SOIL ORGANIC CARBON DYNAMICS UNDER CONSERVATION AGRICULTURAL SYSTEMS

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Abstract

Soil organic carbon (SOC) is a key element in the valuation of natural resources and the evaluation of how management affects soil quality and ecosystem services derived from soil. This paper describes a summary of some recent research aimed at understanding how SOC contributes to (a) various soil properties and processes, (b) global cycling of carbon, and (c) support of various ecosystem services. Stratified SOC with depth under conservation agricultural approaches helps soil function to an optimum. Conservation management approaches focusing on minimizing soil disturbance, maximizing soil cover, and stimulating biological activity can be achieved with different cropping choices and production goals in different environments all around the world. In the southeastern USA, SOC sequestration was 0.30 + 0.05 Mg ha^{-1} yr^{-1} in no-tillage systems without cover crop and 0.55 + 0.06 Mg ha^{-1} yr^{-1} in no-tillage systems with cover crop, suggesting that greater C input with increasing cropping system complexity of no-tillage systems will be beneficial to SOC storage. The key to success for adoption of conservation agriculture will be to consider the agronomic, ecological, environmental, and economic constraints within a particular farm setting. On-going research continues to support the key contributions that enhanced SOC with conservation agricultural approaches can give to farmers and society.

Keywords: Ecosystem services; Integrated crop-livestock systems; No-tillage management; Pasture management; Soil organic matter

Soil Organic Carbon

Soil organic carbon (SOC) is a key factor in land valuation schemes, soil fertility and quality evaluation, and climate change investigations. The following text describing SOC was originally described in Franzluebbers [1]. Carbon is found in soil as organic matter and carbonate minerals (e.g. $CaCO_3$). Soil organic matter is an assorted mixture of organic compounds, having been processed over varying lengths of time by soil organisms. It may be living – plant roots, insects, fungi, protozoa, bacteria, etc. – or it may be dead, dying, or partially decayed. The most abundant constituent of soil organic matter is C (50-58% C), thus the congruence between SOC and soil organic matter. Living components of soil organic matter are rather small in percentage (<10%), but play enormously important roles in decomposition, nutrient cycling, plant root zone modification, soil structural manipulation, aggregate stabilization, and ecological resilience through underground biodiversity development. The living components of soil have been investigated only scantily compared with other components [2]. Non-living components of soil organic matter are categorized in different manners according to the complexity of compounds. A traditional approach has been through a fractionation scheme that first removes relatively large particles of organic matter (>50 µm) and water-soluble organic matter to yield humus. Humus can then be further subdivided into non-humic biopolymers (e.g. polysaccharides, sugars, proteins, amino acids, fats, waxes, other lipids, and lignin), humic acid (soluble in alkaline solution, but precipitate when acidified), fulvic acid (soluble in alkaline solution and remain soluble when acidified), and humin (insoluble in alkaline solution). Another approach for fractionation of soil organic matter has been based on decomposition rate, where at least three pools of organic matter are characterized on a continuum from readily decomposable to recalcitrant forms through laboratory or field incubations (active, slow, and passive) [3].

Global plant biomass captures ~110 Pg (10^{15} g) C yr^{-1} from the atmosphere through photosynthesis. Maintenance and decay of plants and animals occurs simultaneously and returns ~110 Pg C yr^{-1} as CO_2 to the atmosphere through autotrophic respiration (50 Pg C yr^{-1}) and heterotrophic respiration (60 Pg C yr^{-1}). Soil to a depth of 1 m stores about 1600 Pg of C in organic matter; an additional 700 Pg of C is stored in soil as carbonate minerals [4]. The atmosphere contains ~800 Pg of C as CO_2 and has been increasing in CO_2 concentration since the beginning of the 20th century. Estimates from the first decade of the 21st century indicate emissions of 7.7 Pg C yr^{-1} from burning of fossil fuels and 1.4 Pg C yr^{-1} from deforestation [4]. Sinks for this additional CO_2 in the atmosphere have been 2.3 Pg C yr^{-1} in the oceans and 2.7 Pg C yr^{-1} to land biomass, leaving behind 4.1 Pg C yr^{-1} accumulating in the atmosphere [4].

Assuming a global loss of 20% SOC (i.e. 400 Pg from an original level of 2000 Pg) via historical land clearing that caused erosion and oxidation of organic matter [5, 6], there is an enormous potential to recapture at least 400 Pg of SOC with technological innovations and restoration activities. Assuming that an aggressive global restoration could occur within the next century, nearly all of the current rate of CO_2 increase in the atmosphere (i.e. 4.1 Pg C yr^{-1}) could be mitigated through soil restoration (400 Pg C / 5 billon ha of agricultural land / 100 yr = mean soil organic carbon sequestration rate of 0.8 Mg C ha^{-1} yr^{-1}; certainly a tremendous goal, but also plausible!). Clearly the potential for soil restoration with SOC could have a major impact on the atmosphere; it is our collective willingness to achieve this goal that may be questioned. Obviously, the time required to fully restore SOC may be longer than a century and the rate of release of fossil fuel-derived CO_2 cannot be considered static. In addition, Lal [7, 8] more conservatively suggested that only 42-78 Pg of C might have been lost from soils worldwide, although estimates have varied from 44 to 537 Pg of C.

