Received: 17 August 2020 | Accepted: 9 October 2020 | Published online: 2 March 2021

DOI: 10.1002/saj2.20176

Soil Science Society of America Journal

SOIL & WATER MANAGEMENT & CONSERVATION

Soil organic carbon sequestration calculated from depth distribution

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Assigned to Associate Editor Craig F Drury.

Funding information
USDA Agricultural Research Service

Abstract

Sequestration of organic C in agricultural soils is necessary to improve soil health to meet the challenges of climate change, diminishing biodiversity, water quality deterioration, and rising demands for food and fiber production. New assessment approaches are needed to quantify how conservation agriculture might contribute to soil health improvement and soil organic C (SOC) sequestration. In the southeastern United States, conservation management has been repeatedly shown to stratify SOC concentration with depth. Starting immediately below a zone of tillage influence (i.e., 30-cm depth), SOC concentration is rarely affected by management due to low C inputs and high decomposition potential, whereas concentration increases toward the surface in a nonlinear manner, presumably with greater inputs of residue and root inputs and changing temperature and moisture conditions. Using these observations as an ecological foundation, SOC sequestration was calculated as the summation of SOC stock greater than the baseline condition at 30-cm depth. Data from literature sources were mathematically fitted with this new approach as a validation. Two on-farm surveys with different agricultural management practices (5–40 yr) in the southeastern United States yielded preliminary estimates of SOC sequestration. The interquartile range of calculated SOC sequestration was 4.2–9.4 Mg C ha^{-1} for conventional-tillage cropland (n = 45 fields), 13.6–29.7 Mg C ha^{-1} for no-tillage cropland (n = 97 fields), and 15.9–26.1 Mg C ha^{-1} for perennial pasture (n = 29 fields). This new approach will be valuable to estimate SOC sequestration from a greater diversity of conservation agricultural systems practiced on farms within a region and independent of soil type.

1 | INTRODUCTION

Soil contains a large reservoir of organic C (2,273 Pg in 0–2 m depth) and is an important part of the global C cycle (Jackson et al., 2017). Much has been written of how certain soils and management systems might be contributing as sources or sinks to the atmospheric pool of C, currently estimated as 864 Pg, or 272 Pg greater than prior to industrialization (Lal, 2019). Debate continues as to whether conservation agricultural systems might be sequestering SOC or just

Abbreviations: BD, bulk density; IQR, interquartile range; SOC, soil organic carbon.

redistributing C in the soil profile (Angers & Eriksen-Hamel, 2008; Kravchenko & Robertson, 2011).

In the southeastern United States, soils have had a long history of agricultural cultivation, with enormous losses of soil through erosion (Trimble, 1974) and a general decline of SOC from a precultivated condition (Hendrix et al., 1998). Loss of SOC with cultivation may have been as much as 20–60% of native conditions (Davidson & Ackerman, 1993; Guo & Gifford, 2002), which would have been a loss of 12–36 Mg C ha^{-1} if original conditions were 60 Mg C ha^{-1} in the surface 30 cm of soil. Precultivated SOC conditions are difficult to determine for the diversity of soil types in the southeastern United States because there are few pristine areas remaining, especially for agriculturally productive soil types that are widespread across the region. Research has shown that regaining lost SOC through conservation agricultural management can be significant in the region (Franzluebbers, 2010) and comparable to rates of SOC accumulation in other regions of the United States (Franzluebbers & Follett, 2005). Estimates of SOC sequestration have been variable, and management and edaphic factors contributing to this variation have not been easily discerned with the limited number of research studies under highly controlled soil and management conditions (Franzluebbers, 2010). Long-term management comparisons require dedicated resources and repeated analyses over time, which are expensive requirements to obtain this valuable information. However, weather variations and changes in management can cause additional uncertainty in SOC sequestration estimates. An approach to gather more and lower-cost estimates of SOC sequestration across a wider diversity of soil types and land management conditions would greatly assist the scientific endeavor and help understanding of the factors contributing to SOC sequestration.

Detecting change in SOC sequestration with increasing depth in the profile is challenging (Syswerda et al., 2011) due to progressively lower SOC concentrations deeper in the profile and greater random variation among replicates or pseudoreplicates that can mask relatively small changes that may be occurring (Franzluebbers, 2010). In eastern Nebraska, SOC sequestration to 150-cm depth was asserted from multiple years of switchgrass (*Panicum virgatum* L.) biofuel production, despite enormous random variation that increased with progressively greater soil depth (Follett et al., 2012). Across 42 paired-field comparisons in Minnesota, North Dakota, and South Dakota, SOC concentration was statistically greater at a depth of 0–5 cm under switchgrass than under cropland fields (difference of 4.3 g kg^{-1}) and marginally greater at the 30-to-60-cm and 60-to-90-cm depths (difference of 1.0 g kg^{-1}) (Liebig et al., 2005). Curiously though, a significantly greater SOC concentration was found with switchgrass than with cropland in only 14% of all depth increments of all fields within the surface 30 cm, whereas 9% of observations were lower with switchgrass than cropland. Below 30-cm depth, significantly greater SOC concentration under switchgrass than cropland was found in 10% of observations, whereas 6% of observations were lower with switchgrass than cropland. Other paired management comparisons can lead to equivocal results when landscape settings are not adequately matched (Blanco-Canqui & Lal, 2008; Boddey et al., 2009; Franzluebbers, 2009). Chronosequences with mixed edaphic- and management-controlled variations can lead to wild estimates of SOC sequestration (Machmuller et al., 2015).

Core Ideas

- Soil organic carbon (SOC) sequestration can be calculated from profile distribution of C.
- SOC is highly stratified with depth in conservation systems in the southeastern United States.
- The surface 30 cm of soil reflects the majority of management-induced SOC.
- No tillage cropland and perennial pastures resulted in significant SOC sequestration.

In the southeastern United States, the amount of organic C that can be deposited below the plow layer (i.e., typically considered the 0-to-30-cm layer) is oftentimes low even under perennial grasses that have deep rooting and potentially high productivity (Garten & Wullschleger, 1999; Ma et al., 2000) because root C inputs progressively decline with depth. Root mass of 3-yr-old bermudagrass [*Cynodon dactylon* (L.) Pers.] estimated from soil depths of 0–30, 30–60, and 60–90 cm was 3.3 ± 1.7, 0.9 ± 0.5, and 0.9 ± 0.5 Mg ha^{-1}, respectively (Adams et al., 1966). In other studies, root mass to 20-cm depth only was 6.7 ± 1.2 Mg ha^{-1} under a variety of warm-season grasses in Florida (Siqueira da Silva et al., 2019), 9.4 ± 1.5 Mg ha^{-1} under bermudagrass with different N fertilizer levels (Liu et al., 2017), and 2.5–5.5 Mg ha^{-1} under bermudagrass (Alderman et al., 2011). Warm-moist conditions persist throughout the year in this region and lead to high decomposition rates, contributing to relatively low SOC concentrations. At least in upland soils of the southeastern United States, perhaps it would be a better assumption that insignificant SOC accumulation occurs below the plow layer; instead, information on SOC distribution within the plow layer should be used to make SOC sequestration calculations. This was the premise of this study that SOC concentration immediately below the zone of tillage influence could be used as a baseline condition to which SOC concentrations nearer the surface could be compared. This assumption may not be valid in saturated soils with variable organic deposition and migration of organic matter with Fe and Al (e.g., Histosols or Spodosols) (Franzluebbers, 2013). The hypothesis was that SOC sequestration could be calculated from a SOC stock change minus that of an assumed baseline condition, determined for each soil profile from SOC concentration immediately below the zone of tillage influence (i.e., at 30-cm depth). It is recognized that SOC could potentially accumulate below 30 cm depth, but it is my contention that this would require several decades and centuries to find statistically significant change in SOC concentration due to management (unless physically deposited through injection or deep tillage in upland soils and natural migration in saturated soils). Therefore, a better approach to quantify the effects of contemporary management would be to focus on the upper 30 cm to get more useful information to make urgent decisions with our rapidly changing environment.

