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Soil organic carbon and nitrogen storage estimated with the root-zone enrichment method under conventional and conservation land management across North Carolina

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Abstract: Agriculture is a globally dominating land use, so efforts to restore soil organic carbon (C) and nitrogen (N) lost through historical degradation could have enormous benefits to production and the environment, particularly by storing an organic reserve of nutrients in soil and avoiding the return of a small portion of biologically cycling C to the atmosphere. Estimates of soil organic C and N storage from conservation agricultural management are still limited when considered in proportion to the large diversity of environmental and edaphic conditions. A study was undertaken to determine the total, baseline, and root-zone enrichment stocks of soil organic C and N as affected by land use on 25 research stations distributed throughout North Carolina. Root-zone enrichment of organic matter is that portion influenced by contemporary management, and baseline is that portion dominated by pedogenesis. These fractions were compared with more traditional estimation procedures. Soil organic C and N were strongly negatively associated with sand concentration. Although physiographic region influenced overall soil C and N contents, variations in soil type and research station management within a region were equally influential. Soil organic C and N stocks were strongly affected by land use, which did not interact with the soil textural effect. Across the 25 research station locations, root-zone enrichment of soil organic C followed the order ($p < 0.01$) conventional-till cropland (11.1 Mg C ha^{-1}) < no-till cropland (21.5 Mg C ha^{-1}) < grassland (29.6 Mg C ha^{-1}) < woodland (38.6 Mg C ha^{-1}). Root-zone enrichment of total soil N followed a similar order, except grassland and woodland effects were reversed. Root-zone enrichment provided an integrated soil-profile assessment and a more targeted response of soil organic C and N change than did more traditional paired land use approaches, primarily due to separation of a variable pedogenic influence among sites. These point-in-time results gave a clear indication that conservation agricultural management approaches will foster surface soil organic C and N restoration across a diversity of soil types in the southeastern United States.

Keywords: carbon—grazing land—land management—nitrogen—no-till cropland—woodland

Soil organic carbon (SOC) content is a key trait that reflects the cumulative effects of pedogenesis and historical management, both from long-term and relatively recent management (Kögel-Knabner and Amelung 2021). How SOC accumulates and its extent of accumulation in long-term agricultural systems continues to be the focus of ongoing field research projects in the United States (Bowles et al. 2020) and around the world (Liu et al. 2006). The diversity of edaphic (e.g., soil texture and mineralogy) and environmental conditions (e.g., mean annual temperature and precipitation) found in different ecoregions can be important variables necessary to understand how long-term management interacts with the environment. Disaggregating management from pedogenetic conditions requires a diversity of studies across different ecoregions. As well, environment × management interactions might change along with a changing climate, which may not only affect temperature and precipitation in a region, but also the types of management that become most appropriate to adapt to biophysical changes in the climate (Gusli et al. 2020; Lal 2020; Anton et al. 2021). Developing agricultural management approaches to foster soils in becoming net positive C sinks has become a global priority (Minasny et al. 2017; Rumpel et al. 2020), so more field studies with similar management comparisons across a diversity of environments will be necessary to formulate best adaptation strategies to climate change.

The southeastern US is a warm, humid region known for its history of widespread erosion and loss of surface soil organic matter following decades of clean cultivation techniques (Trimble 1974; Franzluebbers 2005). Adoption of conservation tillage and cover cropping is still not widespread in the region (Farmaha et al. 2022), but erosion has been markedly reduced in the past century with transition of clean-tilled row crop agricultural production to naturalized and planted timber, pasture-based livestock systems, and more recently to no-till crop production (Causarano et al. 2006; Franzluebbers 2010). Generally, soils in the region have moderate base saturation with coarse texture, such that leaching of inorganic nutrients can be a significant challenge to maintain soil fertility (Farmaha et al. 2022). However, specific variations in soil texture and moisture regime present challenges in understanding how management affects soil properties and functions across different pedogenic conditions in the region.

Calculation of SOC sequestration requires that net accumulation be considered over time (Ellert et al. 2002; Qin et al. 2014). Sequestration has been determined in the past with a variety of approaches to estimate net positive change in stock of SOC. In its most basic form, SOC stock at time zero is sub-

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tracted from SOC stock at a designated later period, particularly with a specified management approach that may be assumed to cause a change (Ogle et al. 2010). For example, SOC stock of the surface 30 cm measured in 2010 and again in 2020 could be used to estimate stock change over a 10-year period. Another approach has been to assume that previous history of management would be similar between two contrasting land uses that have subsequently been managed differently over a specified period (Christopher et al. 2009; Novara et al. 2012). For example, two parcels of land managed the same prior to 2010 were subsequently managed differently until 2020 when soil was sampled and SOC stock difference between the two fields was compared. The elapsed time of 10 years could be used to calculate SOC sequestration of one system over that of another. This latter approach has become more commonly used to compare SOC differences between conventional and conservation land uses (Blanco-Canqui and Lal 2008; Follett et al. 2009). Without initial sampling of soil prior to the management change, this approach assumes that conditions between land uses were the same prior to the management change. Validation of this assumption may not always be possible. Further, when comparing SOC stocks under forested and agricultural land uses, an assumption of similar soil condition prior to the management change may not be valid due to landscape position that often favors one land use over another. Pedogenic factors or even relatively small antecedent soil conditions prior to management change could influence the presumptive change in SOC over the evaluation period. Therefore, an alternative SOC calculation method has been described from depth distribution calculation to overcome this limitation of potentially different antecedent conditions (Franzluebbers 2022). With this approach, root-zone enrichment of SOC is separated from an assumed baseline condition of SOC concentration at 30 cm depth in the profile. Concentration of SOC at 30 cm depth is assumed to be relatively unaffected by management in the period of a human generation. Each soil profile can be assumed to have its own baseline SOC condition when concentrations of multiple depths are fitted to a nonlinear mathematical expression (Franzluebbers 2021d). This alternative calculation of SOC depth distribution could help alleviate concerns about different antecedent conditions of paired land uses, but further testing and validation of this concept are needed.

Total soil nitrogen (TSN) is an important soil property that is directly related to soil fertility through the supply of organic N to plant growth via soil microbial activity (Franzluebbers et al. 2018). Total soil N has been shown to have strong correlation with SOC concentration, but also varies among soil types due to the nature of C and N cycling (Farmaha et al. 2022). Both SOC and TSN concentrations with depth in the profile have been used successfully to calculate root-zone enrichment of SOC and TSN as a function of agricultural management in the southeastern United States (Franzluebbers 2021b).

The objectives of this study were to (1) test whether baseline SOC and TSN concentrations at 30 cm were different among land uses within a research station location, as well as across research station locations that were diverse in soil and environmental conditions; (2) calculate root-zone enrichment of SOC and TSN as affected by conservation land uses (grassland and woodland) practiced throughout North Carolina and compare these estimates with conventional-till and no-till cropland as common agricultural land uses; (3) compare root-zone enrichment calculations of SOC and TSN stocks with traditional SOC and TSN stock measurements; and (4) determine if soil texture or other edaphic factors interacted with land use management to alter root-zone enrichment calculations of SOC and TSN stocks. One hypothesis was that conservation land uses would accumulate greater quantities of SOC and TSN in the primary root-zone (i.e., 0 to 30 cm depth) than under conventional-till cropland. Another key hypothesis was that SOC and TSN concentrations at 30 cm depth would not vary among land uses, because recent management changes during the past several decades would only change soil organic matter properties in the primary root-zone. However, if SOC or TSN concentrations at 30 cm depth were indeed different among land uses, then reasonable estimates of root-zone enrichment of SOC and TSN could still be calculated and would more fairly differentiate the effect of land use on SOC and TSN storage.