Relationship of SOC with Ecosystem Services

Soil organic C is a vital component of ecosystem properties, processes, and functions [1]. It has highly relevant physical, chemical, and biological features. This wide diversity of features has given SOC deserved attention as a key indicator of soil quality (i.e., how soil management affects the functioning of soil) [9].

Attributes of soil organic carbon that affect soil and ecosystem properties include:

Physical

- Color – the dark color of organic matter alters thermal properties, i.e. absorbing heat;
- Low solubility – ensures that organic matter inputs are retained and not rapidly leached from the soil profile;
- Water retention – directly helps to absorb several times its mass of water and indirectly retains water through its effect on pore geometry and soil structure; and
- Stabilization of soil structure – binding of mineral particles to form water-stable aggregates and improve water infiltration into the surface soil.

Chemical

- Cation exchange capacity – high charge enhances retention of nutrient cations, such as Al, Fe, Ca, Mg, NH_4;
- Buffering capacity and pH effects – avoids large swings in pH to keep acidity/alkalinity in more acceptable range for plants;
- Chelation of metals – complexation with metals to enhance dissolution of minerals, enhance availability of P, reduce losses of micronutrients, and reduce toxicity; and
- Interactions with xenobiotics – alter biodegradability, activity, and persistence of pesticides and other organic contaminants, such as antibiotics and endocrine disrupting chemicals.

Biological

- Reservoir of metabolic energy – energy embedded in organic molecules to drive biological proceses;
- Source of macronutrients – mineralization of organic matter releases N, P, S and other elements;
- Enzymatic activities – both enhancement and inhibition of enzymes are possible by various humic materials; and
- Ecosystem resilience – accumulation of soil organic matter can enhance the ability of an ecosystem to recover from various disturbances (e.g. drought, flooding, tillage, fire, etc.).

Soil formation is a geologically time consuming process driven by the influences of CLORPT [10]:

- CLimate – whereby temperature and moisture alter chemical reactions;
- Organisms – whereby plant roots penetrate and

deposit residues, animals burrow and create cavities, and bacteria feed upon organic remains;

- Relief – whereby the shape and direction of land surface affect sunlight and moisture exposure;
- Parent material – whereby the underlying bedrock provides different minerals that contribute the chemical and physical conditions of soil;
- Time – whereby different numbers of millennia allow the other factors to take place.

These same factors have a large influence on soil organic matter formation and its capacity to sustain ecosystem functions. It may have taken Nature 200 years to form 1 cm of soil, but it took humans about that same amount of time to enable Nature to erode the entire Southern Piedmont landscape (a region of hilly land southeast of the Appalachian Mountains from Alabama to Virginia in the USA) when previously forested land was denuded and covered only intermittently with a sparse cotton crop; the process of which eventually removed an average of 18 cm of soil from the entire 17 Mha of land [11]! Small wonder that soils of the southeastern USA are considered poor and infertile when >30 Mg C ha^{-1} would have been lost from the upper soil horizon (calculation of author based on presumed mean SOC concentration of 12 g C kg^{-1} soil and bulk density of 1.4 Mg m^{-3} in surface 18 cm of soil).

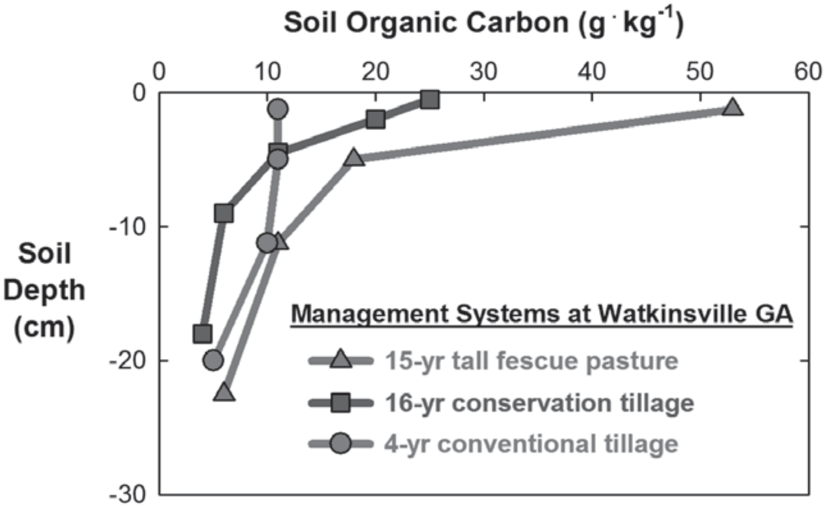

Figure 1. Depth distribution of SOC concentration by agricultural land management system in the Georgia Piedmont [12].