The objective of this study was to develop a SOC sequestration calculation method based on depth distribution of SOC concentration. Soil-profile data from several published studies were assembled to make calculations and compare results with more standard approaches to calculation of SOC sequestration. Mathematical description of SOC depth distribution was presented before (Franzluebbers, 2013), but the approach of calculating SOC sequestration based on an internal soil-profile reference condition is novel and developed here for potential further use.

2 | MATERIALS AND METHODS

2.1 | Experimental sites and characteristics

Data from several previous studies in the southeastern United States with SOC concentration (determined by dry combustion in all cases) by multiple depth increments were assembled for this analysis, including from a forage utilization study on perennial pasture in Georgia (GA-1); a tillage and cover crop study in Georgia (GA-2); a biofuel production study in North Carolina (NC-1); a switchgrass cultivar study in North Carolina (NC-2); a survey of crop and pasture land uses in Alabama, Georgia, South Carolina, North Carolina, and Virginia (SE-1), and a survey of corn (*Zea mays* L.) production fields in North Carolina, South Carolina, and Virginia (SE-2).

Study GA-1 was a 12-yr beef cattle pasture comparison near Farmington, GA (33°44′ 38″ N, 83° 23′57″ W). Soil at the site was Cecil, Madison, and Pacolet sandy loam and sandy clay loam (fine, kaolinitic, thermic Typic Kanhapludults). Forage base was 'Coastal' bermudagrass during the first 5 yr and mixed bermudagrass/'Georgia 5′ tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] during the final 7 yr. Soil cores (4-cm diameter) were collected at depth increments of 0–5, 15–30, 30–60, 60–90, 90–120, and 120–150 cm with a hydraulic probe at initiation of management in 1994, at the end of 5 yr in 1999, and at the end of 12 yr in 2006. Soil organic C concentration was reported in Franzluebbers and Stuedemann (2009). This study had 12 treatments (3 nutrient sources × 4 forage utilization strategies) and was replicated in the field three times. Nutrient sources were (a) broiler litter two times per year for the first 5 yr and three times per year for the final 7 yr, (b) crimson clover (*Trifolium incarnatum* L.) cover crop plus inorganic N for the first 5 yr and broiler litter once per year and inorganic N twice per year for the final 7 yr, and (c) inorganic N twice per year during the first 5 yr and inorganic N three times per year for the final 7 yr. Forage utilization was unharvested Conservation Reserve Program simulation, low grazing pressure to maintain high residual forage mass (~2 Mg ha^{-1}), high grazing pressure to maintain low residual forage mass (~1 Mg ha^{-1}), and hayed monthly when sufficient forage accumulated.

Study GA-2 was a multiple-year cropping comparison following termination of long-term pasture near Watkinsville, GA (33°52′ 55″ N, 83° 25′30″ W). Soil was Cecil sandy loam and sandy clay loam. Grain crops were grown in rotation with cover crops, which were either grazed by cattle or accumulated for conservation. Tillage was with (a) initial moldboard plow and subsequent disk tillage and (b) no tillage using chemical termination. Soil cores (4-cm diameter) were collected at depth increments of 0–20, 20–40, 40–60, 60–90, 90–120, and 120–150 cm at the end of 6 yr of management in 2007, but primary calculations of SOC sequestration were from 0-to-60-cm depths only. Soil organic C concentration was reported in Franzluebbers and Stuedemann (2013). Four treatments (2 tillage systems × 2 cover crop utilization strategies) were replicated eight times. Soil was also collected from depth increments of 0–3, 3–6, 6–12, 12–20, and 20–30 cm at the end of Years 1, 3, 5, and 7 (Franzluebbers & Stuedemann, 2014). Narrow-depth increments were a composite of five to eight cores (4-cm diameter) at each sampling event.

Study NC-1 was an evaluation of biofuel crop management near Salisbury NC (35° 41′ 12″ N, 80° 36′ 31″ W). Soil was Mecklenburg clay loam (fine, mixed, active, thermic Ultic Hapludalfs). Biofuel crops of switchgrass, giant miscanthus (*Miscanthus × giganteus*), and biomass sorghum [*Sorghum bicolor* (L.) Moench] were grown in comparison with traditional tall fescue hay and a common 2-yr crop sequence of corn–wheat (*Triticum aestivum* L.)/soybean [*Glycine max* (L.) Merr.]. Soil cores (4-cm diameter) were collected at depth increments of 0–6, 6–12, 12–20, and 20–30 cm at the end of 3 yr of management in 2015. Soil organic C concentration was reported in Wang et al. (2017). The five management systems were replicated four times.

Study NC-2 was an evaluation of two fields of different switchgrass cultivars near Clayton, NC (35°39′59″ N, 78°30′36″ W). 'Colony' and 'Performer' switchgrass cultivars were grown on separate fields ~1 km apart. Colony was grown on a Varina loamy sand (fine, kaolinitic, thermic Plinthic Paleudults), and Performer was grown on a Wagram loamy sand (loamy, kaolinitic, thermic Arenic Kandiudults). Both cultivars were lowland ecotypes developed by USDA

Agricultural Research Service, North Carolina Agricultural Research Service, and North Carolina State University, for which Colony was noted for high biomass production and Performer was developed for greater digestibility for grazing. Soil cores at depth increments of 0–5, 5–15, and 15–30 cm were collected in early spring 2015 after ∼15 yr of grass establishment (unpublished data). Three areas (separated by ∼30 m) in each field served as pseudo-replicates from which eight cores (4-cm diameter) were composited in each.

Study SE-1 was a multisite survey of crop and pasture lands in a five-state region of the southeastern United States (Causarano et al., 2008). Dominant soils were Kanhapludults, Kandiudults, Hapludults, and Paleudults, with loamy to clayey texture in thermic to mesic temperature regimes. Three management systems were sampled: conventionally tilled cropland, no-till cropland, and pastureland from adjacent fields within each of three locations in two physiographic regions (Coastal Plain and Piedmont) of Alabama, Georgia, South Carolina, North Carolina, and Virginia (target of 90 fields, but only 87 sampled). Management duration of no-till cropland and pastures after conversion from conventionally tilled cropland was from 5 to 40 yr, but good records were not available to discriminate duration among sites. Soil cores (5-cm diameter) at depth increments of 0–5, 5–12.5, and 12.5–20 cm were collected from May 2004 to May 2005.

Study SE-2 was a multisite survey of corn production fields in North Carolina (58 fields), South Carolina (two fields), and Virginia (29 fields). Soils varied widely but were dominated by Ultisols and including some Alfisols and Entisols. Crop fields varied in previous crop, tillage history, and use of livestock manure. Management duration was variable, but all sites were at least 5 yr in no-till cropland and more often with 20 yr or more. Soil cores were collected in March–May periods of 2015–2017, and SOC concentration was reported in Franzluebbers (2018, 2020). Four pseudoreplicate samples were collected from a composite of eight cores (4-cm diameter) at depth increments of 0–10, 10–20, and 20–30 cm.