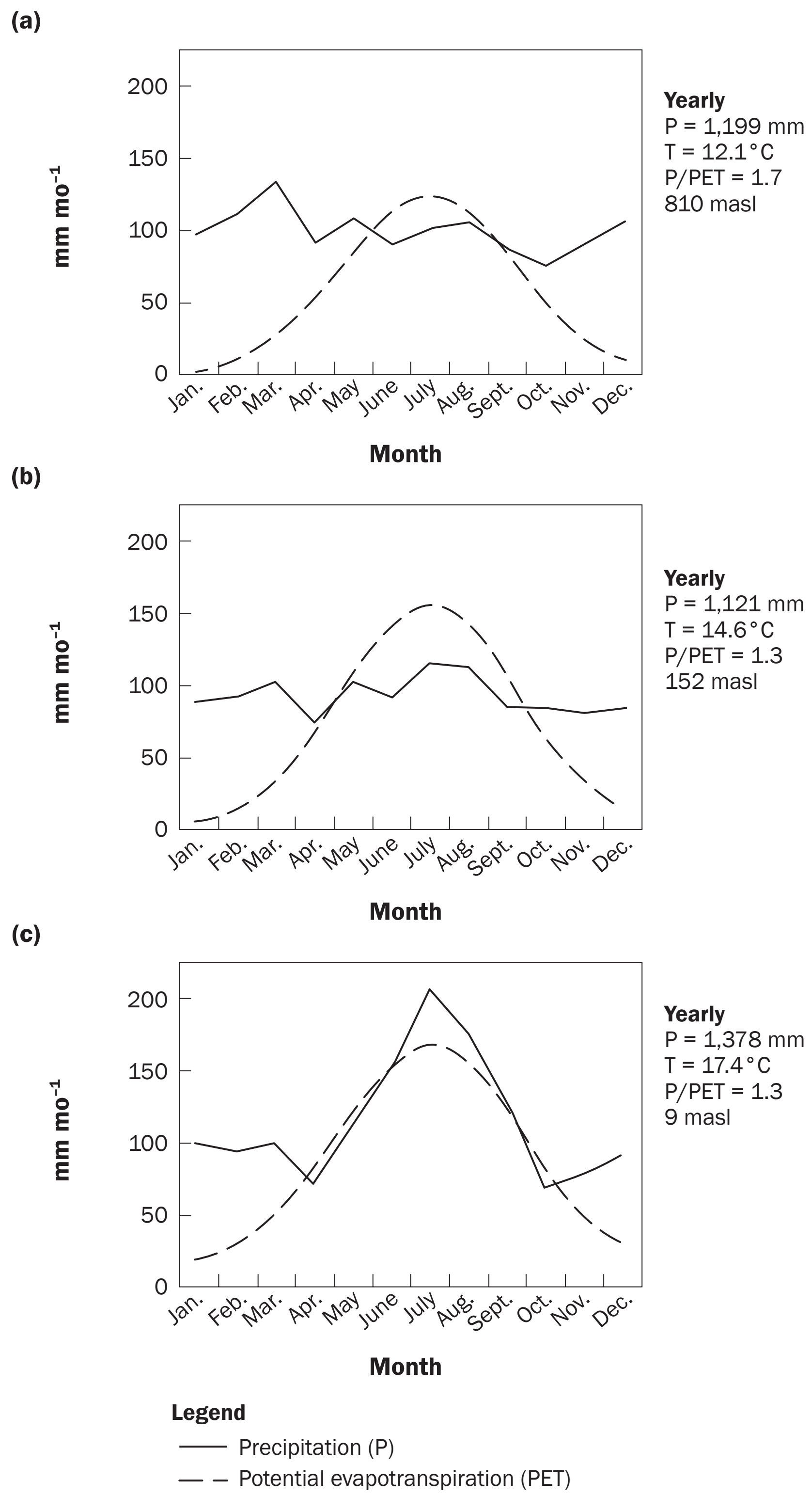
Materials and Methods

Site Characteristics and Management. Climatic conditions in North Carolina are generally warm and humid temperate, but variations occur most dramatically from east (Atlantic Coast Flatwoods) to west (Southern Blue Ridge) as a function of elevation (figure 1). Research stations throughout North Carolina were selected for this evaluation of SOC and TSN affected by land use (figure 2). Research stations were part of joint management between North Carolina Department of Agriculture and Consumer Services and North Carolina State University. At each of 25 locations, four land uses were sought for sampling of long-term management effects on SOC and TSN, including conventional-till cropland, no-till cropland, grassland, and woodland. At each location, four fields (or if limited number of distinct fields, then four locations separated by at least 30 m within a field, which mostly occurred in limited number of woodland fields) were selected semirandomly for sampling. Not all land uses were present at each of the research stations, but at least two contrasting land uses were sampled in all cases. Fields representing typical soil types for the location were preferred, which limited total random selection. Of the 310 fields sampled, 87% were ultisols (214 udults, 56 aquults) and the remaining 13% were inceptisols (13), alfisols (10), spodosols (8), entisols (7), and histosols (2). Location, soil taxonomy, and historical management of land uses are described in table 1. Soil characteristics at each research station location can be found in supplementary table S1.

Soil Sampling and Analyses. Soil was sampled from 310 fields of 25 research stations from December 11, 2020, to February 3, 2021. Within each field, a representative site was selected and marked with global positioning system (GPS) coordinates to match with soil taxonomical description from SoilWeb (California Soil Resource Lab 2022). Surface residue from a height of 5 cm aboveground to mineral soil was collected from within a 30 cm diameter ring placed at a representative location of each site. At each sampling site, up to five cores were composited, i.e., in the center and in four cardinal directions at distances of 10 m from the central location. Soil at 0 to 10 cm depth was collected with a 4 cm inside diameter push probe at each of the five coring locations. Soil at 10 to 30 and 30 to 60 cm depths was collected with a 3.2 cm diameter auger using a battery-powered drill that deposited soil into a 7.6 L plastic bucket through a steel-flange-reinforced opening at the bottom. Soil from all five locations was

Figure 1

Monthly and yearly climatic conditions at three locations ([a] Waynesville, [b] Oxford, and [c] Wilmington) distributed throughout North Carolina. Data are from 1961 to 1990 (www.worldclimate.com).



collected for the 10 to 30 cm depth and from only three locations for the 30 60 cm depth. A total of 658 to 947 g dry soil (middle 50% of observations) was collected from each site and sampling depth. Soil was transferred into labeled paper bags in the field and dried in an oven at 55°C for ≥3 d until constant weight. Soil was passed through a screen with 4.75 mm openings and stones and visible plant residues removed before further processing. Coarse fragments (>4.75 mm) accounted for 0.9% ± 2.6% of the sample.

A soil subsample ground to a fine powder in a ball mill for 1 minute was analyzed for total C and N with a Leco TruMac combustion analyzer (LECO Corporation, St. Joseph, Michigan). Total C was assumed to represent SOC since pH was ≤7.0 for all but four of the samples and was 7.1 in these cases. Soil bulk density of the 0 to 10 cm depth was determined from mass and volume of soil cores. Soil texture was determined with a hydrometer for clay (5 h settling time) and sieve (0.053 mm openings) for sand following shaking overnight of the dry-weight equivalent of 59 mL of soil with 100 mL of 0.1 M tetrasodium pyrophosphate ($Na_4P_2O_7$) in a 125 mL plastic bottle and subsequent dilution to 1 L with deionized water. The mass of soil in the 59 mL scoop of soil was used to calculate sieved soil density.

Surface residues were dried (55°C for ≥ 3d until constant weight) and weighed prior to initial coarse chopping in a flail mill, and then a representative subsample ground further in a Udy mill prior to determination of C and N with a Leco TruMac combustion analyzer.

A subsample of each of the 930 soil samples was submitted to the North Carolina Department of Agriculture and Consumer Services Soil Testing Laboratory for routine soil-testing. Analysis of soil-test phosphorus (P) and potassium (K) was from 2.5 mL of soil extracted with 25 mL of Mehlich-3 solution (Mehlich 1984) and determination with argon plasma emission spectroscopy. Cation exchange capacity was from summation of base cations (calcium [Ca^{2+}], magnesium [Mg^{2+}], and K^+) and acidity (aluminum [Al^{3+}], hydrogen [H^+]). Nutrient values were reported as grams per cubic meter, which would be equivalent to milligrams per kilogram if soil density were 1.0 Mg m^{-3} (Franzluebbers et al. 2021). Density of soil in a 10 mL scoop was 1.08 ± 0.18 Mg m^{-3} among samples. Soil pH was determined in 1:1 soil to 0.01 mol L^{-1} calcium chloride

Figure 2

Geographical distribution of 25 research station locations that were sampled across North Carolina.

($CaCl_2$) and reported as a water pH by adding 0.6 pH units.

Calculations and Statistical Analyses. Soil organic C and TSN at 0 to 10 cm depth were combined with measured bulk density to calculate surface soil C and N contents. Total surface C and N contents were calculated by summing surface residue C and N contents and surface SOC and TSN stocks of the 0 to 10 cm depth.

Stocks of SOC and TSN in the surface 30 cm depth were calculated from a nonlinear mathematical expression of depth distribution of SOC and TSN and estimated bulk density using a pedotransfer function based on SOC concentration (Franzluebbers 2021d). The pedotransfer function was derived from Franzluebbers (2010), equation 1:

$$BD = 1.71 \times e^{(-0.013 \times SOC)}, \quad (1)$$

in which BD is bulk density (Mg m^{-3}) and SOC is soil organic C (g kg^{-1}). Concentrations of SOC (and TSN) were fitted to a nonlinear function dependent on soil depth, according to the descriptions provided in Franzluebbers (2021d), equation 2:

$$SOC = A + B \times [1 - e^{(-b \times SD)}], \quad (2)$$

in which, SOC is soil organic C (g kg^{-1}), A is SOC concentration deep in the profile without management influence ($A \geq 0$ only), and B is the pool of SOC that accumulates at the soil surface and declines exponentially as a function of a rate constant (b, $|cm|^{-1}$) with soil depth (SD, |cm|). All nonlinear regressions were fitted to available data using SigmaPlot v. 14 (Systat Software Inc., Chicago, Illinois). In cases where this equation produced an estimate of $A < 0$, A was set to 0 using a modified form (equation 3):

$$SOC = B \times [1 - e^{(-b \times SD)}]. \quad (3)$$

Data for TSN were fitted in the same manner as that for SOC. These equations were then used to produce estimates of SOC and TSN concentrations at 5 cm depth increments and contents at 0 to 5, 5 to 10, 10 to 15, 15 to 20, 20 to 25, and 25 to 30 cm depth increments. Summation of contents from these increments yielded the stocks of SOC and TSN within the surface 30 cm profile. Therefore, all three depths sampled (0 to 10, 10 to 30, and 30 to 60 cm) were used to produce a single estimate of summed content via regression for each field. Baseline SOC and TSN that was not affected by management was assumed as concentrations at 30 cm depth. Baseline SOC and TSN contents (0 to 30 cm depth) were from concentrations at 30 cm depth multiplied by estimated bulk density at 30 cm depth, and this product projected across the entire 0 to 30 cm profile. Root-zone enrichment of SOC and TSN was calculated from the difference between total stock and baseline stock for each profile.

Statistical distributions of SOC and TSN components within and across land uses were calculated to estimate the 5% to 95% range, interquartile range, and median. Correlations among response variables were considered significant at $p \leq 0.01$, using a stringent criteria since large numbers of observations occurred within each of the four land uses (n = 88 for conventional-till cropland, n = 40 for no-till cropland, n = 98 for grassland, and n = 84 for woodland). Analysis of variance was conducted within a research station location to assess the impact of land use with replication as a blocking criterion, since soil series was matched among replicate blocks as closely as possible among land uses. Analysis of variance was also conducted across research station locations to assess the impact of land use with covariance provided by physiographic region as a class variable or soil texture (0 to 10 cm depth) as a continuous variable. The general linear model of SAS v. 9.4 (SAS Institute Inc., Cary, North Carolina) was deployed and significance of variables declared at $\alpha = 0.05$. Orthogonal contrasts were used to separate a priori effects of (1) cropping (conventional-till cropland and no-till cropland) versus conservation (grassland and woodland), (2) conventional-till cropland versus no-till cropland, and (3) grassland versus woodland management.

Results and Discussion

Across the 310 pedons, SOC was typically highly stratified within the surface 60 cm of the profile (figure 3). Across all fields, SOC was 26.8 ± 21.7 g kg^{-1} at 0 to 10 cm depth, 10.8 ± 12.0 g kg^{-1} at 10 to 30 cm depth, and 6.3 ± 7.5 g kg^{-1} at 30 to 60 cm depth (mean ± standard deviation). This depth distribution summary confirms that many soils in North Carolina are indeed very low in SOC below the typical sampling zone of 0 to 15 cm, as well as 15% of surface samples (0 to 10 cm) with SOC concentration <10 g kg^{-1}. The vast majority (89%) of surface samples with very low SOC was from conventional-till cropland.