Soil organic C accumulates predominately in the upper horizons of soils. By not disturbing soil with tillage, SOC accumulates as plant residues cover the soil and slowly decompose following intermittent precipitation events (Fig. 1). Protection of the soil surface with plant residues and high SOC concentration is important for getting rainfall to infiltrate soil (i.e. lower runoff) and keep the soil surface from washing away (i.e. lower soil loss). By helping to control soil erosion and alter the water cycle, SOC supports and regulates ecosystem services.

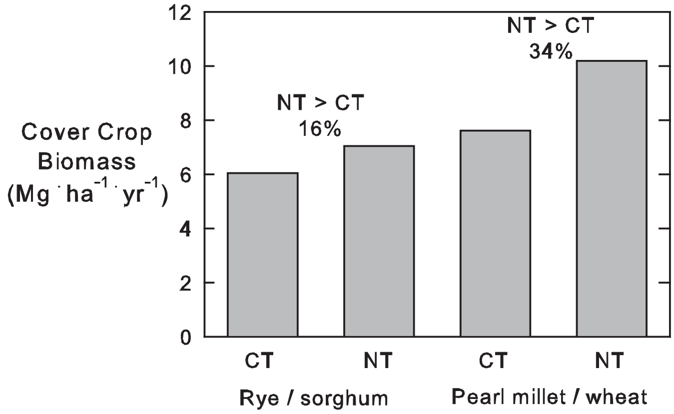

Figure 2. Above-ground biomass production of rye (in rye/sorghum cropping system) and pearl millet (in wheat/pearl millet cropping system) under conventional tillage (CT) and no tillage (NT) in the Georgia Piedmont [14].

With the adoption of inorganic fertilizer application in the 20th century, the nutrient supplying capacity of soil organic matter became widely under-appreciated. Application of inorganic fertilizer can overcome nutrient deficiencies, even in poorly structured soils with low organic matter. However within a particular soil, the level of SOC can have a profound influence on the capacity of soil to produce food, feed, fiber, and fuel [13]. When soils are maintained with high surface-SOC rather than depleted with accelerated oxidation from repeated tillage operations, productivity can also be enhanced due to non-nutrient attributes of soil organic matter (Fig. 2).

Accumulation of plant residues and SOC at the soil surface is also extremely important for protecting the off-site quality of surface waters in nearby streams and lakes. With increasing surface residue and SOC, percentage of rainfall as runoff declines, soil loss declines, and nutrients lost in runoff declines [15].

In Biblical and pre-modern times, soil was thought to be at its best when cultivated with implements to release the nutrients stored within organic matter. Lessons from the American frontiers have informed us that preservation of soil organic matter without soil disturbance is a far better goal of preserving the quality of soil for future generations [16]. The key to sustaining fertility is to match nutrient requirements of crops with various amendments, whether these come from inorganic or organic sources, such as commercial fertilizers, animal manures, nitrogen-fixing green manures, or various industrial or rurally derived composts. The European-influenced culture of clean, bare soil as a vision of agrarian charm has been rightfully replaced in America with the modern vision of crop-residue-blanketed fields protected from the fierce elements of wind and water that can be both bane and blessing for the American landscape.

Stratification of SOC as an Indicator of Soil Quality

This section on stratification of SOC was first presented in Franzluebbers [17]. Conservation agricultural systems typically develop a highly stratified vertical distribution of SOC with time (Fig. 1). Significant changes in SOC that do occur with conservation agricultural systems in the southeastern USA are usually limited to the surface 30 cm of soil and even more typically to the surface 15 cm of soil. The ratio of SOC at 0 to 15 cm to that at 15 to 30 cm in a soil managed under permanent pasture increased from 2.4 at initiation to 3.1 at the end of 5 yr to 3.6 at the end of 12 yr [18].

High surface SOC has important impacts on several soil functions. Enrichment of the surface with SOC is ecologically essential, because the soil surface is the interface that (i) receives much of the fertilizers and pesticides applied to agricultural land, (ii) receives the intense impact of rainfall, and (iii) partitions the fluxes of gases and water into and out of the soil [19]. Therefore, a SOC-enriched surface fosters productivity, regulates terrestrial water flow, sequesters C from the atmosphere, cycles nutrients through biological activity, filters and denatures pollutants, and creates a biologically active and diverse warehouse of soil microorganisms. Soil organic C allows plant roots and soil biota to reconfigure the soil matrix into a stable structure with permanent channels (biopores), a process that is important in achieving high water infiltration. As an example, the positive effect of a high stratification ratio of SOC (an index of biophysical changes in the soil structure) on water infiltration was demonstrated in a controlled infiltration experiment on a Typic Kanhapludult, whereby water infiltration increased 27% with doubling of SOC uniformly throughout a 12-cm depth and increased more than 200% when SOC was concentrated in the surface 3 cm [20]. In field studies with small-plot rainfall simulations (4.6-5.5 m^2) in Mississippi and Ohio [21], soil loss was inversely related to the calculated SOC stratification ratio [15]. Other field-plot and water-catchment studies have documented the positive influence of conservation tillage and pasture management on soil stabilization and the avoidance of water and nutrient runoff (reviewed in [15]). Very few of these studies provided measurements of the depth distribution of SOC, however, which would have probably been highly stratified under conservation systems and uniformly distributed with depth under inversion tillage systems (i.e., bare surface). The assumed surface accumulation and high stratification ratio of SOC under conservation management systems are further supported by observations in the following.

