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Sampling designs for soil organic carbon stock assessment of soil profiles

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ABSTRACT

We investigated four sampling designs for soil organic carbon (SOC) stock assessment of soil profiles: (i) sampling by horizons, (ii) vertical transect sampling, (iii) depth-based stratified random sampling, (iv) fuzzy c-means sampling in which we explored the use of vis-NIR spectroscopy, image analysis and color models. An Alfisol and Mollisol profile wall (1 × 1 m) was divided into a 10 × 10 cm raster and 100 samples (about 200 g each) were collected at the centers of grid cells for SOC analysis. Bulk density samples were collected from each 10-cm depth interval along a single vertical transect and the SOC stock was calculated using 100 points in the profile wall. Horizon-based sampling for the Mollisol (5 horizons) ranged from 231 to 262 Mg C ha^{-1}, whereas it ranged from 69 to 99 Mg C ha^{-1} in the Alfisol (3 horizons). The SOC stocks obtained by 1 to 7 vertical transects ranged from 68 to 81 Mg C ha^{-1} in the Alfisol, and 239 to 246 Mg C ha^{-1} in the Mollisol. Depth-based stratified random sampling resulted in the SOC stocks ranging from 77 to 82 Mg C ha^{-1} in the Alfisol and 234 to 257 Mg C ha^{-1} in the Mollisol, and the standard errors decreased with increasing sample size from 10 to 70. Fuzzy c-means clustering created clusters similar to the field delineated horizons. A sample size of 7 in both profiles was sufficient to estimate the mean profile SOC stock by fuzzy c-means sampling. The CIE $L^*a^*b^*$ color model resulted in more accurate estimation in the Alfisol, but the vis-NIR spectra resulted in more accurate estimation in the Mollisol. Soil depth improved the performance of vis-NIR spectra. It is concluded that in these soils, at least two or three vertical transects are required to capture the horizontal variation for estimating profile SOC stock. Depth-wise stratified random sampling reduces the number of samples and is suitable when horizontal variation is high. Fuzzy c-means sampling is useful to determine the minimum sample size for profile SOC stock assessment but requires ancillary data and processing before sampling the soil profile.

1. Introduction

There is a growing need for accurate estimation of soil organic carbon (SOC) stocks (Minasny et al., 2013). Mapping SOC at a range of scales requires pedon data and recent examples have shown the use of such data for estimating SOC stocks across a range of scales (Akpa et al., 2016; Batjes, 2016; Bonfatti et al., 2016b; Priori et al., 2016; Schillaci et al., 2017). Numerous studies assessed SOC stock for the top 30 cm depth which is the standard IPCC sampling depth (IPCC, 2006). Few efforts have been made on profile SOC stock assessment down to 1 m (Lorenz and Lal, 2005). Deep soil carbon is important for enhancing SOC sequestration (Olson and Al-Kaisi, 2015) and affects nitrate and pesticide sorption and leaching behaviors (Meersmans et al., 2009).

From a soil profile, samples can be collected by horizons or by fixed depth intervals (Allen et al., 2010). Marinho et al. (2017) sampled a single vertical transect in a soil pit at 2-cm intervals and derived a depth function. Wang et al. (2017) compared 20-cm fixed-depth sampling and horizon-based sampling. They found that horizon-based sampling resulted in 16–22% higher SOC stocks in the surface (0–20 cm) and 30–40% higher of the whole profile (0–80 cm). Grüneberg et al. (2010) found that sampling by depth interval is preferred for regional SOC stock estimation, whereas sampling by horizon is essential for pedogenesis studies. Boone et al. (1999) demonstrated that sampling by fixed depth intervals is easier to budget and implement, and it is more practical. Vertical sampling design tends to ignore the horizontal variation of soil (Hole, 1953). In order to investigate soil profile variation and produce soil profile maps, raster sampling has been conducted by Davis et al. (1995) with 20 × 20 cm resolution as well as fine grid sampling on soil monoliths (Roudier et al., 2016).