When sorted by land use across all locations in an unstructured manner, i.e., randomly without regard for research station location, SOC concentration was not affected by land use at 10 to 30 and 30 to 60 cm depths. Soil organic C at 0 to 10 cm depth was greater ($p < 0.001$) under conservation land uses (i.e., grassland and woodland; mean of 34.1 g kg^{-1}) than under cropland (i.e., conventional-till and no-till; mean of 16.6 g kg^{-1}). Soil organic C concentration at 0 to 10 cm depth was not different between tillage systems, but SOC was greater ($p < 0.001$) under woodland (41.2 g kg^{-1}) than under grassland (28.0 g kg^{-1}). These results supported other results summarized from the region with regards to conservation land uses compared with cropland (Franzluebbers 2005), but the lack of difference between tillage systems under cropland was not entirely consistent with some research summaries (VandenBygaart et al. 2003; Johnson et al. 2005) and was consistent with other findings (Luo et al. 2010).

Table 1
Location, soil, and management characteristics of 25 research stations sampled in North Carolina.

Location	Latitude (°N)	Longitude (°W)	USDA soil taxonomy (number of fields)	Soil series (number of fields)	Management characteristics
Atlantic Coast Flatwoods Major Land Resource Area					
Horticultural Crops Research Station Castle Hayne, North Carolina	34.32	77.92	Spodic Paleudults (5), Aeric Paleaquults (4), Umbric Paleaquults (2), Typic Haplohumods (1)	Onslow loamy fine sand (5), Stallings fine sand (3), Pantego loam (2), Lynchburg fine sandy loam (1), Seagate fine sand (1)	CT cropland: strawberry (*Fragaria* × *ananassa*), cucurbit under plasticulture NT cropland: muscadine (*Vitis rotundifolia*) since >20 years Grassland: mowed centipede (*Eremochloa ophiuroides*)
Ideal Farm, Castle Hayne, North Carolina	34.36	77.84	Umbric Endoaquods (5), Terric Haplosaprists (2), Typic Humaquepts (1)	Murville fine sand (5), Pamlico muck (2), Torhunta loamy fine sand (1)	CT cropland: blueberry (*Vaccinium* sect. *Cyanococcus*) since >20 years Grassland: mowed centipede
Tidewater Research Station, Plymouth, North Carolina	35.85	76.66	Typic Umbraquults (12), Typic Endoaquults (2), Typic Fluvaquents (2)	Cape Fear loam (8), Portsmouth fine sandy loam (4), Muckalee loam (2), Roanoke loam (2)	CT cropland: corn (*Zea mays* L.), soybean (*Glycine max* L. [Merr.]), wheat (*Triticum aestivum* L.), potato (*Solanum tuberosum* L.) NT cropland: corn, soybean for five years after grass Grassland: grazed ryegrass (*Lolium perenne*), hayed tall fescue (*Lolium arundinaceum* [Schreb.] Darbysh.)
Border Belt Tobacco Research Station, Whiteville, North Carolina	34.41	78.79	Typic Kandiudults (7), Typic Endoaqualfs (3), Typic Fluvaquents (1), Aquic Paleudults (1)	Norfolk loamy fine sand (7), Grifton fine sandy loam (3), Muckalee sandy loam (1), Goldsboro fine sandy loam (1)	CT cropland: corn, tobacco (*Nicotiana tabacum* L.), cotton (*Gossypium hirsutum* L.) Grassland: mowed warm-season grasses Woodland: hardwood, mixed hardwood-pine
Southern Coastal Plain Major Land Resource Area					
Central Crops Research Station, Clayton, North Carolina	35.67	78.50	Typic Kanhapludults (9), Arenic Kandiudults (2), Typic Kandiudults (1)	Wedowee sandy loam (9), Wagram loamy sand (2), Norfolk loamy sand (1)	CT cropland: corn, cotton, soybean, wheat Grassland: switchgrass (*Panicum virgatum* L.) conservation since 1992 Woodland: 20- to 30-year pines, hardwoods
Wilkerson Farm, Clayton, North Carolina	35.67	78.51	Plinthic Kandiudults (5), Typic Paleaquults (5)	Dothan loamy sand (5), Rains sandy loam (5)	CT cropland: cotton, corn, soybean, wheat, fallow, sorghum (*Sorghum bicolor* L.) Grassland: mowed tall fescue, bahiagrass (*Paspalum notatum*)-centipede Woodland: mixed hardwood, mixed pine-hardwood
Horticultural Crops Research Station, Clinton, North Carolina	35.03	78.28	Typic Kandiudults (6), Typic Kanhapludults (4), Arenic Kandiudults (1), Aeric Paleaquults (1)	Marvyn loamy sand (4), Faceville fine sandy loam (3), Norfolk loamy sand (2), Lynchburg sandy loam (1), Orangeburg loamy sand (1), Wagram loamy sand (1)	CT cropland: pepper, cucumber (*Cucumis sativus*), soybean, squash, collards, strawberries, corn, sorghum, sweet potato (*Ipomoea batatas*), melon, fallow, watermelon (*Citrullus lanatus*),

Continued

Table 1 continued
Location, soil, and management characteristics of 25 research stations sampled in North Carolina.

Location	Latitude (°N)	Longitude (°W)	USDA soil taxonomy (number of fields)	Soil series (number of fields)	Management characteristics
					corn, sorghum, asparagus (*Asparagus officinalis*), stevia (*Stevia rebaudiana*), wheat, ornamentals Grassland: mowed fescue, bahiagrass Woodland: pine, mixed hardwood-pine
Cherry Research Farm, Goldsboro, North Carolina	35.39	78.03	Typic Albaquults (4), Typic Hapludults (4), Typic Paleaquults (3), Arenic Hapludults (2), Typic Endoaquults (2), Typic Quartzipsamments (1)	Leaf loam (4), Wickham loamy sand (4), Kenansville loamy sand (2), Weston loamy sand (3), Lumbee sandy loam (2), Lakeland sand (1)	CT cropland: corn, cotton, soybean, ryegrass, sorghum, sudangrass (*Sorghum* × *drummondii*), wheat, melon, peanut (*Arachis hypogaea* L.) NT cropland: corn, cotton, soybean, oat (*Aevena sativa* L.), fescue, bermudagrass (*Cynodon dactylon*), wheat, peanut since >10 years Grassland: ryegrass, crabgrass, tall fescue, pearl millet (*Pennisetum glaucum* [L.] R. Br.), bermudagrass Woodland: pine, hardwood-pine, hardwood
Caswell Research Farm, Kinston, North Carolina	35.28	77.64	Typic Umbraquults (4), Typic Kandiudults (3), Aeric Alaquods (2), Typic Humaquepts (1)	Portsmouth loam (4), Norfolk loamy sand (3), Leon sand (2), Torhunta loam (1)	CT cropland: clover, grasses, grain crops Grassland: mowed lawn, infrequently mowed fescue Woodland: mixed hardwood-pine
Lower Coastal Plain Research Station, Kinston, North Carolina	35.32	77.57	Typic Kandiudults (7), Typic Paleaquults (3), Aquic Paleudults (2)	Norfolk loamy sand (7), Rains sandy loam (3), Goldsboro loamy sand (2)	CT cropland: tobacco, sweet potato, corn, soybean, wheat Grassland: mowed bahia, tall fescue, clover mixtures since 30 years Woodland: pine, mixed hardwood-pine
Upper Coastal Plain Research Station, Rocky Mount, North Carolina	35.90	77.68	Typic Kandiudults (8), Arenic Kandiudults (4), Aquic Paleudults (3), Typic Paleaquults (1)	Norfolk loamy sand (8), Wagram loamy sand (4), Goldsboro fine sandy loam (3), Rains fine sandy loam (1)	CT cropland: cotton, peanut, soybean NT cropland: corn, soybean since 12 years Grassland: switchgrass conservation, mowed bahiagrass-tall fescue
Fountain Farm, Rocky Mount, North Carolina	35.99	77.76	Typic Endoaquults (4), Typic Hapludults (2), Aquic Hapludults (2), Typic Fluvaquents (2), Aquic Paleudults (1), Fluvaquentic Endoaquepts (1)	Roanoke loam (4), Wickham sandy loam (2), Gritney fine sandy loam (2), Bibb soils (2), Duplin sandy loam (1), Wehadkee silt loam (1)	CT cropland: cotton, sorghum Grassland: mowed tall fescue, bahiagrass, ryegrass Woodland: mixed hardwood-pine
Peanut Belt Research Station, Lewiston-Woodville, North Carolina	36.13	77.17	Typic Kandiudults (6), Aquic Paleudults (3), Aeric Paleaquults (2), Typic Paleaquults (1)	Norfolk sandy loam (6), Goldsboro sandy loam (3), Lynchburg sandy loam (2), Rains sandy loam (1)	CT cropland: peanut, corn, cotton, clary sage (*Salvia sclarea*) Grassland: mowed centipede, bahiagrass, tall fescue Woodland: mixed hardwood-pine, parkland pine, hardwood

Continued

Table 1 continued
Location, soil, and management characteristics of 25 research stations sampled in North Carolina.