In a tillage × cropping system experiment in Watkinsville, Georgia, stratification ratio of SOC (0-6/12-20 cm) was initially 3.7 when a long-term pasture was terminated, and then became widely divergent throughout the subsequent 3 yr of the study [22]. Stratification ratio of SOC was 0.9 and 3.8 under conventional tillage and NT, respectively, at the end of 1 yr, 1.1 and 3.8 at the end of 2 yr, and 1.2 and 3.9 at the end of 3 yr. Similar values for the stratification ratio of SOC (0-5/15-30 cm) were reported for four measurements during 30 yr of experimentation with moldboard plowing (1.7 ± 0.2), NT management (3.4 ± 0.1), and grass sod (4.0 ± 0.2) in Kentucky [23].

In a survey of agricultural land uses in Alabama, Georgia, South Carolina, North Carolina, and Virginia, stratification ratio of SOC (0-5/12.5-20 cm) averaged 1.4 with conventional-tillage cropland and reached a plateau of 2.8 within 10 yr on conservation-tillage cropland and a plateau of 4.2 with perennial pasture [24]. This survey included a wide diversity of cropping histories and soil types, which may have contributed to the wide variation observed. In a survey of cropland fields on three different soil types in the Virginia Coastal Plain, stratification ratio of SOC (0-2.5/7.5-15 cm) was linearly related to the number of years of continuous NT (initially 1.5 following conventional tillage and increasing to 3.6 with 14 yr of NT) [25].

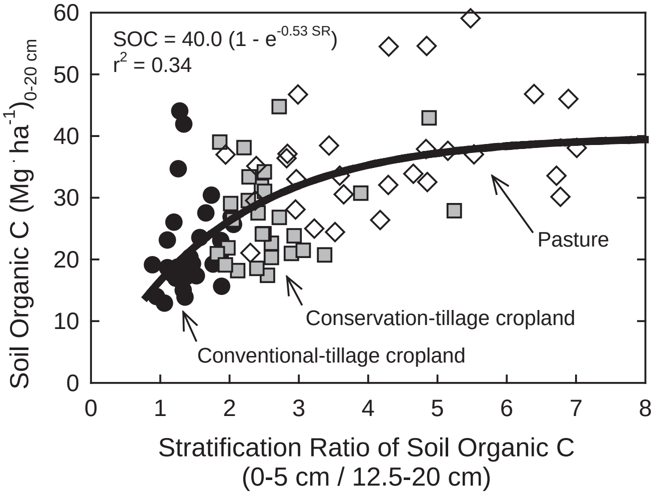

Figure 3. Stock of SOC to a depth of 20 cm as a function of stratification ratio of SOC, independent of land management [24].

Stratification of SOC with depth may also be predictive of terrestrial C storage with conservation agricultural systems in the southeastern USA. In the land use survey by Causarano et al. [24], stratification ratio of SOC (0-5/12.5-20 cm) was related to the total stock of SOC in the surface 20-cm depth (Fig. 3). This relationship indicates that the majority of C stored under conservation management in these Ultisols and Alfisols of the region occurred within the surface 5 cm. More data will be needed to extend the applicability of this relationship throughout the region. When using only the surface 2.5 cm of soil for calculation of the stratification ratio, there was little relationship between stratification ratio and the stock of SOC in the surface 15 cm of conservation-tilled Coastal Plain soils in Virginia [25]. Taking these data together suggests that significant accumulation (if not the majority) of SOC occurs within the surface 5 cm with conservation management.

Responses of SOC to Conservation Agricultural Management

SOC usually increases with adoption of conservation agricultural management due to minimum soil disturbance and soil surface covered with residues, attributes that are at the core of conservation agriculture. Conservation agricultural systems have three guiding principles that can be globally applied, typically resulting in enhanced SOC with time:

- Minimize soil disturbance, consistent with sustainable production goals;
- Maximum soil surface cover by managing crops, pastures, and crop residues; and
- Stimulate biological activity through crop rotations, cover crops, and integrated nutrient and pest management.