Proximal soil sensing and other instruments have been used to improve soil profile characterization and quantification (Hartemink and Minasny, 2014). In particular, visible near-infrared spectroscopy has shown strong relationships with many soil properties, especially SOC (Stenberg et al., 2010). Lab-based high-resolution vis-NIR imaging spectroscopy has been used for profile C mapping and evaluation of soil profile variation (Schreiner et al., 2015; Steffens and Buddenbaum,

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2013). Color is a useful proxy for SOC concentration and can be assessed by Munsell color chart, a digital camera, scanner, and vis-NIR spectroscopy and various studies have estimated SOC from a color model (Stiglitz et al., 2017; Viscarra Rossel et al., 2008; Wills et al., 2007).

There is an increasing need for new soil data for a range of studies, in particular SOC assessment, and there are a range of technologies and approaches being tested in addition to long standing approaches such as in the IPCC. Bonfatti et al. (2016a) used data from 10 pedons to compare four methods for SOC stock estimation: horizon values with discrete data, exponential function, equal-area exponential function, and equal-area quadratic spline function. It was found that different methods produced significantly different results of SOC stocks and values derived from equal-area exponential and equal-area splines were more similar to those of the horizons.

In this paper, we present several sampling approaches for assessing SOC stocks in soil profiles. We have explored different sampling strategies based on sampling soils across the landscape and soil sampling theory and practices. Transect sampling has been used to collect samples along toposequences (Odgers et al., 2008). Stratified random sampling has been used to create strata with similar attributes to improve the sampling efficiency (Webster and Lark, 2012). Stratified sampling like the fuzzy clustering method (de Gruijter et al., 2010), has been used for soil sampling to collect representative calibration dataset for vis-NIR spectra models and digital soil mapping (Ramirez-Lopez et al., 2014; Schmidt et al., 2014). A fuzzy clustering algorithm has been used to delineate soil horizons with vis-NIR spectroscopy by Fajardo et al. (2016). In summary, these approaches have been used to sample two soil profiles and assess the SOC stocks. The objectives of this paper were to: (i) investigate profile sampling designs for profile SOC stock assessment; (ii) evaluate the feasibility of using vis-NIR spectroscopy to estimate SOC in a soil profile; and (iii) explore the possibility of incorporating image analysis and color models for improved sampling and SOC quantification of soil profiles.

2. Materials and methods

2.1. Study area and soil profiles

An Alfisol and Mollisol were studied and sampled in August 2014 and 2015. The Alfisol was located in the Driftless Area of Wisconsin (WGS84 43.03° N, 90.05° W). The altitude of this area is 320 m.a.s.l. The mean annual precipitation is about 860 mm and mean annual temperature is about 7.4 °C. The field was covered by grass at the time of sampling. The soil pit was located at the shoulder position of the landscape with 6% slope. The soil was formed in loess over a mixture of sand, clay, and glauconite weathered from the underlying sandstone, dolomite, and shale bedrock. The soil was classified as fine-silty over clayey, mixed, superactive, mesic Typic Hapludalfs (NewGlarus series). Three horizons were identified in the field down to 1 m depth. Horizon thickness was measured in the middle of the profiles. The Ap horizon (0–22 cm) had granular and subangular blocky structure and silt loam texture, with very dark grayish brown (10YR 3/2, moist) and light brownish gray (10YR 6/2, dry) colors. The Bt horizon (22–68 cm) had subangular blocky structure and silty clay loam texture, with dark yellowish brown (10YR 4/4, moist) and light yellowish brown (10YR 6/4 dry) colors. The 2Bw horizon (68–100 cm) had subangular blocky structure and sandy clay loam texture, with strong brown (7.5YR 4.5/7, moist) and strong brown (7.5YR 5/7 dry) colors.