Location	Latitude (°N)	Longitude (°W)	USDA soil taxonomy (number of fields)	Soil series (number of fields)	Management characteristics
Williamsdale Biofuel Lab, Wallace, North Carolina	34.76	78.10	Typic Paleaquults (6), Oxyaquic Paleudults (4)	Rains fine sandy loam (6), Noboco loamy fine sand (4)	CT cropland: corn, sorghum Grassland: sugarcane (*Saccharum officinarum*), giant miscanthus (*Miscanthus* × *giganteus*), switchgrass since five years after CT cropland Woodland: mixed pine-hardwood
Southern Piedmont Major Land Resource Area					
Beef Cattle Field Lab, Butner, North Carolina	36.17	78.80	Typic Kanhapludults (7), Aquic Hapludults (5)	Helena sandy loam (5), Herndon silt loam (4), Georgeville silt loam (3)	NT cropland: corn-hay rotation since 35 years Grassland: grazed tall fescue pasture since 35 years Woodland: mixed pine-hardwood
Umstead Research Farm, Butner, North Carolina	36.18	78.77	Aquic Hapludults (6), Typic Hapludults (6)	Helena sandy loam (6), Vance sandy loam (6)	NT cropland: corn, soybean, wheat since 35 years Grassland: grazed and hayed tall fescue pasture Woodland: mixed pine-hardwood
Sandhills Research Station, Jackson Springs, North Carolina	35.19	79.68	Grossarenic Kandiudults (9), Arenic Kanhapludults (3)	Candor sand (9), Ailey loamy sand (3)	CT cropland: cotton, soybean, wheat Grassland: mowed bahiagrass, centipede Woodland: mixed pine-hardwood
Oxford Tobacco Research Station, Oxford, North Carolina	36.31	78.62	Aquic Hapludults (7), Typic Hapludults (5)	Helena sandy loam (7), Vance sandy loam (5)	CT cropland: tobacco, wheat, soybean, corn Grassland: switchgrass conservation since 20 years, mowed tall fescue-centipede-bermudagrass Woodland: pine, mixed hardwood-pine
Currin Farm, Oxford, North Carolina	36.33	78.66	Typic Hapludults (5), Typic Kanhapludults (2), Aquic Hapludults (1)	Vance sandy loam (5), Appling sandy loam (2), Helena sandy loam (1)	CT cropland: tobacco, wheat, soybean, corn since 35 years following woodland clearing Grassland: mowed tall fescue
Lake Wheeler Road Field Lab, Raleigh, North Carolina	35.73	78.69	Typic Kanhapludults (16)	Cecil sandy loam (10), Pacolet sandy loam (5), Appling sandy loam (1)	CT cropland: wheat, corn NT cropland: corn, sorghum silage, small grains since three to five years Grassland: switchgrass conservation, grazed tall fescue pasture Woodland: mixed hardwood-pine, oak parkland
Piedmont Research Station, Salisbury, North Carolina	35.69	80.61	Ultic Hapludalfs (5), Rhodic Kanhapludults (4), Fluvaquentic Dystrudepts (3), Aquic Hapludults (2), Typic Hapludalfs (2)	Lloyd clay loam (4), Mecklenburg clay loam (4), Chewacla loam (3), Dorian fine sandy loam (2), Wynott-Enon complex (2), Enon fine sandy loam (1)	CT cropland: hemp (*Cannabis sativa*), tomato (*Solanum lycopersicum*), squash, eggplant (*Solanum melongena* L.), watermelon, corn, soybean, wheat, peanut, cotton, winter cover crops

Continued

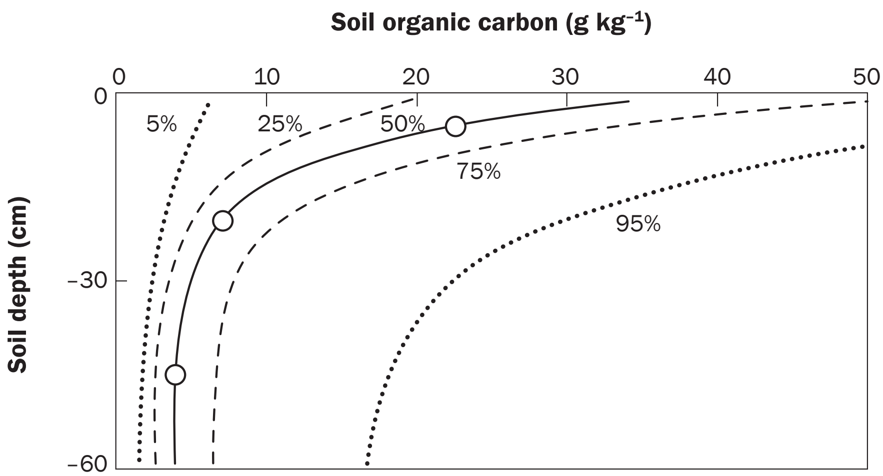
Table 1 continued
Location, soil, and management characteristics of 25 research stations sampled in North Carolina.

Location	Latitude (°N)	Longitude (°W)	USDA soil taxonomy (number of fields)	Soil series (number of fields)	Management characteristics
					NT cropland: corn, soybean, fescue, Christmas trees since >20 years Grassland: mowed tall fescue-bermudagrass-ryegrass Woodland: mixed hardwood
Upper Piedmont Research Station, Reidsville, North Carolina	36.39	79.70	Typic Hapludults (9), Typic Kanhapludults (3)	Rhodhiss sandy loam (6), Casville sandy loam (3), Clifford sandy clay loam (3)	NT cropland: corn silage for 10 years Grassland: grazed and hayed tall fescue pasture Woodland: mixed hardwood
Southern Blue Ridge Major Land Resource Area					
Upper Mountain Research Station, Laurel Springs, North Carolina	36.40	81.30	Typic Hapludults (7), Cumulic Humaquepts (4), Humic Dystrudepts (1)	Watauga loam (7), Toxaway loam (4), Tusquitee loam (1)	CT cropland: corn, tobacco, small grains Grassland: grazed and hayed tall fescue-orchardgrass
Mountain Horticultural Crops Research and Extension Center, Mills River, North Carolina	35.42	82.56	Typic Kanhapludults (8), Typic Hapludults (7), Typic Udifluvents (1)	Hayesville loam (8), Elsinboro loam (4), Bradson gravelly loam (3) ,Comus (colvard) fine sandy loam (1)	CT cropland: corn, soybean NT cropland: corn, soybean, rye cover crop since three to five years Grassland: mowed bluegrass (*Poa pratensis*)-tall fescue mixture Woodland: mixed hardwood
Mountain Research Station, Waynesville, North Carolina	35.48	82.97	Typic Hapludults (10), Fluvaquentic Humudepts (2)	Evard-Cowee complex (5), Braddock clay loam (4), Cullowhee-Nikwasi complex (2), Fannin loam (1)	CT cropland: tobacco, tomato, pumpkin (*Cucurbita pepo* L.), silage corn, forage sorghum with winter cover crops Grassland: grazed tall fescue-orchardgrass pasture Woodland: mixed hardwood

Notes: CT = conventional-till. NT = no-till.

When a more structured analysis was undertaken that used research station location and field replicate within a location as blocking criteria, then SOC was significantly greater (1) under conservation land uses than cropland at all depths, (2) under no-till than conventional-till cropland at 0 to 10 cm depth, and (3) under woodland than grassland at 0 to 10 cm depth (table 2). This analysis revealed that SOC concentration differences among land uses were most intensive near the surface and diminished greatly with increasing soil depth. In fact, the lack of difference in SOC at 30 to 60 cm depth between no-till and conventional-till cropland was consistent with most literature comparing deep SOC concentrations and stocks (Franzluebbers 2021a). The lack of difference in SOC concentration at 30 to 60 cm depth between woodland and grassland might be surprising, based on expectations of differences in root development and major differences in aboveground canopy structure. However, in a review of literature from other regions, there was no significant difference in SOC concentration between paired sites of conventional-till cropland and woodland and between conventional-till cropland and grassland at 30 cm depth (Franzluebbers 2022). Not all land uses summarized in table 2 were present at each location, so the significant difference in SOC concentration at lower depths was curious. There were 4 of 25 research station locations that had a significant land use effect on SOC concentration at 30 to 60 cm depth. Two of those were for greater concentration with woodland than with other land uses, one was for greater concentration with no-till cropland, and one was for lower concentration with no-till cropland than other land uses. The survey nature of this study didn't always allow exact soil type matches among land uses. It is argued that based on the preponderance of evidence presented here and that from the literature (Franzluebbers 2022), SOC concentration at 30 cm and deeper should not be considered affected by contemporary management, if given similar initial conditions. On the other hand, with centuries of timber growth and periodic harvest, it is possible that SOC concentration under woodland could be greater than with other land uses. This historical management effect should be considered relatively small and inconsequential within a reasonable period of one to two human generations of management. The fact that SOC and TSN concentrations at 30 to 60 cm depth under grassland were similar to that under woodland would suggest that centuries-old land use of woodlands compared with less than a century of grassland management (at least likely in most cases) was not the primary reason for occasional differences, but rather more likely due to pedogenic factors based on field position.

Figure 3
Statistical limits of soil organic carbon distribution by depth across 310 fields in North Carolina.



Surface residue C and N contents were significantly greater under conservation land uses (grassland and woodland) than under cropping (table 2). This was an expected result based on the intensive deposition of surface litter in perennial land-use systems compared with annual cropping systems. Surface residue C and N contents were also significantly greater with no-till than with conventional-till cropping, which was consistent with results obtained from private farms using conventional and conservation tillage in North Carolina (Franzluebbers 2021c). Surface residue N content of 121 kg N ha^{-1} under no-till cropping compared with only 43 kg N ha^{-1} under conventional-till cropping may be one reason that long-term conservation cropping systems can supply a greater quantity of readily mineralizable N to subsequent crops and to reduce overall N fertilizer required (Franzluebbers 2020). Although this shift in soil N availability has not been adequately characterized regarding nitrous oxide (N_2O) emissions, it may be another mechanism to reduce net greenhouse gas emissions from conservation cropping systems if fertilizer N input could be reduced by relying more on internal soil N cycling.

Surface residue N was greater under woodland than under grassland, mostly due to the greater mass of residues that accumulated in woodland than grassland sites (table 2). However, total surface N (residue + soil at 0 to 10 cm depth) was greater under grassland than woodland due to the greater content of TSN in surface soil. Although N fertilization of grasslands occurred at some locations, it was not a universal practice. Fertilization could have allowed some inorganic N to be incorporated into stable soil organic matter, whereas it seemed to have been limited in most woodland sites. Total surface C:N ratio was greater under woodlands (21.9 ± 5.3) than under all other land uses (14.9 ± 4.1). Surface residue quality of woodlands may have been a limiting factor for decomposition, but this same feature might also be one reason for greater SOC content near the surface.

