

SOIL ORGANIC CARBON SEQUESTRATION WITH CONSERVATION AGRICULTURE IN THE SOUTHEASTERN USA: POTENTIAL AND LIMITATIONS

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INTRODUCTION

The carbon (C) cycle is the basis for greenhouse gas emissions and global warming. Globally, agriculture is responsible for about 20% of the greenhouse gas emissions. However, this percentage does not take into account the large role that agriculture plays in the opposing processes of photosynthesis and respiration (Figure 1), as well as contributions to soil organic C sequestration via animal manure application and crop residue inputs with conservation agricultural systems. The C cycle can be either positively or negatively affected by agricultural activities, depending upon management choices.

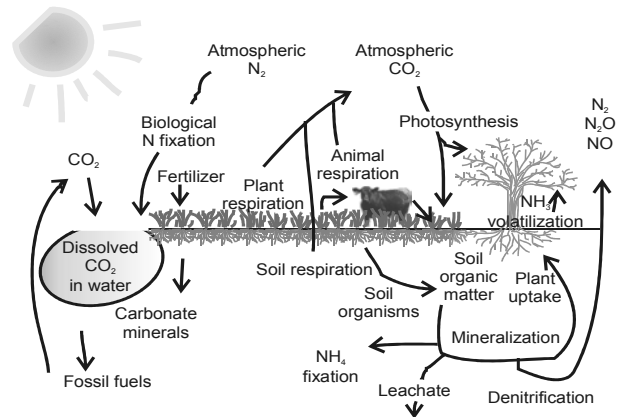


Figure 1. Illustration of the terrestrial C cycle.

Agriculture consumes fossil fuels during the manufacture of equipment, fertilizer, and other chemical inputs, as well as during machinery and grain handling operations (e.g., tractor operations, grain drying, etc.). Fuel consumption can be reduced in cropland agriculture with the adoption of conservation tillage systems. Conservation tillage systems have been employed in many regions of the world, so we know that they work, but further progress on adoption of this technology is possible. Conservation tillage systems have been given names, such as direct drilling, no tillage, strip tillage, reduced tillage, and ridge tillage, all with the goal of reducing trips across the field and leaving crop residues at the soil surface for controlling erosion and building soil organic matter.

Emission of nitrous oxide (N₂O) is a large component of the total greenhouse gas emissions from agriculture (Figure 2). Since N₂O causes 296 times as much radiative forcing as a molecule of CO₂, only small emissions of N₂O are necessary to have a large effect on climate change. Soil microbial transformations are responsible for most of the N₂O emission associated with agriculture through two natural processes (i.e., nitrification and denitrification). Soil microorganisms (i.e., bacteria and fungi) naturally

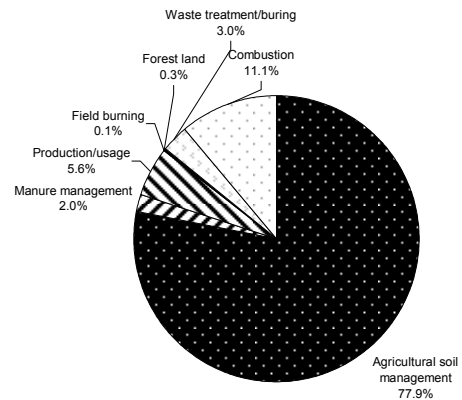


Figure 2. Sources of nitrous oxide emission to the atmosphere in the USA (USEPA, 2007).

decompose organic matter and convert some organically bound N to N₂O during the nitrification step of this decomposition process. Highly productive agricultural systems require abundant soil N, but it is this abundant soil N that can result in substantial N₂O emission through a process of denitrification. Whether soil N comes from inorganic fertilizers or animal manures, about 1% of the applied N is typically emitted as N₂O. Therefore, for a typical farming system with 100 kg N/ha applied, the equivalence of 465 kg of CO₂/ha (or 127 kg CO₂-C/ha) would be emitted.