2.2 | Nonlinear depth distribution calculations

A minimum of three depth increments were needed to fit a nonlinear response of soil organic C concentration (g kg^{-1}) with soil depth (cm). The following nonlinear equation was used for all soil-depth profiles:

$$\mathrm{SOC} = A + B * \left(1 - e^{(-b*\mathrm{SD})}\right) \tag{1}$$

where SOC is soil organic C (g kg^{-1}), A is SOC deep in the profile without management influence (i.e., baseline SOC condition, $A \geq 0$ only, g kg^{-1}), and B is the pool of SOC that accumulates at the soil surface (g kg^{-1}) and declines exponentially as a function of a rate constant (b, |cm|$^{-1}$) at any particular soil depth (SD, |cm|). All nonlinear regressions were fitted to available data using SigmaPlot v. 14 (Systat Software Inc.). In cases where Equation 1 produced an estimate of $A < 0$, A was set to 0 using a modified form:

$$\mathrm{SOC} = B * \left(1 - e^{(-b*\mathrm{SD})}\right) \tag{2}$$

In other cases that would be valid with five or more measured soil depth increments, a two-pool nonlinear model might be considered appropriate:

$$\mathrm{SOC} = A + B * \left(1 - e^{(-b*\mathrm{SD})}\right) + \mathrm{C} * \left(1 - e^{(-\mathrm{c}*\mathrm{SD})}\right) \tag{3}$$

where A, B, and b are as described for Equation 1, and C is a pool of SOC that accumulates at an intermediate depth between the soil surface and deep within the profile and declines exponentially as a function of a rate constant (c, |cm|$^{-1}$) at any particular soil depth (SD, |cm|).

In Studies GA-1 and GA-2, SOC depth distribution calculations were made from (a) a full set of depth increments from 0 to 150 cm and (b) a reduced set of depth increments from 0 to 60 cm. Comparing these two different sets of depth increments was only across mean values of selected treatments, yielding four treatments (no harvest, low and high grazing pressure, and hayed) at the end of 12 yr in GA-1 and four treatments (2 tillage × 2 cover crop management systems) at the end of 6 yr in GA-2. This restricted comparison was conducted to test whether sampling depth limit influenced calculated SOC estimates.

In all evaluations, soil bulk density (BD, Mg m^{-3}) was assumed using the pedotransfer function described in Franzluebbers (2010):

$$\mathrm{BD} = 1.71 * e^{(-0.013*\mathrm{SOC})} \tag{4}$$

where SOC is soil organic C (g kg^{-1}), 1.71 Mg m^{-3} is maximum BD with low SOC, and –0.013 is a decay coefficient in response to changing SOC concentration. The pedotransfer function allowed calculation of SOC stock at multiple 5-cm depth increments throughout the entire 30-cm profile. However, soil BD was also measured in studies with narrow depth increments in the surface 30 cm, and comparisons were made against values predicted with the pedotransfer function ($n = 546$). Root mean square error was calculated from the 1:1 correspondence that was expected.

In all evaluations, after fitting SOC profile concentration at 5-cm depth intervals with the nonlinear depth distribution function, SOC stock of each 5-cm depth increment was calculated from the average values of the product of predicted SOC concentration and predicted BD at upper and lower depth limits. Soil organic C stock of the 0-to-30-cm depth was from the summation of 5-cm increments. Base SOC stock was calculated from SOC concentration at 30-cm depth (SOC [g kg^{-1}] × BD [Mg m^{-3}] = SOC [kg m^{-3}]) projected across the entire 0-to-30-cm depth. Calculated SOC sequestration was from SOC stock – SOC base. With a time frame, calculated SOC sequestration (Mg C ha^{-1}) could be used to calculate SOC sequestration rate (Mg C ha^{-1} yr^{-1}). An appropriate elapsed time could sometimes be assumed, but in other cases management duration was difficult to ascertain. Predicted concentration of SOC at 30-cm depth was selected as a value to compare among treatments and across studies as a standardized soil property.

Data of SOC stock, base SOC stock, calculated SOC sequestration, and basal SOC concentration at 30-cm depth from studies GA-1, GA-2, NC-1, and NC-2 were subjected to ANOVA using the general linear model of SAS v. 9.4 (SAS Institute Inc.), according to the original experimental design of each separate study with associated replication. Significance among treatments was declared at $\alpha = .05$. Orthogonal contrasts were used to separate multiple treatments within an experimental design. These same four response variables were calculated for the two on-farm survey studies. Categories of management and physiographic region were tested for significance using orthogonal contrasts and paired Student t tests. Results were interpreted with view toward traditional calculations reported in the literature and as in original reports from these experiments. Data were plotted with SigmaPlot v. 14.

3 | RESULTS AND DISCUSSION

3.1 | Forage utilization regimes (Study GA-1)

TABLE 1 Soil organic carbon (SOC) stock (0-to-30-cm depth), SOC base calculation (based on SOC concentration [kg m^{-3}] at 30-cm depth projected throughout the 0-to-30-cm depth), SOC sequestration as the difference between SOC stock and SOC base (0-to-30-cm depth), and basal SOC concentration at 30-cm depth as affected by forage utilization in a long-term pasture study near Farmington, Georgia

Forage utilization	SOC stock	SOC base	SOC sequestration	Basal SOC
	Mg C ha^{-1}			g kg^{-1}
Initially in 1994				
Unharvested CRP	42.6	19.4	23.2	4.0
Low grazing pressure	43.7	19.7	24.0	4.1
High grazing pressure	42.2	19.1	23.0	3.9
Hayed	43.3	19.4	23.9	4.0
SE	1.1	0.9	0.9	0.2
At end of 5 yr				
Unharvested CRP	47.4a	17.0	30.3a	3.5
Low grazing pressure	50.3a	18.0	32.3a	3.7
High grazing pressure	47.7a	15.4	32.3a	3.1
Hayed	41.7b	17.7	24.1b	3.7
SE	1.5	2.1	1.7	0.5
At end of 12 yr				
Unharvested CRP	52.6b	17.3	35.2b	3.6
Low grazing pressure	59.1a	18.0	41.0a	3.7
High grazing pressure	54.4ab	14.4	40.0a	2.9
Hayed	45.8c	16.5	29.3c	3.4
SE	1.3	2.0	1.1	0.4

Note. Means within a sampling year and column not sharing the same letter are significantly different at $p < .05$. CRP, Conservation Reserve Program simulation.

Using the proposed SOC depth distribution method, SOC stock was not different among forage utilization treatments at initiation of the experiment in 1994; nor was there any difference in SOC base and calculated SOC sequestration (Table 1). After 5 yr of pasture management, SOC stock in the surface 30-cm depth was greater with unharvested and cattle grazing systems than with hayed management. This was due to an increase in SOC sequestered while the SOC base remained unchanged or declined slightly. After 12 yr of pasture management, these same effects became more clearly expressed, and greater SOC sequestration occurred with both low and high grazing pressures than with unharvested forage. All effects were similar to those measured in original depth increments and summation of depths from traditional analysis of SOC (Franzluebbers & Stuedemann, 2009).

Soil organic C stock at initiation of this pasture grazing experiment was nearly equally divided between base SOC stock and SOC sequestered from some undescribed recent history that included a few years of pasture establishment (Table 1). Implicit in the argument for this separation of SOC sources was that base SOC stock was derived over centuries through soil-forming processes and that of calculated SOC sequestration was of relatively recent history, although the exact time of that history was not clearly defined in this setting. In this specific case, a rather large pool of SOC sequestered in the upper 30 cm would seem likely from management over a longer period of time than the few years of green fallow and pasture preparation stages required to get the ~0.7-ha paddocks ready for experimentation. The site was considered to be highly eroded and in a degraded condition prior to the experiment, but these data suggest that significant surface SOC accumulated in recent history, assuming SOC concentration throughout the 0-to-30-cm depth was more similar to that of the 30-cm depth itself. Consistent with observation from the original report was an estimated decline over time in basal SOC concentration at 30-cm depth. Across all data, SOC base declined significantly (p = .02), but when estimated for each forage utilization treatment separately, the decline was significant only for high grazing pressure (p = .005). Change in dry combustion instrumentation for determining SOC concentration between the initial sampling and the later samplings cannot be ruled out as a possible contributing factor (i.e., small differences in calibration might have magnified changes in SOC concentration). Clearly though, there was no evidence for a positive effect of pasture management systems on SOC at the proposed baseline depth of 30 cm.