Soil Bulk Density. Density of surface soil (0 to 10 cm depth) was significantly affected by land use when accounting for variations among locations and replicates. Across all locations, soil bulk density was greatest with conventional-till cropland (1.41 ± 0.01 Mg m^{-3}; mean ± standard error) and lowest with woodland (0.98 ± 0.01 Mg m^{-3}). Cropland had greater ($p < 0.001$) bulk density than under conservation land uses. Bulk density

Table 2
Soil organic carbon (SOC) and total soil nitrogen (TSN) concentrations, surface residue C and N, and total surface C and N (surface residue + soil at 0 to 10 cm depth) as affected by land use across 25 research stations in North Carolina (*n* = 88 for conventional-till [CT] cropland, *n* = 40 for no-till [NT] cropland, *n* = 98 for grassland, and *n* = 84 for woodland).

	SOC (g kg⁻¹)			TSN (g kg⁻¹)			Surface C (Mg C ha⁻¹)			Surface N (Mg N ha⁻¹)		
Land use	0 to 10 cm	10 to 30 cm	30 to 60 cm	0 to 10 cm	10 to 30 cm	30 to 60 cm	Surface residue	Soil in 0 to 10 cm	Total surface	Surface residue	Soil in 0 to 10 cm	Total surface
CT cropland	14.5	9.7	5.8	0.90	0.59	0.40	1.4	18.7	20.2	0.04	1.21	1.26
NT cropland	19.8	8.8	5.7	1.39	0.53	0.39	3.5	25.4	28.9	0.12	1.83	1.95
Grassland	28.3	11.9	7.2	2.07	0.65	0.43	4.5	32.9	37.4	0.17	2.43	2.61
Woodland	42.9	13.4	7.2	2.18	0.61	0.37	12.6	39.4	52.0	0.33	1.99	2.32
Analysis of variance	**Pr > F**											
Cropping vs. conservation	<0.001	<0.001	0.02	<0.001	0.07	0.90	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
CT vs. NT cropping	0.04	0.58	0.91	<0.001	0.44	0.76	0.05	0.001	<0.001	0.009	<0.001	<0.001
Grassland vs. woodland	<0.001	0.17	0.96	0.29	0.49	0.12	<0.001	<0.001	<0.001	<0.001	<0.001	0.001

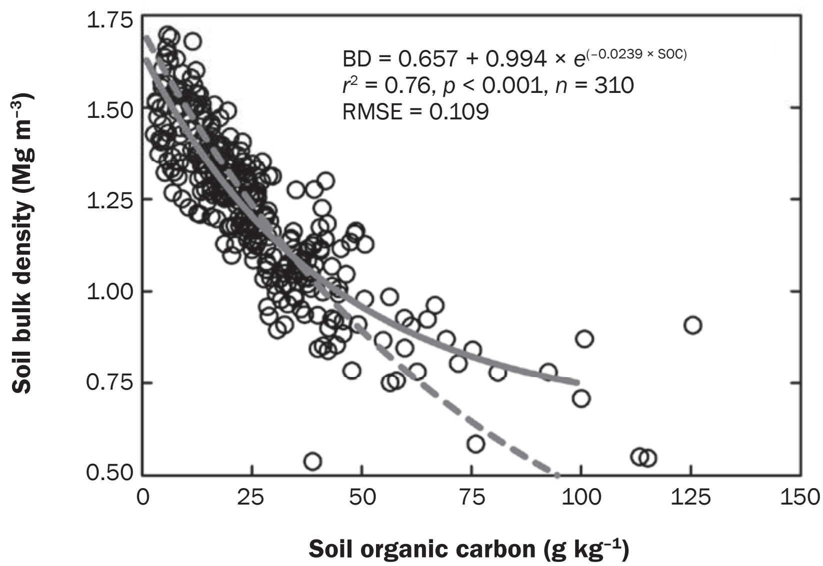
under no-till cropland (1.37 ± 0.02 Mg m^{-3}) was trending (p = 0.06) lower than under conventional-till cropland. Bulk density under grassland (1.22 ± 0.01 Mg m^{-3}) was greater (p < 0.001) than under woodland. Three quarters of the variation in soil bulk density could be explained by SOC alone (figure 4). Since organic matter is lighter than mineral soil particles, an increase in SOC leads to a decline in soil bulk density. This type of association has been found across soils with diverse pedogenic origin (Manrique and Jones 1991; Benites et al. 2007) and from similar soils with different management (Franzluebbers 2010). This inverse relationship is also a fundamental reason why soil bulk density is critically needed for assessment of SOC stocks from different land uses and sampling depths.

The depth distribution method of calculating root-zone enrichment of SOC accounts for the nonlinear association between SOC concentration and bulk density. The pedotransfer function to estimate bulk density from the concentration of SOC resulted in a similar, but slightly more variable fit against field measurements of bulk density. Root mean square error of the pedotransfer function described in the methods was 0.134 Mg m^{-3} against all measured bulk density values. With removal of four extreme deviations (three from the Ideal Farm in the Flatwoods and one from the Piedmont Research Station), root mean square error was reduced to 0.116 Mg m^{-3} against measured bulk density values. This value was close to the measured association shown in figure 4 of 0.109 Mg m^{-3}. In both cases, available evidence suggests that bulk density could be reasonably estimated from SOC concentration. This was especially critical with large differences in SOC concentration within a soil profile and among land uses. The upper limit of bulk density estimation was either 1.66 Mg m^{-3} with the association in figure 4 or 1.71 Mg m^{-3} with the pedotransfer function, both of which seem to be reasonable for soils in the southeastern United States (Franzluebbers 2010).

Predicted bulk density from the pedotransfer function reported in the methods was highly associated with measured bulk density from the surface 10 cm of soil (figure 5). This association further supports the use of the pedotransfer function for predicting bulk density from SOC concentration, particularly for those deeper samples that could not be estimated alone using the drill auger.

Figure 4

Association of soil bulk density (BD) from 0 to 10 cm depth with soil organic carbon (SOC) from 0 to 10 cm depth across 310 fields in North Carolina. The solid regression line represents data and equation noted in the figure. The dashed line represents the pedotransfer function used for calculation of total, baseline, and root-zone enrichment stocks of SOC.



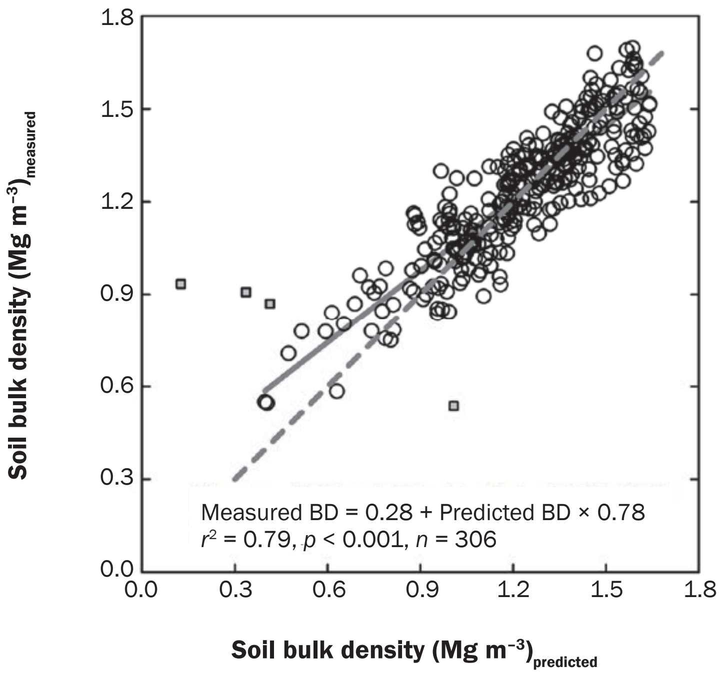
Stocks of Soil Organic Carbon and Total Soil Nitrogen. Stock of SOC at a depth of 0 to 30 cm varied from 21.0 to 112.3 Mg C ha^{-1} across all research station locations and fields (5% to 95% range). Of all variation, 48% could be attributed to specific research station location, 24% could be attributed to land use within each location, and 28% to random variation among fields within a land use. Therefore, as expected, location as a reflection of inherent pedogenic factors and climate conditions was a significant determinant of the stock of SOC that was achieved. Aggregation of locations by physiographic region (Flatwoods, Coastal Plain, Piedmont, and Blue Ridge) explained only 20% of total variation, so each specific location within a physiographic region had a large influence on SOC stock (table S1). Variation in TSN was distributed as 17% due to physiographic region, 36% due to specific research station location, 16% due to land use, and 31% due to random variation among fields within a land use. Specific soil type sampled within a location was also a factor at some locations, as exemplified by the large variation in stock of SOC among replicates and land uses at the Lower Coastal Plain Research Station in Kinston, North Carolina (table 3), as a result of the location intertwined with both the Coastal Plain and Flatwoods regions. However, consistency of land use effect on stock of SOC occurred irrespective of soil type.

The effect of physiographic region on SOC and TSN stocks was likely a combination of elevation, climatic conditions, and soil mineralogy. Soil organic C stock to 30 cm depth was 78.8 ± 2.2 Mg C ha^{-1} (mean ± standard error) in the Flatwoods, 51.4 ± 1.6 Mg C ha^{-1} in the Coastal Plain, 47.4 ± 1.6 Mg C ha^{-1} in the Piedmont, and 70.2 ± 2.5 Mg C ha^{-1} in the Blue Ridge. Total soil N to 30 cm depth was 3.81 ± 0.13 Mg N ha^{-1} in the Flatwoods, 3.31 ± 0.10 Mg N ha^{-1} in the Coastal Plain, 3.42 ± 0.10 Mg N ha^{-1} in the Piedmont, and 5.34 ± 0.15 Mg N ha^{-1} in the Blue Ridge.

Stocks of SOC and TSN were significantly (p < 0.01) affected by soil texture. Sand concentration was the most dominant component of the textural effect, as this reflected the combined effects of both clay and silt concentrations (i.e., inverse relationship with sand concentration). Most SOC and TSN fractions were negatively associated with sand concentration, which was expected based on previous literature (Konen et al. 2003; Galantini et al. 2004; Zinn et al. 2007). Although there were absolute differences in SOC and TSN stocks between land use systems (table 4), the change in total, baseline, and root-zone enrichment stocks of SOC and

Figure 5

Association of soil bulk density (BD) measured from 0 to 10 cm depth and that predicted from the pedotransfer function [i.e., BD = 1.71 $e^{(-0.013 \times SOC)}$] across 310 fields in North Carolina. The solid line represents the regression, excluding four outliers shown as gray-filled squares. The dashed line represents a 1:1 association that could be expected.



