where FSS_i = fine soil stocks and $surface_{sample}$ is the surface area of the probe.

In response to , Poeplau, Vos, and Don (2017)¹⁸, Hobbey, Murphy, and Simmons (2017)¹⁹ state that the most accurate calculator of SOC stock is:

$$C_{Stock} = C_{content,fine} \times (1 - mass\ proportion_{coarse}) \times \rho \times d \quad (4)$$

Where ρ = bulk density of soil sample ($g\ cm^{-3}$), d = depth (cm), $C_{content\ fine}$ = mass proportion of C in the fine soil fraction (gkg^{-1}), and $mass\ proportion\ coarse$ = mass proportion of coarse soil in the whole soil sample (gkg^{-1}) (i.e., rock content).