Using calculated SOC sequestration with this depth distribution method, values were regressed over time to compare the rate of SOC sequestration against the traditional SOC stock change calculation, as in the original report. The sequestration rate of SOC over the 12-yr period of this experiment using the depth distribution method was calculated as 0.98 ± 0.13 Mg C ha^{-1} yr^{-1} (mean ± SE among three nutrient sources and three replications) under unharvested management, 1.40 ± 0.10 Mg C ha^{-1} yr^{-1} under low grazing pressure, 1.39 ± 0.14 Mg C ha^{-1} yr^{-1} under high grazing pressure, and 0.47 ± 0.11 Mg C ha^{-1} yr^{-1} under continuously hayed management. Soil organic C sequestration values of the surface 30 cm were reported as 0.80 ± 0.38, 1.40 ± 0.20, 0.92 ± 0.16, and 0.19 ± 0.19 Mg C ha^{-1} yr^{-1} for unharvested, low grazing pressure, high grazing pressure, and hayed treatments, respectively (mean ± standard deviation among three nutrient sources) (Franzluebbers & Stuedemann, 2009). Therefore, these two different estimation procedures yielded generally similar results relative to treatment effects.

Calculated SOC sequestration with the depth distribution method increased with time (i.e., calculated SOC sequestration was 1.21 ± 0.01 times that of base SOC stock among the four forage utilization regimes at initiation) to 1.76 ± 0.26 times that of base SOC stock at 5 yr and to 2.21 ± 0.37 times that of base SOC stock at 12 yr. This relatively quick and large change in estimated SOC sequestration provides ample evidence that contemporary SOC sequestration can be indicated with this depth distribution approach and that the initially large estimate of SOC sequestration in 1994 (at the beginning of the experiment) may have been attributable to management during 15–25 yr, based on projection of the rates of SOC sequestration during the 12-yr period of experimentation. Rampant erosion of unprotected soil during past decades to centuries of agricultural production could have produced estimated basal SOC concentration of 3.6 ± 0.3 g kg^{-1} throughout the entire 0-to-30-cm plow layer.

Soil organic C stock, base SOC stock, and basal SOC concentration at 30-cm depth were not significantly altered when only three depth increments (0–15, 15–30, and 30–60 cm) were used to estimate depth distribution parameters of SOC compared with all six depth increments (0–15, 15–30, 30–60, 60–90, 90–120, and 120–150 cm). However, SOC sequestration was greater when estimated with six depth increments than with three depth increments (36.4 vs. 35.9 Mg ha^{-1}; $p = .04$). Estimated SOC concentration at 30-cm depth tended to be slightly greater when restricting depth of sampling to 60 cm than full sampling to 150 cm (3.6 vs. 3.4 g kg^{-1}, respectively; $p = .06$). This comparison was made to alleviate concern that the shape of the depth distribution function might be significantly altered using different depth limits. This comparison suggests that this effect of depth limit was small and of minor significance.

TABLE 2 Soil organic carbon (SOC) stock (0-to-30-cm depth), SOC base calculation (based on SOC concentration [kg m^{-3}] at 30-cm depth projected throughout the 0-to-30-cm depth), SOC sequestration as the difference between SOC stock and SOC base (0-to-30-cm depth), and basal SOC concentration at 30-cm depth as affected by 6 yr of tillage and cover crop management in a pasture–crop rotation study near Watkinsville, Georgia

Tillage	Cover crop	SOC stock	SOC base	SOC sequestration	Basal SOC
		Mg C ha^{-1}			g kg^{-1}
Conventional	ungrazed	48.8	23.5	25.3	4.9
Conventional	grazed	46.4	27.9	18.5	5.9
No-till	ungrazed	53.2	25.8	27.4	5.4
No-till	grazed	52.3	23.4	28.9	4.9
Pasture	grazed	58.4	26.2	32.2	5.5
SE		2.7	2.1	3.1	0.5

Note. None of the treatments was significantly different at $p < .05$.

3.2 | Tillage and cover crop management (Study GA-2)

Using the depth distribution method, SOC stock tended to be greater under no tillage than under conventional tillage ($p = .06$) and was not different whether cover crops were grazed or not (Table 2). Stock of SOC tended to be lower with any cropping system than under the reference condition of long-term pasture ($p = .08$). When calculating the assumed SOC base from that of the 30-cm depth, there were no differences among treatments. Lack of treatment difference in the SOC base on the same soil type should be viewed as a positive assessment of the depth distribution method. Basal SOC concentration at 30-cm depth averaged 5.3 g kg^{-1} among treatments. Calculated SOC sequestration as the difference in standing stock of SOC minus that of the SOC base was greater under no tillage than under conventional tillage ($p = .05$), was not different whether cover crops were grazed or not, and was not different between cropping and reference grass condition. Calculated SOC sequestration from the difference in estimates between no tillage and conventional tillage were 2.1–10.4 Mg C ha^{-1}. From traditional calculations, SOC sequestration with no tillage compared with conventional tillage was 4.3–6.8 Mg C ha^{-1} at 0-to-20-cm depth ($p = .04$) and 3.7–3.9 Mg C ha^{-1} at 0-to-40-cm depth ($p = .17$). Therefore, estimated SOC sequestration and its statistical significance were similar between approaches.

TABLE 3 Soil organic carbon (SOC) stock (0-to-30-cm depth), SOC base calculation (based on SOC concentration [kg m^{-3}] at 30-cm depth projected throughout the 0-to-30-cm depth), SOC sequestration as the difference between SOC stock and SOC base (0-to-30-cm depth), and basal SOC concentration at 30-cm depth as affected by year of sampling of shallow increments (0–3, 3–6, 6–12, 12–20, and 20–30 cm) and tillage management in a pasture-crop rotation study near Watkinsville, Georgia

Year	Management	SOC stock	SOC base	SOC sequestration	Basal SOC
		Mg C ha^{-1}			g kg^{-1}
1	conventional tillage	48.7	45.2	3.6	10.0
1	no tillage	52.2	30.1	22.1	6.4
3	conventional tillage	46.0	33.8	12.2	7.3
3	no tillage	51.5	30.4	21.1	6.4
5	conventional tillage	47.2	34.9	12.3	7.5
5	no tillage	50.7	25.7	25.0	5.4
7	conventional tillage	52.1	32.9	19.2	7.0
7	no tillage	58.6	31.4	27.2	6.7
SE		1.0	1.7	1.0	0.4
Orthogonal contrast		Pr > F			
Linear time effect		<.001	.002	<.001	.002
Conventional vs. no tillage		<.001	<.001	<.001	<.001
Year × management		.27	.003	<.001	.002

A large portion of calculated SOC sequestration from the depth distribution method (26.5 ± 4.6 Mg C ha^{-1}; Table 2) could be attributed to the previous 20 yr of pasture management prior to cropping, especially because continuation of pasture management was greatest among treatments at 32.2 Mg C ha^{-1}. Variation in calculated SOC sequestration from depth distribution estimates was rather large in this study, with a standard error of 3.1 Mg C ha^{-1}. This variation may have been a result of relatively large plots (0.2–0.5 ha each) over a total of 9 ha on a sloping landscape position.

None of the SOC responses in Table 2 was significantly altered when all six depth increments (0–20, 20–40, 40–60, 60–90, 90–120, and 120–150 cm) were used to estimate depth distribution parameters of SOC compared with only three depth increments (0–20, 20–40, and 40–60 cm) (data not shown). Therefore, even more conclusive than the calculation for Study GA-1, there was no difference in estimations of SOC properties in the surface 30 cm when using different depth limits.