TSN with increasing sand concentration was not altered by land use system. There were a couple of trends, though, in which (1) total stock of TSN increased more (p = 0.02) under grasslands than under woodlands with greater clay + silt concentration, and (2) root-zone enrichment of TSN increased more (p = 0.03) under no-till cropland than under conventional-till cropland with greater clay + silt concentration. These results indicate that soil texture had a strong influence on absolute SOC and TSN stocks, but relative differences in SOC and TSN stocks between land uses were maintained independent of soil texture. Some studies have provided evidence that coarse-textured soils may be more responsive to conservation management than fine-textured soils (Franzluebbers and Arshad 1996; Dieckow et al. 2009), but data in the current study did not support this interaction between soil texture and conservation management.

Averaged across locations and adjusted for differences in sand concentration since not all land uses were present at each location, stocks of SOC and TSN were variably affected by land use management (table 4). Conservation land uses (grassland and woodland) were clearly greater in stock of SOC and TSN than compared with cropland. Total stock of SOC was not different between no-till cropland and conventional-till cropland, but stock of TSN was greater with no-till than with conventional-till cropland. Total stock of SOC was greater under woodland than under grassland, but stock of TSN was lower under woodland than under grassland. These results illustrate the strong positive effect of conservation land use on accumulation of SOC and TSN, which is consistent with a growing body of literature comparing land use systems around the world (Pulleman et al. 2000; Celik 2005; Guimarães et al. 2013; Zhou et al. 2019). Marginal to significantly greater stocks of SOC and TSN under no-till cropland than under conventional-till cropland is consistent with many of the variable results on this topic (Angers and Eriksen-Hamel 2008; Franzluebbers 2010; Luo et al. 2010). The greater stock of SOC with woodland than with grassland, but lower stock of TSN with woodland than with grassland was a curious result. Both similar and greater quantities of SOC have been reported for woodland compared with grassland ecosystems (Franzluebbers 2005; Don et al. 2011), but the reversal of effects between C and N has not been a common occurrence. This result illustrates the need to quantify C and N resource inputs in conservation management systems to understand the implications for long-term soil changes.

Separation of stocks into baseline and root-zone enrichment fractions was also important in the interpretation of results. Across all locations, total stock of SOC was more closely associated with baseline stock of SOC (r = 0.84, p < 0.001, n = 310) than it was with root-zone enrichment of SOC (r = 0.39, p < 0.001). A similar difference in association occurred between total stock of soil N and baseline stock of soil N (r = 0.81, p < 0.001), whereas the association between total stock of soil N and root-zone enrichment of soil N was negative (r = –0.23, p < 0.001). Baseline stock of SOC varied from 38% to 66% of total SOC stock (interquartile range), and baseline TSN varied similarly from 40% to 67%.

Root-Zone Enrichment of Soil Organic Carbon and Total Soil Nitrogen. Separation of root-zone enrichment of SOC and TSN from that of baseline SOC and TSN should be considered an important step necessary to estimate the influence of contemporary conservation

Table 3

Example of variation in stock of soil organic carbon (C, Mg C ha⁻¹) at 0 to 30 cm by land use management and soil type blocked within a replicate at the Lower Coastal Plain Research Station in Kinston, North Carolina.

Soil series (replication)	Conventional-till cropland	Grassland	Woodland	Block mean
Norfolk loamy sand (1)	17.1	58.2	65.6	47.0
Norfolk loamy sand (2)	26.3	48.3	53.2	42.6
Rains sandy loam (3)	51.5	105.5	120.3	92.5
Goldsboro loamy sand/ Norfolk loamy sand (4)	29.6	57.7	69.6	52.3
Land use mean	31.1	67.4	77.2	58.6 ± 30.1

Table 4

Mean stocks (0 to 30 cm depth) and analysis of variance of soil organic carbon (SOC) and total soil nitrogen (TSN) fractions (total, baseline, and root-zone enrichment) as affected by land use and adjusted for covariance with sand concentration across 25 locations in North Carolina.

	SOC (Mg C ha^{-1})			TSN (Mg N ha^{-1})		
Land use	**Total stock**	**Baseline stock**	**Root-zone enrichment**	**Total stock**	**Baseline stock**	**Root-zone enrichment**
Conventional-till (CT) cropland	44.5	33.4	11.1	2.98	2.20	0.78
No-till (NT) cropland	48.7	27.2	21.5	3.48	1.80	1.68
Grassland	64.7	35.1	29.6	4.55	2.10	2.45
Woodland	74.4	35.8	38.6	3.80	1.79	2.01
Analysis of variance	**Pr > F**					
Location × replication	<0.001	<0.001	0.008	<0.001	<0.001	0.04
Cropping vs. conservation	<0.001	0.008	<0.001	<0.001	0.57	<0.001
CT vs. NT cropping	0.17	0.06	<0.001	0.005	0.01	<0.001
Grassland vs. woodland	<0.001	0.76	<0.001	<0.001	0.01	<0.001
Sand concentration	<0.001	<0.001	0.39	<0.001	<0.001	0.15

management on SOC change. Frequency distributions of SOC fractions illustrate this importance, wherein total stock of SOC within the surface 30 cm had some degree of separation among land uses, although mostly in the lower quartiles of distribution (figure 6). When baseline stock of SOC within the surface 30 cm was separated from the total stock, there was convergence of land uses to a similar frequency distribution. This reflects the dominant influence of pedogenic SOC to this fraction, which varied among research station locations and can be assumed little affected by contemporary management. Calculation of root-zone enrichment of SOC resulted in the strongest separation of land uses, further supporting the concept that contemporary management is the primary factor affecting this fraction of SOC.

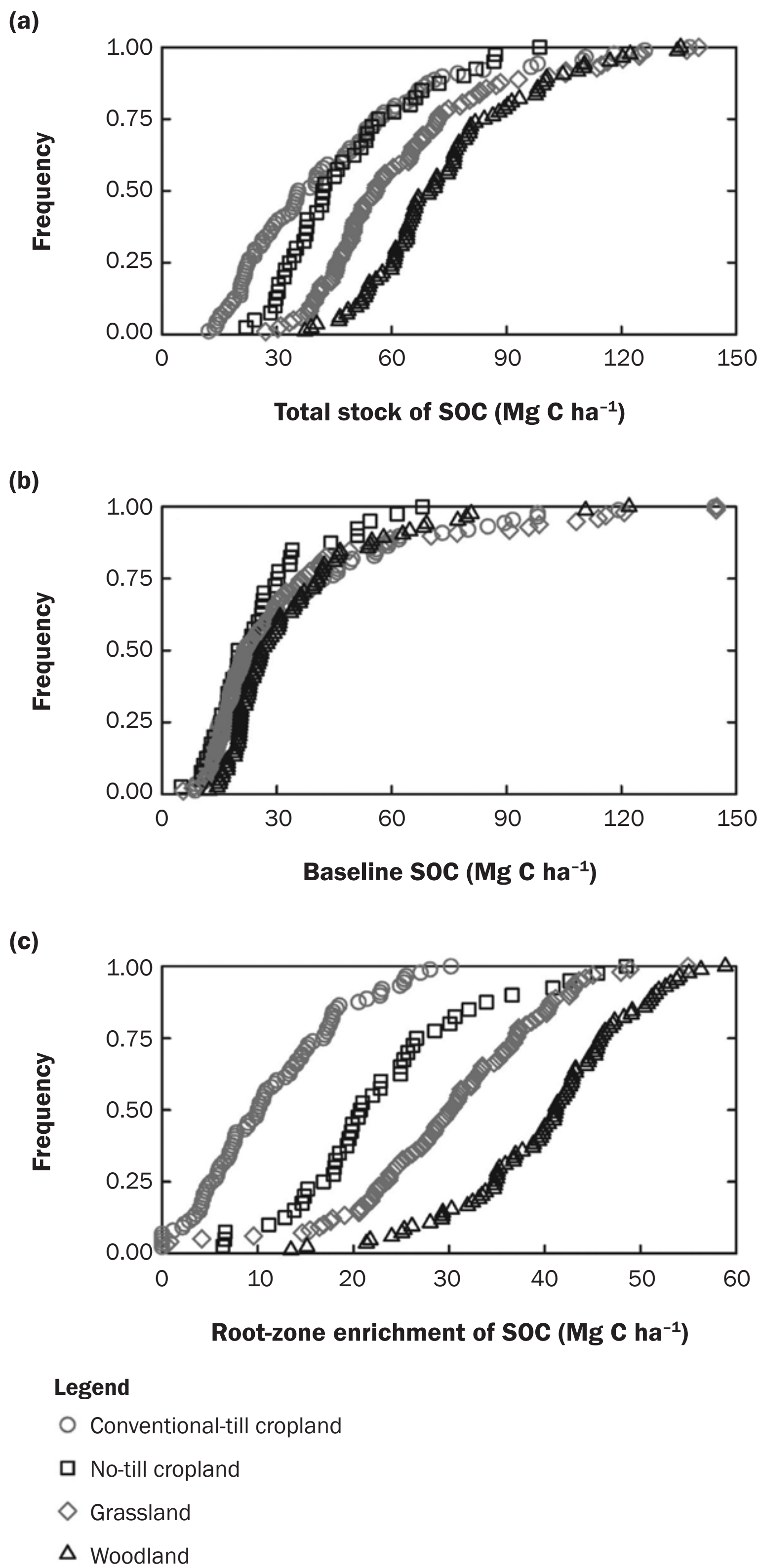
Total stock of SOC at 0 to 30 cm depth was significantly affected by land use management at 16 of the 25 research station locations. Whenever differences occurred, they followed the trends in total SOC stock by land use shown in table 4. This analysis would suggest that paired land use sampling effectively detected significant differences in total SOC stock in 64% of cases. However, the covarying influence of baseline SOC stock with minor differences among pedons could mask the true effect of historical land use on SOC accumulation. Baseline stock of SOC was significantly affected by land use at only 2 of the 25 research station locations. Differences were observed at (1) the Upper Coastal Plain Research Station in Rocky Mount, North Carolina, where baseline SOC stock was elevated under no-till cropland than all other land uses; and (2) the Williamsdale Biofuel Field Lab in Wallace, North Carolina, where baseline SOC stock was lower under woodland than under conventional-till cropland and grassland. Both differences were counter-intuitive to trends in the literature of how land use might affect SOC stock. The lack of difference among land uses within a location suggests that the baseline stock of SOC did not vary as a function of management, but rather as a function of pedogenic origin. By separating out the influence of baseline SOC stock from total stock of SOC, root-zone enrichment of SOC stock was significantly affected by land use at 21 of 25 research station locations. Thus, the root-zone enrichment calculation method was able to detect significant differences in SOC accumulation by land use in 84% of cases rather than 64% of cases as with the traditional paired land use approach. The root-zone enrichment calculation method detected differences in TSN by land use in 72% of cases, while the traditional paired land use approach detected differences in 60% of cases.