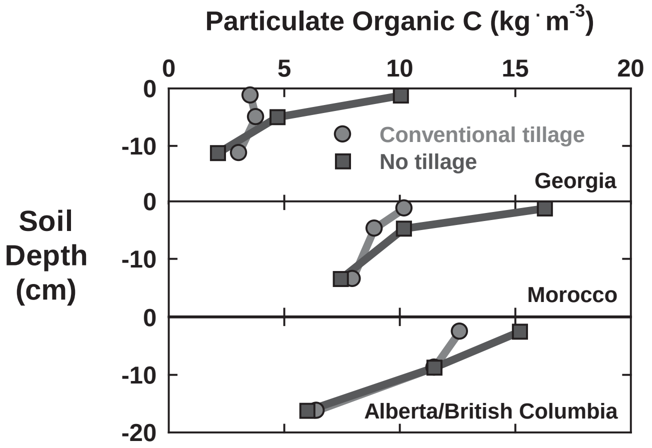

Figure 4. Depth distribution of particulate organic C as a function of tillage system in three different environments. Data from [26, 27, 28].

Disturbance of soil causes aggregate breakdown and mixing of surface residues throughout the tillage layer, both of which enhance microbial decomposition of residues and SOC. Limiting disturbance of soil, therefore, enhances retention of SOC compared with inversion tillage systems (Fig. 4). As noted from a review of several studies conducted around the world [29], no-tillage systems often have greater total quantities, as well as greater depth stratification, of active and passive fractions of SOC in addition to surface residue C.

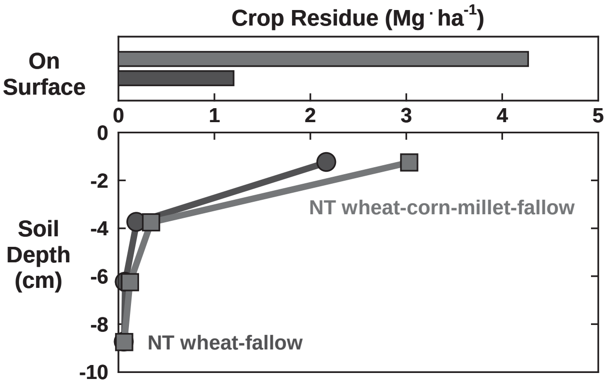

Figure 5. Crop residue distribution in soil (lower panel) and on the surface of soil (top panel) in two cropping systems in Colorado [30].

No-tillage systems are well known for protecting the soil surface from intense rainfall by supplying the surface with a blanket of crop residues. However, the type of cropping system can make a large impact on how much surface crop residues are present, as well as how much of those residues eventually get incorporated into SOC (Fig. 5). Cropping systems that maximize the time with an actively growing crop often lead to greater surface residue inputs [31], but this is also dependent on the types of crops and how much residue they produce. In the southeastern USA, winter annual grains (such as wheat, rye, oat, barley) provide 3-6 Mg ha^{-1} of residues that can sufficiently cover the soil for summer cash crops with relatively low residue production (such as cotton and soybean). Corn and grain sorghum are high-residue producing summer annual crops that also enhance surface residue cover.

As summarized previously [17], SOC sequestration in the southeastern USA was 0.30 + 0.05 Mg C ha^{-1} yr^{-1} in no-tillage systems without cover crop and 0.55 + 0.06 Mg C ha^{-1} yr^{-1} in no-tillage systems with cover crop. Increasing the complexity of the cropping system has also led to greater SOC sequestration in the southeastern USA [32], in Canada [33], and from a global dataset [34]. Cropping complexity generally influenced the quantity of C input to soil, but other factors may be equally important, including timing of water utilization to stimulate or retard decomposition, nature of organic inputs that could affect susceptibility to decomposition, and biochemical inputs that could alter aggregation and microbial community structure.

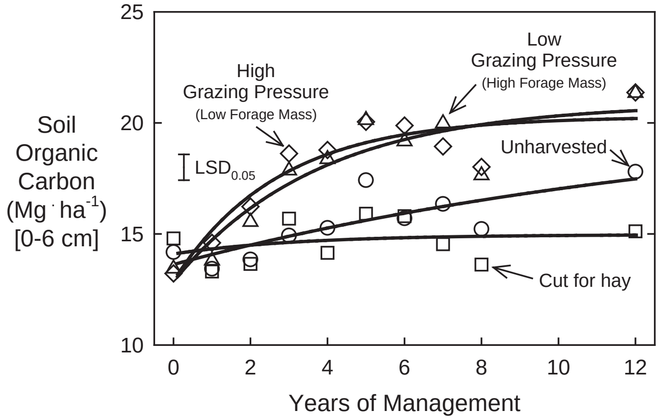

Figure 6. Soil organic C content as affected by forage utilization regime and years of management [35].