Analysis of narrower depth increments within the surface 30 cm (i.e., 0–3, 3–6, 6–12, 12–20, and 20–30 cm) resulted in greater sensitivity to depth stratification, especially with no tillage and with continuation of the perennial pasture. The standard error of calculated SOC sequestration estimates among the 4 yr was 1.0 Mg C ha^{-1} (Table 3), compared with 3.1 Mg C ha^{-1} in the wider depth increments and deeper in the profile (Table 2). Values of calculated SOC sequestration at the end of 7 yr of management with narrow depth increments were reasonably similar to those at the end of 6 yr of management with wider depth increments. A significant difference in calculated SOC sequestration between tillage systems was detected in all years with narrower depth increments (Table 3), but no differences were detected whether cover crops were grazed or not (data not shown), consistent with the original results. One difference between the two approaches was for greater basal SOC concentration at 30-cm depth (and resultant greater base SOC stock) with narrower than wider depth increments. Basal SOC concentration at 30-cm depth was 5.3 ± 0.4 g kg^{-1} with wider depth increments, 8.0 ± 1.2 g kg^{-1} with narrower depth increments under conventional tillage, and 6.2 ± 0.5 g kg^{-1} with narrower depth increments under no tillage. Greater basal SOC concentration at 30-cm depth with conventional tillage was likely due to initial moldboard plowing that redistributed SOC to ∼25 cm depth and at least initially created an elevated baseline condition based on curve fitting. Estimated basal SOC concentration at 30-cm depth declined with time under conventional tillage. Restricting soil sampling to within the 0-to-30-cm profile did appear to elevate the estimate of basal SOC concentration at 30-cm depth because a lower SOC concentration was observed with deeper sampling. This lower SOC concentration deeper in the profile appeared to have shifted estimated SOC concentration at 30-cm depth by ∼1 g kg^{-1}, so having a depth increment below 30 cm may be beneficial to getting a more accurate estimate of the baseline condition.

3.3 | Biofuel crop management (Study NC-1)

Stock of SOC in the upper 30 cm of this study was high in all management systems relative to Studies GA-1 and GA-2 (Table 4). This study followed termination of a long-term tall fescue hayfield, which could have had elevated surface-SOC concentration (Franzluebbers & Poore, 2020). This soil also had high clay content that may have enhanced C retention potential. Stock of SOC was greater in continuation of the traditional tall fescue hay system than in biofuel cropping systems, which was likely due to the maturing status of the biofuel crops after only 3 yr since establishment. Chemical termination of the original tall fescue sod and initially slow establishment of the perennial biofuels of miscanthus and switchgrass would have likely contributed to the small decline in SOC stock. In addition, the switchgrass stand was disked after initial stand failure to get better seed-to-soil contact.

Calculated SOC sequestration was 28.2 ± 2.1 Mg C ha^{-1} (mean ± standard deviation among all systems), which was nearly equal to the SOC base of 29.7 ± 4.1 Mg C ha^{-1} (with basal SOC concentration at 30-cm depth of 6.3 ± 0.9 g kg^{-1}).

TABLE 4 Soil organic carbon (SOC) stock (0-to-30-cm depth), SOC base calculation (based on SOC concentration [kg m^{-3}] at 30-cm depth projected throughout the 0-to-30-cm depth), SOC sequestration as the difference between SOC stock and SOC base (0-to-30-cm depth), and basal SOC concentration at 30-cm depth as affected by biofuel crop management compared with traditional grain and forage crop management at a site near Salisbury, North Carolina

Cropping system	SOC stock	SOC base	SOC sequestration	Basal SOC
	Mg C ha^{-1}			g kg^{-1}
Corn–soybean rotation	58.6ab	29.8ab	28.8	6.3ab
Tall fescue hay	62.1a	32.5a	29.6	6.9a
Miscanthus	60.8ab	34.5a	26.3	7.4a
Sorghum	55.8bc	30.5ab	25.3	6.5ab
Switchgrass	52.9c	22.1b	30.8	4.6b
SE	1.4	2.1	1.5	0.5

Note. Means within a column not sharing the same letter are significantly different at $p < .05$.

Therefore, calculated SOC sequestration was more likely due to the decades of tall fescue management than the few years of biofuel grass management. Previous history of tall fescue management nearly doubled the SOC content of the surface 30 cm. If the time interval were set to 50 yr of tall fescue management (a rough estimate of when forage stand was established), then effective SOC sequestration rate would have been 0.56 ± 0.04 Mg C ha^{-1} yr^{-1} (0-to-30-cm depth). Across various grass management experiments in the southeastern United States, SOC sequestration was estimated as 0.84 ± 0.11 Mg C ha^{-1} yr^{-1} (Franzluebbers, 2010). Accumulation of this large stock of SOC during recent history seems reasonable with several decades of hay production, which was supplemented with large inputs of poultry litter as fertilizer prior to the experiment. Having an estimate of basal SOC concentration was vital in making these calculations.

3.4 | Switchgrass cultivars (Study NC-2)

Stock of SOC to a depth of 30 cm was greater under Performer than under Colony (Table 5). At first glance, this result appeared contradictory to the expected greater root production with Colony having high biomass production potential than the more digestible and likely less productive Performer. However, no data were collected on aboveground or belowground production, so this is only an assumed expectation. Importantly, basal SOC concentration at 30-cm depth and base SOC stock were also greater under Performer than under Colony. This result highlights how soil type and historical conditions are important in making calculations of SOC sequestration with this method. Calculated SOC sequestration was the same between the two fields ($p = .12$), averaging 18.7 Mg C ha^{-1}. The ratio of sequestered SOC to that of base SOC stock was 0.8–1.2.

TABLE 5 Soil organic carbon (SOC) stock (0-to-30-cm depth), SOC base calculation (based on SOC concentration [kg m^{-3}] at 30-cm depth projected throughout the 0-to-30-cm depth), SOC sequestration as the difference between SOC stock and SOC base (0-to-30-cm depth), and basal SOC concentration at 30-cm depth as affected by long-term switchgrass production on two nearby fields at Clayton, North Carolina

Cultivar	SOC stock	SOC base	SOC sequestration	Basal SOC
	Mg C ha^{-1}			g kg^{-1}
Colony	30.8b	14.3b	16.6	2.9b
Performer	47.3a	26.4a	20.8	5.6a
SE	1.9	1.2	1.1	0.3

Note. Means within a column not sharing the same letter are significantly different at $p < .05$.

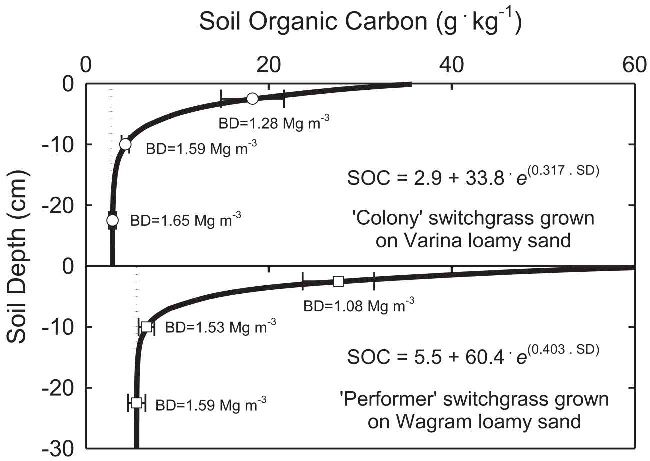

FIGURE 1 Depth distribution of soil organic C (SOC) in two nearby fields of switchgrass. Symbols and error bars are mean and standard deviation among three pseudoreplicates in the field. Solid regression lines illustrate the fit of nonlinear decay functions to strong depth stratification. Vertical dotted line represents the baseline SOC condition at 30 cm extended to the soil surface. The difference between solid line and dotted line represents the change in SOC concentration, which would be multiplied by bulk density to yield SOC sequestration. BD, bulk density; SD, soil depth