Root-zone enrichment of TSN yielded land use trends that were like those of SOC (table 4), except for the difference in the comparison between grassland and woodland. Root-zone enrichment of TSN was greater under grassland than under woodland, whereas root-zone enrichment of SOC was significantly lower under grassland than under woodland. The effective C:N ratio of the root-zone enrichment fraction was lower under grassland (12.1 ± 4.7) than under woodland (20.2 ± 7.2), indicating that grassland systems were more N enriched, either with external N fertilizer inputs or recycling of higher quality residues than in woodland systems that may often be N limited without N fertilizer inputs and periodic extraction with timber harvest. Greater soil C:N ratio under woodland than under grassland is consistent with other observations (Franzluebbers and Stuedemann 2002; Banerjee et al. 2016), because of differences in nutrient dynamics within these different plant communities that ultimately affect litter and root nutrient qualities (Zhou et al. 2018).

The practice of no-till cropping on 10 of the 25 research stations was for as little as three years since management change at two of the locations and as long as 35 years at two other locations. Duration was 16 ± 12 years. There was no relationship between no-till cropland duration and root-zone enrichment of SOC or TSN. As with many farming operations, there were likely some confounding management factors on these research station fields that caused unintended variations. It must be noted that

Figure 6

Cumulative frequency distribution of soil organic carbon (SOC) stocks (0 to 30 cm depth) separated by land use (conventional-till cropland, no-till cropland, grassland, and woodland) into (a) total stock, (b) baseline stock, and (c) root-zone enrichment.



the intent of this study was not to create a chronosequence of management, but simply to survey conditions that were present on these research stations with some reasonable description of management.

Grasslands were mostly mowed fields and areas around station buildings. Only 7 of the 25 research stations had grazed/hayed fields that were sampled, since pasture-based livestock production was not an emphasis on many of these research stations. Therefore, results may not be directly applicable to ruminant-grazed pastures typical of the region. When comparing the 7 grazed/hayed locations with those of the 18 mowed grassland locations, root-zone enrichment of SOC tended to be greater (p = 0.06) with grazing/haying (32.8 Mg C ha^{-1}) than with mowing (28.0 Mg C ha^{-1}). However, the grass management effect was not significant (p = 0.25) when considering that grazed fields had greater clay + silt concentration than mowed fields. Root-zone enrichment of TSN was significantly greater ($p < 0.001$) with grazing/haying (2.99 Mg N ha^{-1}) than with mowing (2.21 Mg N ha^{-1}), and even when considering the covarying factor of clay + silt concentration (2.81 versus 2.28 Mg N ha^{-1}, respectively; p = 0.009). After accounting for soil texture differences, these effects were consistent with trends in total stock of SOC between sites with grazing/haying and mowing (67.2 versus 61.5 Mg C ha^{-1}, respectively; p = 0.32), in total stock of TSN (5.14 versus 4.20 Mg N ha^{-1}, respectively; $p < 0.001$), in measured stock of SOC at 0 to 10 cm (35.4 versus 31.7 Mg C ha^{-1}, respectively; p = 0.27), and in measured stock of TSN at 0 to 10 cm (2.87 versus 2.25 Mg N ha^{-1}, respectively; $p < 0.001$). An additional, more structured testing of grassland management with side-by-side comparisons within a location would build greater confidence in the interpretation of these results, but until then, these preliminary results suggest that managed grazing may provide additional SOC and TSN sequestration possibilities. It should be noted that mowing returns cut plant materials back to the soil for decomposition, unlike that of haying with removal of forage to be fed to livestock elsewhere on the farm or sold off the farm. Therefore, these results are unique from management comparisons of grazing versus haying often presented in the literature (Franzluebbers et al. 2012; Gilmullina et al. 2020).

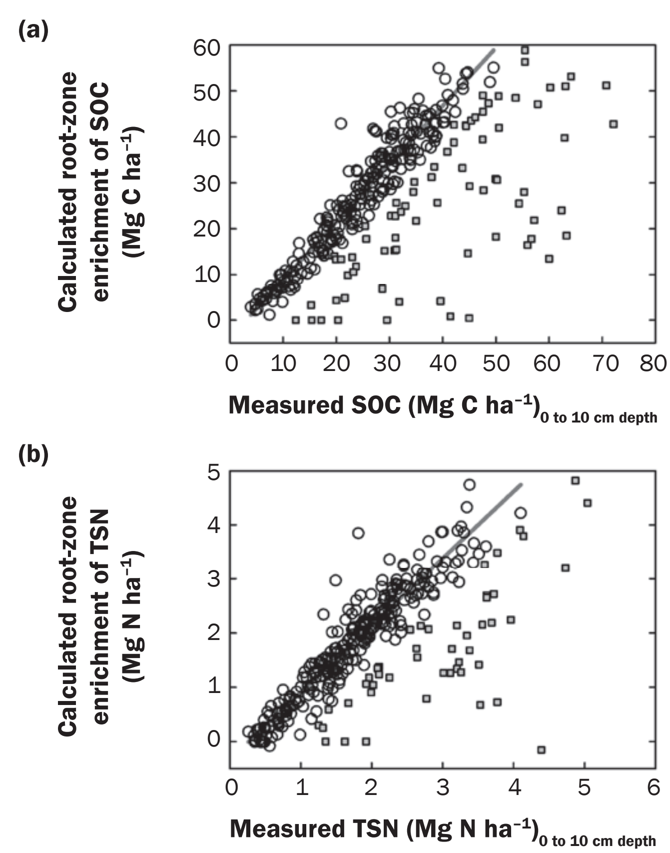
Comparing Calculation Approaches. Soil organic C and TSN contents of the surface 10 cm were determined from measured bulk density and SOC and TSN concentrations of surface samples. This was the most direct method of calculating the stocks of SOC and TSN undertaken in this study, but it was limited in its characterization of depth in the profile. With prediction of bulk density based on a pedotransfer function adjusted with SOC concentration, stocks of SOC and TSN could also be calculated at a 0 to 30 cm profile depth. An alternative calculation method was proposed based on depth distribution of SOC and TSN, such that baseline and root-zone enrichment fractions could be separated from total stocks of SOC and TSN. These three methods of calculating SOC and TSN had strong associations across all data (r = 0.51 ± 0.21, $p < 0.001$ for SOC estimates and r = 0.78 ± 0.08, $p < 0.001$ for TSN estimates), and especially when soils were of similar pedogenic nature. However, there were differences in SOC and TSN stock estimates when large differences in soil types were included in the analyses. These differences in soil types can occur on the same research station (or private farm), and therefore, some adjustments in approach may be needed to balance the needs for accuracy, human resource investment in the sampling process, simplicity, and expediency. The basis for this concern is presented below.

When plotting data of measured surface SOC stock (measured SOC concentration and measured bulk density from 0 to 10 cm depth) against calculated root-zone enrichment of SOC (fitted depth distribution from three measured SOC concentrations and bulk density estimated from the pedotransfer function), there was a strong linear association that emerged among most data, but wide distribution among a portion of the data set (figure 7). An initial estimate of the strong linear function was hypothesized as $y = -5 + 1.25x$ based on similarity of regressions from individual research locations. Deviations from this hypothetical regression were calculated for each point and residuals calculated and rank sorted. The largest positive deviations (25% of the population of SOC data and 15% of TSN data) from measured minus theoretical estimates were removed and analyzed separately for characterization. The remaining bulk of data (75% to 85% of total data set) showed that 89% to 92% of the variation in root-zone enrichment of SOC and TSN could be estimated with measured SOC and N in the surface 10 cm. This result suggests that sampling of surface soil (0 to 10 cm) with simultaneous determination of bulk density using a 4 cm diameter coring device at multiple random locations within a field would be a reasonable approach to attain most information needed to estimate SOC storage trajectory. The outlying 15% to 25% of data needs to be understood as to how and why they occurred.

Outlying data in figure 7 were spread across the range of root-zone enrichment levels and could be seen as more skewed toward higher measured SOC and TSN levels. This raises the concern that measured SOC and TSN may not portray accurately the true management-induced change in SOC components but may also include some inherent qualities of soil based on pedogenic origin. From the outlying data set, root-zone enrichment of SOC was strongly negatively correlated with baseline stock of SOC, i.e., of pedogenic origin ($r = -0.57$, $p < 0.001$, n = 78). A similar negative correlation occurred for outlying data of root-zone enrichment of TSN with baseline stock of TSN ($r = -0.48$, $p < 0.001$, n = 47). Baseline stock of SOC in the outlying data set was strongly positively associated with total stock of SOC at 0 to 30 cm depth (r = 0.80, $p < 0.001$) and measured SOC content at 0 to 10 cm depth (r = 0.53, $p < 0.001$). Baseline stock of SOC was greater in the outlying data set than the majority data set (64.3 ± 30.0 versus 22.1 ± 9.2 Mg C ha^{-1}, $p < 0.001$). This led to greater total