Sequestration of SOC can also be efficiently established with re-introduction of perennials into cropping systems, either as permanent or temporary pastures, multi-year crop rotations with forages, and/or other novel integrated crop-livestock systems. In the southeastern USA, establishment of perennial pastures on previously eroded cropland led to SOC sequestration of 0.84 + 0.11 Mg C ha^{-1} yr^{-1} [17]. How pastures are managed can have nearly an equally large of an effect on changes in SOC as simply establishing pastures on cropland. In mixed bermudagrass-tall fescue pastures in Georgia, SOC sequestration in the surface 6 cm was 0.59-0.62 Mg C ha^{-1} yr^{-1} when grazed, 0.32 Mg C ha^{-1} yr^{-1} when unharvested, and 0.07 Mg C ha^{-1} yr^{-1} when hayed (Fig. 6). No difference in SOC sequestration occurred whether forage was fertilized inorganically or organically with broiler litter. A similar outcome occurred in tall fescue pastures: (a) nearly year-round grazing for 8 years resulted in SOC sequestration in the surface 6 cm of 1.36 Mg C ha^{-1} yr^{-1} compared with 0.69 Mg C ha^{-1} yr^{-1} when hayed and (b) no difference in SOC sequestration occurred whether forage was fertilized inorganically or organically with broiler litter [36].

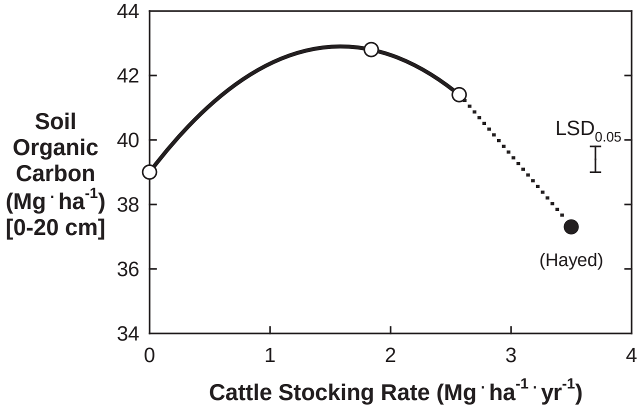

Figure 7. Soil organic C content as a function of cattle stocking rate on bermudagrass in Georgia [38].

Stocking rate of perennial pastures can affect the balance between photosynthesis and decomposition, such that greater pressure by more grazers will eventually compromise photosynthetic potential and limit C input to soil. Odum et al. [37] described an optimization relationship between stress exerted on an ecosystem (i.e. grazing pressure in this example) and productivity potential of that ecosystem; a moderate level of stress could enhance productivity compared with no stress, but that high stress could have negative impacts on productivity or even lethal effects with extreme stress. In a 5-yr bermudagrass experiment in Georgia, this same optimization response was found when stock of SOC increased with moderate compared with no stocking rate, but then declined with simulated high stocking rate (Fig. 7).

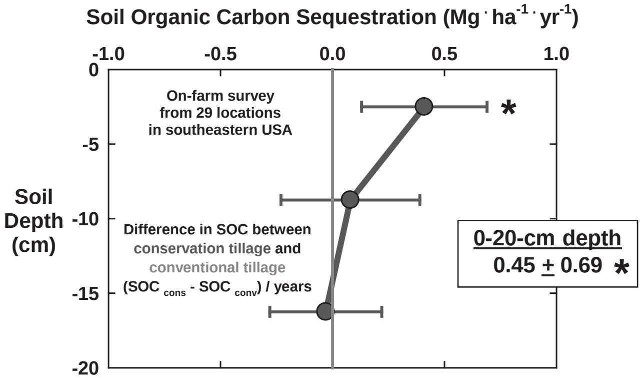

Figure 8. Calculation of SOC sequestration between two paired land uses with known duration by summation of differences at multiple depths. Data from [24].

Changes in SOC can be estimated in different manners, the impact of which can have subtle or enormous influence on the calculated rate of SOC sequestration. Some examples will be given to illustrate some of the issues and assumptions involved in calculation of SOC sequestration rate. In a land-use survey in Southern Piedmont and Coastal Plain regions of the southeastern USA, SOC was determined under paired conventional-tillage and no-tillage croplands (Fig. 8). Sequestration of SOC in this example was calculated as the difference in SOC between no-tillage and conventional-tillage cropland and divided by the number of years of practice of the innovative management (i.e. no tillage). Values for the region were then averaged across paired sites within the region (i.e. 29 locations).

Both conventional- and conservation-tillage management systems may be static or undergoing changes with time. However in chronosequence land-use comparisons, it is often assumed that the conventional system is static or similar at the time of sampling as it was at the time of implementation of an improved management system. Although long-term temporal data are relatively few in the literature, there is evidence for both static and dynamic values of SOC with time. How such assumptions about the history of land use can influence the rate of SOC sequestration is illustrated in Figure 9. In all cases, relative differences between systems can be detected after a decade or two of management. However, absolute differences between systems can vary depending upon what is assumed about the conventional system, and whether, a true SOC sequestration rate of a conservation system is desired independent of comparison with a conventional or business-as-usual type of system. To obtain the best estimate of SOC sequestration for each particular management system, data collected over numerous years from the beginning of management would be ideal. However, such data are not often available, and therefore, relative differences between systems can be a reasonable alternative. Scenario A in Figure 9 exemplifies an ideal assumption about the conventional system, wherein it does not change in SOC value across many years of potential sampling. The decline in SOC with conventional tillage in Scenario B may occur in soils that were recently converted from a natural condition, and therefore, still have large potential to lose SOC. The increase in SOC with conventional tillage in Scenario C represents a condition, wherein soil has been improved with other management inputs despite continuation of inversion tillage. New crop varieties, inputs of organic amendments, and starting the evaluation from a highly degraded condition are all potential factors that could lead to increasing SOC with conventional tillage.