Depth distribution of these two switchgrass cultivars on two different fields can serve to illustrate a few key points about SOC calculations (Figure 1). First, basal SOC concentration was different between these fields, and this was not necessarily a limitation in comparing the effect of recent management. This basal SOC concentration is an important determinant of calculated SOC sequestration with the depth distribution method. Although SOC concentration near the surface was greater with Performer than with Colony, basal SOC concentration normalized the difference, resulting in similar SOC sequestration. It is the difference between the

TABLE 6 Soil organic carbon (SOC) stock (0-to-30-cm depth), SOC base calculation (based on SOC concentration [kg m^{-3}] at 30-cm depth projected throughout the 0-to-30-cm depth), SOC sequestration as the difference between SOC stock and SOC base (0-to-30-cm depth), and basal SOC concentration at 30-cm depth as affected by land use management in two physiographic regions across a five-state area of the southeastern United States

Region	Management	SOC stock	SOC base	SOC sequestration	Basal SOC
		Mg C ha^{-1}			g kg^{-1}
Coastal Plain	conventional tillage	25.5	21.8	3.7	4.4
	no tillage	32.9	22.8	10.1	4.7
	pasture	42.8	25.5	17.3	5.3
Piedmont	conventional tillage	30.9	23.2	7.7	4.7
	no tillage	35.2	21.7	13.6	4.4
	pasture	47.7	23.5	24.1	4.8
SE		2.0	2.0	1.7	0.4
Orthogonal contrast		Pr > F			
Coastal Plain vs. Piedmont		.009	.82	.001	.83
Conventional vs. no tillage-pasture		<.001	.64	<.001	.69
No tillage vs. pasture		<.001	.33	<.001	.34
Region × management		.78	.83	.67	.78

solid and dotted lines in Figure 1 that determines the effective SOC concentration change, which when multiplied by the associated soil BD yields an estimate of SOC sequestration (Mg C ha^{-1}) upon integration over the 0-to-30-cm profile. In this example, 79 ± 5% of calculated SOC sequestration occurred in the top 5 cm, 96 ± 2% occurred in the top 10 cm, 99 ± 1% occurred in the top 15 cm, and 100% occurred in the top 25 cm of the 0-to-30-cm profile.

3.5 | Land use comparison in the southeastern United States (Study SE-1)

Among 87 fields sampled throughout a five-state region sharing both Coastal Plain and Piedmont physiographic regions, basal SOC concentration at 30-cm depth (4.7 ± 0.4 g kg^{-1}) was not different among land uses of conventional-tillage and no-tillage cropping and perennial pasture (Table 6). Differences among management systems were detected in total SOC stock to a depth of 30 cm, but differences were even more prominent in calculated SOC sequestration above that of the base SOC stock. In the original study, mean stock of SOC (0-to-20-cm depth) across five states and two physiographic regions was reported as 22.2, 27.9, and 38.9 Mg C ha^{-1} under conventional tillage, no tillage, and pasture, respectively (Causarano et al., 2008). Soil organic C stock values across physiographic regions in Table 6 were ∼6.1 Mg C ha^{-1} greater, which gave very reasonable agreement between the two approaches considering the differences in depth.

Sequestration of SOC with the depth distribution method was 6.4 ± 3.6 Mg C ha^{-1} under conventional tillage (mean ± standard deviation among 5 states × 2 physiographic regions), 12.3 ± 3.0 Mg C ha^{-1} under no tillage, and 21.2 ± 6.9 Mg C ha^{-1} under perennial pasture. The difference in calculated SOC sequestration between no tillage and conventional tillage was 5.8 ± 4.3 Mg C ha^{-1}. Although duration of management was not clearly defined in this survey (5–40 yr), a reasonable assumption was for an average age of 20 yr (for no tillage). With this assumption, the average rate of SOC sequestration of no tillage over that of conventional tillage would have been 0.29 Mg C ha^{-1} yr^{-1} and would have been in relatively good agreement with other estimates of SOC sequestration following adoption of no-tillage management of cropland (Lal, Kimble, Follett, & Cole, 1998). Assuming that calculated SOC sequestration derived from the depth distribution method was a function of the past 40 yr of management, then SOC sequestration rates would have been 0.16 ± 0.11 Mg C ha^{-1} yr^{-1} under conventional tillage, 0.31 ± 0.13 Mg C ha^{-1} yr^{-1} under no tillage, and 0.54 ± 0.23 Mg C ha^{-1} yr^{-1} under perennial pasture. This temporal assumption was combined with the assumption that soil started from a highly degraded SOC base condition, which seems reasonable with >200 yr of crop cultivation in the region and numerous reports of widespread and intensive soil erosion (Endale et al., 2000; Galang et al., 2007; Langdale & Shrader, 1982; McGregor et al., 1975).

This survey illustrated clearly the increasingly greater potential for SOC sequestration when transitioning from conventional-tillage to no-tillage cropping to perennial pasture in the southeastern United States. The survey was structured so that all three land uses were in the same local vicinity but not necessarily from the same farm. These pairings were repeated within a state and physiographic region and across the five states. Therefore, a diversity of management choices within these broad categories would have occurred among observations. Despite such variations, there was relatively low residual variation, with standard error of 1.7 Mg C ha^{-1} for calculated SOC sequestration. This level of variation was similar to residual variation from other controlled studies on research stations (1.5 ± 0.7 Mg C ha^{-1}; Tables 1–5).

3.6 | Corn production in the southeastern United States (Study SE-2)

From a survey of corn production fields in the Carolinas and Virginia, the base SOC stock varied considerably more

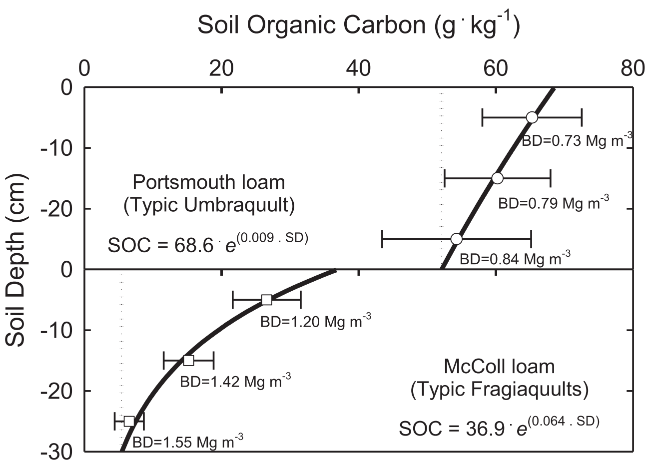

FIGURE 2 Depth distribution of soil organic C (SOC) in two different fields cropped to corn in the Coastal Plain of North Carolina. Portsmouth loam was disk tilled in Lenoir County, and McColl loam was no tilled in Scotland County. Symbols and error bars are mean and standard deviation among four pseudoreplicates in the field. Solid regression lines illustrate the fit of nonlinear decay functions to depth stratification. Vertical dotted line represents the baseline condition at 30-cm depth extended to the soil surface. The difference between solid line and dotted line represents the change in SOC concentration, which would be multiplied by bulk density to yield SOC sequestration. The Portsmouth loam had calculated SOC sequestration of 4.9 Mg C ha^{-1}, and the McColl loam had calculated SOC sequestration of 39.1 Mg C ha^{-1}. BD, bulk density; SD, soil depth

than in other studies (i.e., 15.6–67.6 Mg C ha^{-1} at 5th and 95th percentile limits). This variation was due to several unique soil types in the Coastal Plain and Blue Ridge regions that had much greater residual basal SOC concentrations at 30-cm depth than more typical upland soils of the region. These unique soil types were, however, useful in demonstrating the value of the soil depth distribution method in calculating SOC sequestration (Figure 2). Despite having high SOC throughout the plow layer, the Portsmouth loam shown in Figure 2 had muted SOC depth stratification due to management with disk tillage for several years. The McColl loam, however, had low basal SOC concentration and reflected the ~20 yr of no-till management that led to significantly greater SOC sequestration. Note the SOC concentration and BD differences between soil types in Figure 2.