The Mollisol was located at the University of Wisconsin-Madison West Madison Agricultural Research Station in south-central Wisconsin (WGS84 43.07° N, 89.54° W). The altitude of this area is 330 m.a.s.l. The mean annual precipitation is about 840 mm and mean annual temperature is about 7.8 °C. The field was covered by alfalfa and grass. The soil pit was located at the footslope position and the soil was moderately well-drained to well-drained. The soil was formed in loess over outwash underlain by dolostone bedrock. It was classified as fine-loamy, mixed, superactive, mesic Pachic Argiudolls (Troxel series). Five horizons were identified in the field down to 1 m depth, and the soil contained a buried A horizon at 59 cm depth. The Ap1 horizon (0–18 cm) had granular structure and silt loam texture, with very dark brown (10YR 2/2, moist) and dark grayish brown (10YR 4/2, dry) colors. The Ap2 horizon (18–39 cm) had platy structure and silt loam texture, with very dark brown (10YR 2/2, moist) and dark grayish brown (10YR 4/2, dry) colors. The A2 horizon (39–59 cm) had subangular blocky structure and silt loam texture, with very dark brown (10YR 2/2, moist) and dark grayish brown (10YR 4/2, dry) colors. The thick A-horizon was formed in sediments of eroded topsoils higher in the landscape. The Ab horizon (59–77 cm) had subangular blocky structure and silt loam texture, with black (10YR 2/1, moist) and dark grayish brown (10YR 4/2, dry) colors. The Bt horizon (77–100 cm) had angular blocky structure and silty clay loam texture, with dark yellowish brown (10YR 3/4, moist) and yellowish brown (10YR 5/4, dry) colors (Grauer-Gray and Hartemink, 2016).

2.2. Sample collection and analysis

Soil pits (2 m L × 2 m W × 1.2 m D) were dug and the Alfisol and Mollisol profile walls (1 × 1 m) were divided into a 10 × 10 cm raster. One sample (about 200 g, covering 75% of the raster cell) was collected at the center of each cell for a total of 100 samples. The samples were air-dried, ground, sieved to a diameter smaller than 2 mm. The SOC concentration was determined by dry combustion method with a Flash EA 1112 Series NC Soil Analyzer (Thermo Fisher Scientific Inc.). Bulk density samples were collected at each 10-cm depth interval along a single vertical transect on the left of the soil profile wall assuming that bulk density was uniform across the soil profile. Bulk density was determined by 250 mL rings, and oven-dried bulk soil at 105 °C for 72 h.

2.3. Profile SOC stock

The SOC stock of the 100 grid points was calculated by multiplying SOC concentration, bulk density and 10-cm depth. There were no coarse fragments in the two soils. The SOC stock of each vertical transect was calculated by adding up the SOC stocks for each of the 10 grids. The profile SOC stock was the average of the 10 vertical transects. The grand average SOC stock was used as a standard to compare with the SOC stocks obtained by the four sampling designs.

2.4. vis-NIR spectra collection and analysis

Air dried soil samples were scanned by a portable PSR-3500 vis-NIR spectroradiometer (Spectral Evolution Inc.). The PSR-3500 spectrometer operates in the range of 350–2500 nm with three detectors: (i) a 512-element silicon PDA covering the visible range and part of the near infrared (350–1000 nm) with a resolution of 3 nm; (ii) a 256-element InGaAs array covering 1000–1900 nm with a resolution of 8 nm; and (iii) a 256-element InGaAs array covering 1900–2500 nm with a finer spectral resolution of 6 nm. The reflectance data were resampled to 1 nm for output resulting in 2151 spectral points. The reflectance spectrum was recorded by averaging 50 readings per soil sample measurement, and 3 replicates were taken for each sample by repositioning the probe between each scan. The PSR-3500 was calibrated by a polytetrafluoroethylene (PTEE) white plate with high diffuse reflectance. The vis-NIR spectroradiometer was calibrated every 10 soil samples.

The following preprocessing techniques were implemented on the vis-NIR spectra:

1) The raw reflectance data (R) were converted to absorbance data (A) by $A = \log(1/R)$;
2) A second order Savitzky-Golay filter with a smoothing window of 11