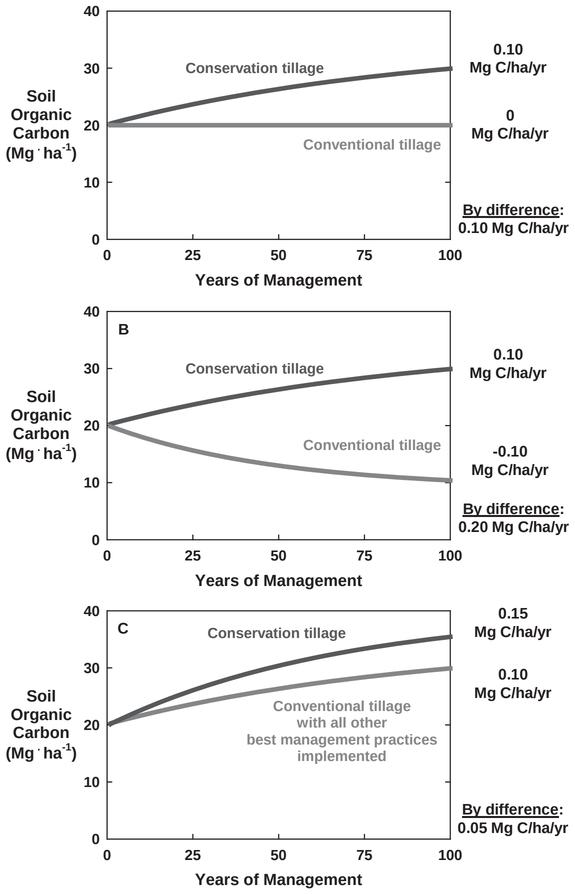

Figure 9. Hypothetical description of changes in SOC with time and management.

Recent Evaluations of SOC in *Soil & Tillage Research*

Some of the most recent publications in Soil and Tillage Research have highlighted the importance of concentration of SOC with conservation agricultural systems for enhancing soil quality around the world. This section briefly describes some of these recent studies.

In a 21-year-old experiment in southwestern Spain on a Chromix Haploxerert (59% clay, 7% sand), SOC at a depth of 0-5 cm was 8.1 g kg^{-1} under conventional tillage (moldboard plowing to 50 cm, field cultivation to 15 cm, crop residues burned), 10.4 g kg^{-1} under minimum tillage (field cultivation to 15 cm, crop residues retained), and 13.9 g kg^{-1} under no tillage (spraying glyphosate) [39]. These differences in SOC were also reflected in greater β-glucosidase, DTPA-extractable Mn, Cu, and Zn, and citrate-bicarbonate-extractable Mn under no tillage than under the other tillage systems. Despite these differences in SOC and micronutrient concentrations, greenhouse growth studies revealed no differences in plant-leaf concentrations of these nutrients.

In an Orthic Luvisol (FAO Taxonomy) in the Czech Republic, SOC was greater with no tillage than with conventional tillage (moldboard plowing, disking) at a depth of 0 to 10 cm, but not different between tillage systems at a depth of 10 to 30 cm [40]. Greater stratification of SOC with depth under no tillage compared with conventional tillage was accompanied by even stronger depth stratification of microbial biomass C. Soil at a depth of 0 to 10 cm following 6 to 12 years of no-tillage management contained greater hydrophobic organic components than under conventional tillage.

Water repellency of soil from Rio Grande do Sul, Brazil (various Udorthent, Dystrudept, Hapludalf, Albaqualf, Endoaqualf, Paleudalf, Hapludox, Haplohumult, Paleudult, Argiudoll, Hapludert) was determined and related to various soil fractions [41]. Although water repellency was related with SOC concentration, the relationship was weak and composition of organic matter appeared to be more important than quantity. Water repellency was greater in subsoil, associated particularly with higher clay content.

From an evaluation at the end of 15 years of management on an Aquic Hapludult (18% clay, 56% sand) in North Carolina, SOC at a depth of 0 to 15 cm under no tillage was nearly double that under conventional tillage (moldboard plowing, disking) [42]. No tillage with organic inputs [soybean meal] had greater SOC and total N than no tillage alone. Total N and SOC values under no tillage with organic inputs approached values under fescue grasses. No tillage plus organic inputs enhanced soil microbial biomass and activities, whereas conventional tillage with chemical inputs depleted SOC and soil microorganisms.