Despite large variation in base SOC stock due to drained-organic soils compared with upland-mineral soils, calculated SOC sequestration was always greater with no-till cropping (26.1 ± 1.1 Mg C ha^{-1}; mean ± SE) than with conventional-till cropping (10.3 ± 2.3 Mg C ha^{-1}) in all states and physiographic regions (Table 7). Therefore, using basal SOC concentration at 30-cm depth (kg m^{-3}) as a normalizing factor for each soil type was critical in making a reasonable and reliable estimate of SOC sequestration in these fields across a diversity of soil types. The ratio of calculated SOC sequestration to that of the baseline SOC stock was 0.38 ± 0.13 under conventional tillage and 1.11 ± 0.07 under no tillage.

Most numerous field observations were in the North Carolina Piedmont with no tillage, the North Carolina Coastal Plain with no tillage, and the Virginia Great Valley with no tillage. There was no difference in calculated SOC sequestration between the North Carolina Piedmont with no tillage and the Virginia Great Valley with no tillage, but both of these regions had greater SOC sequestration than the North Carolina Coastal Plain with no tillage (28.2 vs. 19.6 Mg C ha^{-1}, respectively; p = .001). Other regions had only a few sites each, and estimates can only be considered preliminary. There is need for more observations in all regions.

3.7 | Overall assessments

Considering that most fields were privately managed in Studies SE-1 and SE-2, they could be viewed as randomly distributed observations across the region. Therefore, frequency distributions of calculated SOC sequestration were plotted in Figure 3. Under both conventional-tillage and no-tillage management, there was a relatively wide range of calculated SOC sequestration (i.e., 0.3–14.5 Mg C ha^{-1} under conventional tillage [range, 5–95% range] and 6.6–39.0 Mg C ha^{-1} under no tillage). However, it was clear that calculated SOC sequestration was much more likely greater with no tillage than with conventional tillage in the surface 30 cm of soil, wherein the interquartile range (IQR) was 3.7–8.2 Mg C ha^{-1} under conventional tillage and 13.3–27.3 Mg C ha^{-1} under no tillage. Additionally, calculated SOC sequestration was affected (p < .05) by physiographic region when cropland was under no tillage (i.e., 15.5 ± 1.5 Mg C ha^{-1} in the Coastal Plain <24.1 ± 1.3 Mg C ha^{-1} in the Piedmont = 27.5 ± 1.9 Mg C ha^{-1} in the Great Valley = 27.9 ± 6.1 Mg C ha^{-1} in the Blue Ridge). Under pastures, calculated SOC sequestration was greater in the Piedmont than the Coastal Plain (24.1 vs. 18.1 Mg C ha^{-1}, respectively; p = .04). No difference in calculated SOC sequestration occurred among regions when cropland was under conventional tillage.

Although SOC sequestration could theoretically occur below 30 cm depth in the southeastern United States, the effect would appear to be extremely small and likely take decades to centuries of conservation management to produce statistically significant changes. Soils of the southeastern United States simply have little propensity for sequestration of SOC deeper in the profile (Franzluebbers, 2010; Franzluebbers & Stuedemann, 2009; Garten & Wullschleger, 1999; Ma et al., 2000), and repeated claims to sample deeper in the profile than the surface 30 cm need to be tempered with realistic expectations. These results indicate that SOC concentration at 30-cm depth varies relatively little among soils of

TABLE 7 Soil organic carbon (SOC) stock (0-to-30-cm depth), SOC base calculation (based on SOC concentration [kg m^{-3}] at 30-cm depth projected throughout the 0-to-30-cm depth), SOC sequestration as difference between SOC stock and SOC base (0-to-30-cm depth), and basal SOC concentration at 30-cm depth as affected by tillage management in corn cropping systems within particular physiographic regions of three states in the southeastern United States

State	Region	Management	No. Obs.	SOC stock	SOC base	SOC sequestration	Basal SOC
				Mg C ha^{-1}			g kg^{-1}
NC	Coastal Plain	conventional tillage	7	82.3	71.4	10.9	21.5
NC	Coastal Plain	no tillage	15	48.0	28.4	19.6	6.1
NC	Piedmont	conventional tillage	4	38.6	23.3	15.2	5.0
NC	Piedmont	no tillage	22	55.9	27.0	28.8	5.7
NC	Blue Ridge	conventional tillage	5	71.4	65.8	5.7	15.8
NC	Blue Ridge	no tillage	2	71.0	43.1	27.9	9.5
SC	Coastal Plain	no tillage	2	38.5	20.2	18.3	4.2
VA	Coastal Plain	no tillage	2	37.9	19.6	18.4	4.0
VA	Piedmont	no tillage	5	55.0	21.5	33.5	4.4
VA	Great Valley	no tillage	20	54.1	26.6	27.5	5.6
SE				5.4	5.6	3.0	2.0
Orthogonal contrast				Pr > F			
Conventional tillage vs. no tillage				.01	<.001	<.001	<.001
Coastal Plain vs. Piedmont-Great Valley-Blue Ridge under no-till				.007	.31	.003	.51
Piedmont vs. Great Valley-Blue Ridge under no-till				.31	.15	.37	.34

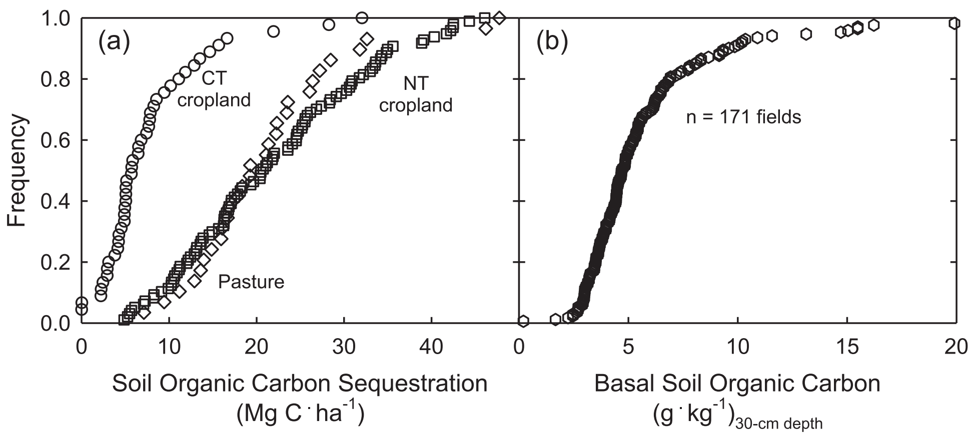

FIGURE 3 Frequency distribution of (a) soil organic C (SOC) sequestration on farmers' fields managed with conventional tillage (circles, $n = 45$), no tillage (squares, $n = 97$), and perennial pasture (diamonds, $n = 29$) throughout the southeastern United States and (b) SOC concentration at 30-cm depth across all locations sampled in Studies SE-1 and SE-2. Data are based on SOC depth distribution calculations reported in Causarano et al. (2008), Franzluebbers (2018), and Franzluebbers (2020). Soil organic C sequestration was 4.2, 5.7, and 9.4 Mg C ha^{-1} at 25, 50, and 75th percentiles, respectively, for conventional tillage (CT); 13.6, 20.8, and 29.7 Mg C ha^{-1} at 25, 50, and 75th percentiles, respectively, for no tillage (NT); and 15.9, 19.3, and 26.1 Mg C ha^{-1} at 25, 50, and 75th percentiles, respectively, for pasture

similar nature, such as Ultisols that dominate throughout the southeastern United States. Some unique soil types may have greater or lower SOC concentrations, but the IQR of SOC at 30-cm depth was 3.7–6.5 g kg^{-1} (Figure 3).