Figure 7

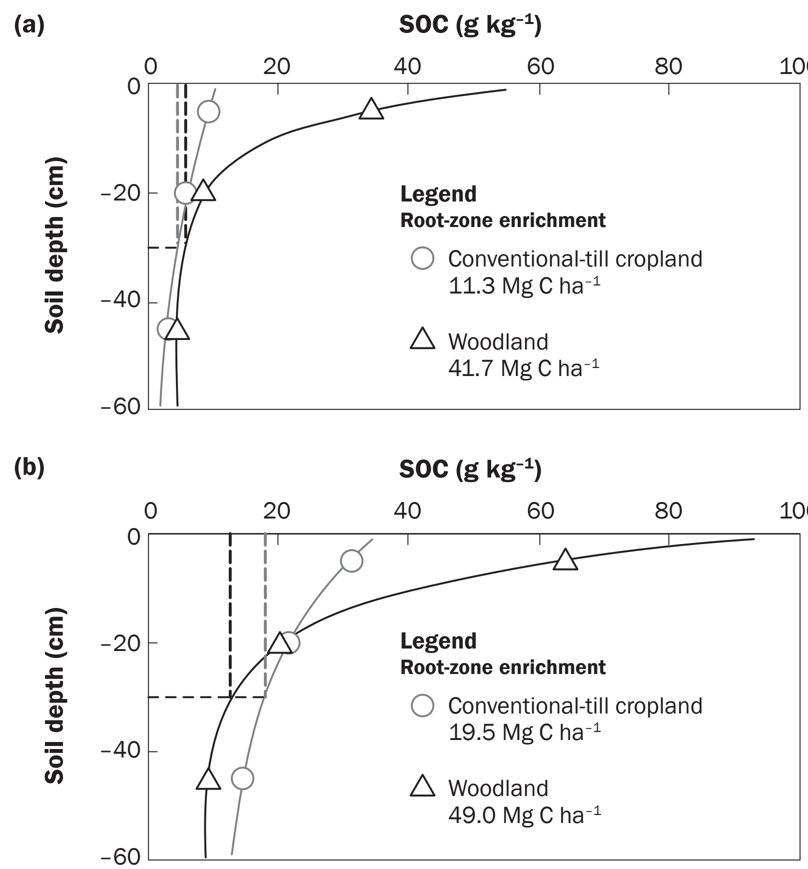
Calculated root-zone enrichment of soil organic carbon (SOC) and total soil nitrogen (TSN) (0 to 30 cm depth) in association with measured SOC and TSN in the surface 0 to 10 cm across all 310 fields from 25 research stations in North Carolina. Note: regression line for SOC in top panel is for 75% of data (open circles) and excludes 25% of deviations (filled squares). The same approach was used for TSN in the bottom panel, excluding only 15% of data. Regression line in top panel is $y = -3.8 + 1.26x$ (r^2 = 0.92, n = 232, $p < 0.001$). Regression line in bottom panel is $y = -0.33 + 1.24x$ (r^2 = 0.89, n = 263, $p < 0.001$).



stock of SOC in the outlying than majority data sets (88.3 ± 24.6 versus 49.1 ± 18.9 Mg C ha^{-1}, $p < 0.001$), despite no difference in root-zone enrichment of SOC between these data sets (24.1 ± 18.1 versus 27.0 ± 13.5 Mg C ha^{-1}, $p = 0.19$). The implications of these differences in baseline SOC stocks are illustrated in figure 8, in which baseline stock of SOC determines the relative contribution of surface SOC concentration to the calculation of root-zone enrichment. Soils with low baseline SOC may have equal opportunity to accumulate SOC as soils with high baseline SOC. However, comparing only the concentration of SOC at the surface without knowing the baseline condition could lead to errors in estimation of potential SOC change. If an approach with limited number of fields sampled does not estimate this internal baseline condition, then repeated sampling over time will be necessary to know if true accumulation might be occurring or if pedogenic conditions are simply different between fields. An alternative might be to sample many fields with similar management of interest against control fields to obtain paired comparisons, but large variation caused by different pedogenic conditions can lead to insensitivity in detection of potential differences.

Figure 8

Depth distribution of soil organic carbon (SOC) from conventional-till cropland and woodland when data were separated into (a) majority (75%) and (b) outlying (25%) sets from 25 research stations in North Carolina. Dashed lines indicate the baseline SOC concentration at 30 cm depth projected to the surface. Nonlinear regressions were fitted to mean SOC concentrations and used to calculate root-zone enrichment of SOC.



With the example data in figure 8, stocks of SOC at 0 to 10 cm depth (SOC and bulk density measured) and at 0 to 30 cm depth (SOC measured and bulk density estimated) were considerably greater (29.4 ± 9.5 Mg C ha^{-1}) in the outlying data set than the majority data set. Root-zone enrichment calculations resulted in a difference of only 7.8 ± 0.5 Mg C ha^{-1}. Land use comparison was the same within each data set, so smaller influence of research station location could have been expected. The difference in SOC accumulation between woodland and conventional-till cropland in this split data set was 19.1 ± 1.1 Mg C ha^{-1} using measured SOC contents at 0 to 10 cm depth, 28.3 ± 7.0 Mg C ha^{-1} using calculated SOC stocks at 0 to 30 cm depth, and 30.0 ± 0.5 Mg C ha^{-1} using the root-zone enrichment calculation method. All three methods were reflective of the large difference in SOC storage between these extremes in land use. One large advantage of using root-zone enrichment is that land use comparisons are not actually necessary, because the internal baseline condition is calculated independently for each soil profile. Root-zone enrichment calculations in figure 8 and in other land use comparisons (Franzluebbers 2021d, 2022) support the independent use of this calculation method rather than necessitating land use comparisons or repeated sampling over time in more traditional approaches.

The outlying data set (n = 78) contained at least one sample from 18 of the 25 research station locations. The most samples were from the Tidewater Research Station in Plymouth, North Carolina (16), Ideal Farm in Castle Hayne, North Carolina (8), Lake Wheeler Road Field Lab in Raleigh, North Carolina (7), Caswell Research Farm in Kinston, North Carolina (6), Williamsdale Biofuel Lab in Wallace, North Carolina (6), and Upper Mountain Research Station in Laurel Springs, North Carolina (6). Several of these research stations were in the Flatwoods region. Most of these sites had an aquic characteristic in its soil taxonomical description (58 of 78 sites). Soil organic C concentration at 30 cm depth in this outlying data set varied widely (17.7 ± 14.3 g kg^{-1}), while the majority data set had a small and relatively narrow range of SOC concentration at 30 cm depth (4.6 ± 2.1 g kg^{-1}). The pattern was similar with TSN concentration at 30 cm depth, but not as variable in the outlying data set (1.09 ± 0.43 g kg^{-1}) relative to that of the majority data set (0.35 ± 0.15 g kg^{-1}). Less variation in baseline TSN may have been a reason for fewer observations deviating from the majority relationship. Nearly half of the sites would have been organic enriched from pedogenic processes, as 34 of the 78 soil taxonomical descriptions included the terms "humic," "umbric," "spodic," or "saprists." In early development of the root-zone enrichment concept, it was noted that spodosols may be one soil order not well suited for fitting of the nonlinear regression function to soil-profile data (Franzluebbers 2013). Fitting of the nonlinear function to soil-profile SOC and TSN concentrations was excellent overall. Only 7% of the profiles had a correlation coefficient of <0.9 for SOC and 10% for TSN. Most of the poorer fits occurred with conventional-till cropland, wherein the mechanical redistribution process of tillage likely created strong discontinuities in SOC and TSN. Also, some tilled soil profiles have nearly uniform depth distribution that naturally causes low correlation coefficient. Correlation coefficient for fitting of SOC was 0.88 ± 0.27 under conventional-till cropland and 0.98 ± 0.12 in all other land uses. Correlation coefficient of TSN was 0.82 ± 0.35 in conventional-till cropland and 0.98 ± 0.08 in all other land uses.

Available evidence suggested that the root-zone enrichment calculation method was the most suitable approach to determine the management-induced, profile contents of SOC and TSN. This approach requires that at least three soil depths be measured for determination of SOC and TSN concentrations, and that soil bulk density can be reasonably estimated from SOC concentration. The pedotransfer function used in this study in North Carolina was derived from soil data collected in Georgia. Estimation of bulk density from this pedotransfer function appeared to be equally effective in soils from outside the southeastern United States as well (Franzluebbers 2022).

Summary and Conclusions

In the warm, humid region of the southeastern United States, SOC and TSN are highly concentrated near the soil surface, especially under conservation management that includes woodland, grassland, and no-till cropland. Across 25 research station locations distributed throughout North Carolina, measured stocks of SOC in the surface 10 cm followed the order of conventional-till cropland (18.7 Mg C ha^{-1}) < no-till cropland (25.4 Mg C ha^{-1}) < grassland (32.9 Mg C ha^{-1}) < woodland (39.4 Mg C ha^{-1}). By including surface residue C content along with surface soil C content, land use effects were amplified and followed the same order of significance: conventional-till cropland (20.2 Mg C ha^{-1}) < no-till cropland (28.9 Mg C ha^{-1}) < grassland (37.4 Mg C ha^{-1}) < woodland (52.0 Mg C ha^{-1}). Increasing clay + silt concentration increased the stock of SOC and TSN but did not alter land use effects. Root-zone enrichment of SOC and TSN in the 0 to 30 cm depth was calculated to distinguish management effects from pedogenic effects on baseline soil condition. This resulted in even greater management effects that were magnified among land uses, with root-zone enrichment of SOC following the order of conventional-till cropland (10.9 Mg C ha^{-1}) < no-till cropland (21.5 Mg C ha^{-1}) < grassland (29.5 Mg C ha^{-1}) < woodland (38.8 Mg C ha^{-1}). Root-zone enrichment of TSN in the 0 to 30 cm depth followed a slightly different order: conventional-till cropland (0.75 Mg N ha^{-1}) < no-till cropland (1.69 Mg N ha^{-1}) < woodland (2.03 Mg N ha^{-1}) < grassland (2.43 Mg N ha^{-1}). Lack of N fertilization and lower leaf litter quality in woodlands appeared to limit TSN accumulation relative to that of grasslands. These results across a diversity of physiographic regions and soil types in North Carolina exemplify the strong and consistent nature of conservation agricultural management on the potential to store SOC and TSN. These land use effects suggest that conservation cropping with the use of no-till management, managed grazing with pasture-based livestock production, pasture-crop rotation with either hay in the rotation of cropping systems or periodic pastures rotated with cropland, and silvopasture or alley cropping may all have strong relevance and potential for increasing SOC and TSN storage in the southeastern United States. More research will be needed to understand the fine-tuned nature of these mixed agricultural systems, but it is clear from the current study that conservation land uses of no-till cropland, grassland, and woodland can bolster SOC and TSN in the primary root zone, i.e., 0 to 30 cm depth.

Supplemental Material

The supplementary material for this article is available in the online journal at https://doi.org/10.2489/jswc.2023.00064.

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