In a hardsetting glacial till soil (3% clay, 73% sand) in Germany, adding organic matter via compost at rates of 0 to 4% resulted in increasingly greater water retention at all water contents [43]. Organic matter addition also reduced bulk density and penetration resistance compared with no organic matter addition, particularly at lower water contents.

In a Typic Argiudoll (29% clay, 27% sand) in Uruguay, SOC and particulate organic C were evaluated at the end of 10 years of conventional and no tillage of either continuous cropping or crop-pasture rotation [44]. Differences in SOC only occurred at a depth of 0 to 3 cm; (a) no tillage greater than conventional tillage and (b) crop-pasture rotation greater than continuous cropping under conventional tillage, not under no tillage. However, particulate organic C was sensitive to management even at a depth of 0 to 18 cm.

In an evaluation of a non-degraded Typic Argiudoll in Argentina (952 mm precipitation, 894 mm potential evapotranspiration, and 14.1 °C), SOC and total N contents were not different between conventional tillage [moldboard plowing, disking, field cultivation] and no tillage (chemical weed control) at the end of 3 and 6 years of management [45]. Lack of treatment differences also occurred for bulk density, particulate organic C and N, and potentially mineralizable N at a depth of 0 to 20 cm. However, there was greater stratification with depth in particulate organic C under no tillage compared with conventional tillage.

In a Calcic Haploxerept in northeastern Spain (525 mm precipitation, 740 mm potential evapotranspiration, and 13.5 °C) soil quality indicators were evaluated under continuous barley production for 10 years using conventional tillage (moldboard plowing to 25-cm depth, harrowing), minimum tillage (chisel plowing to 15-cm depth, harrowing), no tillage, and no tillage with stubble burning [46]. Multivariate and factor analyses were used to select penetration resistance, particulate organic C, and SOC as the most sensitive indicators for the 0 to 5 cm depth. Aggregate stability and particulate organic matter quality were most sensitive at 5 to 15 cm depth. These indicators were positively correlated with soil water retention, earthworm activity, and organic matter stratification. Highest soil quality was found for no tillage at both sampling depths, but particularly at 0 to 5 cm depth.

In an evaluation of two watersheds (34-43 ha) under continuous corn cultivation in Iowa, SOC to a depth of 15 cm averaged 26.6 Mg ha^{-1} under conventional tillage (moldboard plowing early in the study, deep + light disking later in the study) and 34.7 Mg ha^{-1} under ridge tillage [47]. In accordance with the increase in SOC under ridge tillage, water runoff declined from 64 mm yr^{-1} to 33 mm yr^{-1}, sediment yield declined from 12.3 Mg ha^{-1} yr^{-1} to 1.5 Mg ha^{-1} yr^{-1}, C loss in sediment declined from 6.4 Mg ha^{-1} yr^{-1} to 2.0 Mg ha^{-1} yr^{-1}, and corn grain yield increased from 7.3 Mg ha^{-1} yr^{-1} to 7.6 Mg ha^{-1} yr^{-1}. Responses were closely matched with simulations run using the Agricultural Policy/Envionmental eXtender (APEX) model.

From six sites in Ohio, SOC storage was compared after 6 to 44 years of management under conventional-tillage cropping, no-tillage cropping, and woodlots [48]. Storage of SOC at 0 to 40 cm depth was greater under no tillage than under conventional tillage at 4 of 6 sites, but not different at 2 sites. Greater storage tended to occur with longer duration of no tillage. Depletion of SOC with conventional-tillage cropping compared with woodlot management was 26 to 55%, mostly within the plow layer (0 to 20 cm depth).

In a sandy clay loam in Italy (1590 mm precipitation, 12.4 °C), SOC was 19 g kg^{-1} under 70 years of horticultural cropping, 26 g kg^{-1} under native grassland, and 108 g kg^{-1} under indigenous woodland [49]. These values were inversely proportional to cation-exchange capacity, available P, and exchangeable K, a response directly related to long-term management inputs with horticultural cropping. However, direct correlation of SOC occurred with microbial biomass C, light-fraction C, water-soluble organic C, phenolic compounds, and potential C mineralization. A close relationship existed between alkali-soluble phenolics and soil antioxidant activity, suggesting that phenolic compounds might control the rate of organic C mineralization (more than the quantity of easily mineralizable C pool).

Summary

Soil organic C is a key element in the valuation of natural resources and the evaluation of how management affects soil quality and ecosystem services derived from soil. Stratified SOC with depth under conservation agricultural approaches helps soil function to an optimum. Conservation management approaches focusing on minimizing soil disturbance, maximizing soil cover, and stimulating biological activity can be achieved with different cropping choices and production goals in different environments all around the world. A key to success will be to consider the agronomic, ecological, environmental, and economic constraints within a particular farm setting. On-going research continues to support the key contributions that enhanced SOC with conservation agricultural approaches can give to farmers and society.

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