Although management-induced SOC sequestration may be limited to the surface 30 cm in the southeastern United States, this study demonstrated there is large accumulation potential that has been realized on many farms using conservation management approaches. If a 50-yr period were to be used as the time period of SOC sequestration, then interquartile estimates from Figure 3 would have been 0.08–0.19 Mg C ha^{-1} yr^{-1} for conventional tillage and 0.2– 0.59 Mg C ha^{-1} yr^{-1} for no tillage. Although the 50-yr time period would be conservative to estimate the change due to no tillage adoption (likely much less time on average among these farms), the issue of overcoming the longer-term history that contributed to some

SOC sequestration in the surface 30 cm has to be considered. Estimates would be double if a 25-yr period were used (which may be more reasonable on average), but the more conservative approach tempers the estimate with some level of SOC accretion prior to adoption of stricter conservation management. The more robust estimation from this evaluation is the absolute estimate of SOC sequestration independent of time. A reasonable target of calculated SOC sequestration should be to achieve at least the quantity in the base SOC stock, which seemed plausible in many of the studies reported here (i.e., 50% base SOC stock and 50% calculated SOC sequestration). However, a more aggressive approach to SOC sequestration may be to double that of the base SOC stock (i.e., 33% base SOC stock and 67% calculated SOC sequestration), which was achieved in only 6% of the cases in these studies. In this manner, targets for SOC sequestration in different soil types and regions could be set not by an absolute rate of SOC accumulation but by a proportion of that determined by the basal SOC condition. This would allow each soil type to meet its potential based more on inherent capacities rather than on arbitrary levels that may be easy or difficult to achieve. However, this idea needs to be validated with further testing.

Although this evaluation had some estimations of SOC sequestration from pastures on research station experiments and from private farms (Study SE-1), it is clear that additional field investigations of pastures on private farms is needed to get good estimates of SOC sequestration, especially using top-tier management. Estimated SOC sequestration from pastures on research stations reported here was 23.1–34.2 Mg C ha^{-1} in the IQR (n = 132), which was greater than the IQR for the 29 fields mostly in the land use comparison of SE-1. Significant SOC sequestration appears to be possible with pasture management. In Study SE-1, pastures were selected only as nearby fields to the target field of no-tillage cropland; specific pasture management was not documented. Results of Study GA-1 with 12 yr of different forage utilization of pasture illustrates that variations in SOC sequestration will be important by management style. Therefore, more research is needed on private farms to determine what these levels might be and how they vary with management style and among farms.

In this calculation of SOC sequestration among land uses in the southeastern United States, simulated BD was from a pedotransfer function derived from long-term management at a research station in the middle of the region. Direct comparison of predicted soil BD with measured BD showed general agreement between the two approaches (Figure 4). Root mean square error associated with the 1:1 association was 0.15 Mg m^{-3}. However, if 10 and 25% of observations with the most deviation were trimmed from each of the three data sources, then RMSE would have been 0.12 and 0.10 Mg m^{-3}, respectively. This seemed like acceptable variation in BD along the entire range of normal BD levels of 0.7–1.7 Mg m^{-3} for the wide diversity soils in the southeastern United States.

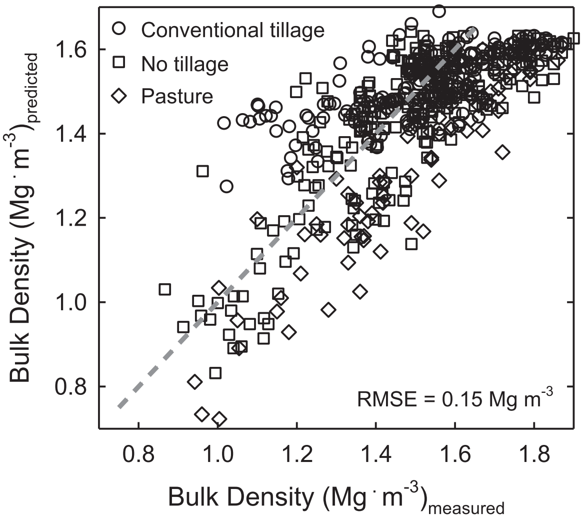

FIGURE 4 Comparison of bulk density predicted from the pedotransfer function (Equation 4; Franzluebbers (2010)] against that measured in the field with the core method. Data were from Study GA-2 with five depth increments within the 0-to-30-cm depth, from Study SE-1 from three depth increments within 0-to-20-cm depth, and from Study SE-2 from three depth increments within the 0-to-30-cm depth. There were 177 observations for conventional tillage, 259 observations for no tillage, and 110 observations for pasture. Dashed line is 1:1, and RMSE is deviation from this association

With this reasonable accuracy and need to estimate BD in 5-cm increments to make SOC sequestration calculations, simulated BD was considered the better choice for these calculations. Measured BD could also be used, but separation into smaller depth increments would be necessary, either directly through a series of 5-cm increments or indirectly with regression analysis over several depth increments covering the range of conditions.

It should be emphasized that this calculation procedure was intended to make reasonable estimates of SOC sequestration within a field from single-point-in-time measurements of SOC depth distribution, which until now has not been considered. This procedure would not reduce the need to continue long-term studies to better estimate SOC sequestration with high accuracy, nor would it preclude initiating new field studies to obtain spatial and temporal estimates of SOC sequestration. However, adopting this procedure would facilitate many more estimates of SOC sequestration among a diversity of agricultural conditions throughout the region with the intent to build consensus around sound conservation agricultural management approaches. This procedure could be viewed as a validation and widespread low-cost survey supplement to resource-intensive field studies. The need to characterize a wider diversity of management approaches remains a high priority, and this SOC sequestration calculation method could help meet this need.

4 | CONCLUSIONS

Soil organic C sequestration was effectively and reasonably calculated with an internal standard from mathematical description of soil-profile distribution of organic C using multiple depth increments. This calculation method assumes that soils have undergone historic degradation, which is reasonable throughout much of the southeastern United States. Sequestration of SOC can then be implied from the accumulation of SOC greater than that of the baseline condition, set in this approach as the SOC concentration at 30-cm depth (kg m^{-3}) expressed throughout the 0-to-30-cm profile. Calculations of SOC sequestration matched those reported from traditional approaches using randomized and spatially replicated plot experiments repeated over time. Conservation agricultural management treatments could be easily distinguished in SOC sequestration potential from those of conventional tillage cropland, which typically had smaller SOC sequestration but significant values in some cases. This calculation method avoids the need for a paired plot or repeated measures over time. This depth distribution method of SOC sequestration illustrated that deficits of SOC could be as low as 33% of potential SOC storage and that this deficit can be filled with conservation agricultural management (e.g., 9–26 Mg C ha^{-1} sequestered from the IQR of studies evaluated). This method gives promise to estimating SOC sequestration from a wide diversity of soil types and management systems throughout the southeastern United States and possibly beyond.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ACKNOWLEDGMENTS

Erin Silva, Ellen Leonard, and Steven Knapp provided sound technical support over years of investigation that led to this summary interpretation, and they are gratefully acknowledged. Financial support was provided by USDA Agricultural Research Service and some notable grant providers of long-term research, including U.S. Department of Energy and USDA National Institute of Food and Agriculture. Cotton Incorporated provided recurring support that stimulated this synthesis.

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How to cite this article: Franzluebbers AJ. Soil organic carbon sequestration calculated from depth distribution. *Soil Sci Soc Am J*. 2021;85:158–171. https://doi.org/10.1002/saj2.20176