Emission of methane (CH₄) from agriculture is primarily from methanogenic bacteria living in flooded soils under rice cultivation and in the digestive systems of ruminant livestock (e.g., cattle, sheep, goats, horses) (Figure 3). Other sources of CH₄ from agriculture are from decomposition of animal manure, especially when stored in lagoons, and from crop residues when decomposing under very wet conditions. Well-aerated soils can actually consume CH₄ from the atmosphere, especially those soils with high surface soil organic matter content under conservation agricultural systems.

Carbon sequestration is defined as the removal of CO₂ from the atmosphere into various long-lived chemically bound forms, either on land or in the ocean. Through the process of photosynthesis, CO₂ is sequestered from the atmosphere into plant tissues. Photosynthesis represents the largest transfer of CO₂ in the C cycle, and therefore, is of great importance in understanding how to manage the global C cycle. Carbon sequestration on land (or terrestrial C sequestration) occurs in standing biomass (e.g., trees), long-term harvested products (e.g., lumber), living biomass in soil (e.g., perennial roots and microorganisms), recalcitrant organic matter in surface soil (e.g., humus), and inorganic C in subsoil (e.g., carbonates) (Johnson et al., 2007). Soil organic and inorganic C pools are generally the most long-lived terrestrial C sequestration forms.

Sequestration of soil organic C from plant biomass is a key sequestration pathway in agriculture; offering an offset strategy (i.e., mitigation) for agriculture's other greenhouse gas emissions. Soil C sequestration is also important at the farm level to build soil fertility, protect soil from compaction, and nurture soil biodiversity. In addition to its vital role of mitigating greenhouse gas emissions, soil C sequestration provides many other significant off-farm benefits to society. These benefits include the protection of streams, lakes, and rivers from sediment, nutrient, and pathogen runoff from agricultural fields, as well as enhanced wildlife habitat. A full-system cost-to-benefit ratio of soil C sequestration from various conservation agricultural practices has not been adequately addressed, but is needed to more fully appreciate this important pathway.

Conservation agricultural systems promote soil C sequestration by tipping the balance in favor of C inputs relative to C outputs. Carbon sequestration can be achieved by maximizing C inputs and minimizing C outputs (Table 1).

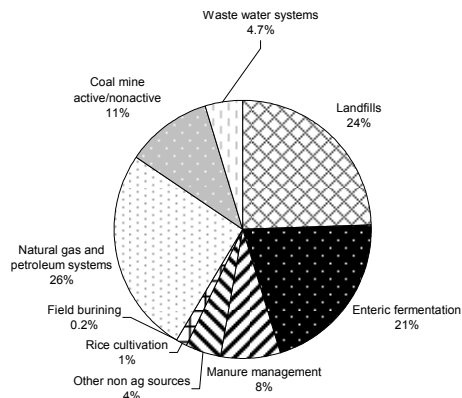


Figure 3. Sources of methane emission to the atmosphere in the USA (USEPA, 2007).

Table 1. Strategies to sequester soil organic C.

(1) Maximizing C input	(2) Minimizing C loss from soil
<input type="checkbox"/> Plant selection <ul style="list-style-type: none"> • Species, cultivar, variety • Growth habit (perennial/annual) • Rotation sequence • Biomass energy crops 	<input type="checkbox"/> Reducing soil disturbance <ul style="list-style-type: none"> • Less intensive tillage • Controlling soil erosion
<input type="checkbox"/> Tillage <ul style="list-style-type: none"> • Type • Frequency 	<input type="checkbox"/> Utilizing available soil water <ul style="list-style-type: none"> • Promotes optimum plant growth • Reduces soil microbial activity
<input type="checkbox"/> Fertilization <ul style="list-style-type: none"> • Rate, timing, placement • Organic amendments 	<input type="checkbox"/> Maintaining surface residue cover <ul style="list-style-type: none"> • Increased plant water use and production • More fungal dominance in soil

Various management approaches should be a part of conservation agricultural systems, including conservation tillage, diverse crop rotations, cover cropping, perennial pastures, and conservation reserve land [e.g., Conservation Reserve Program (CRP)].

REVIEW OF SOIL CARBON SEQUESTRATION IN THE SOUTHEASTERN USA

The impact of conservation tillage on soil organic C sequestration may be greater in degraded soils than in fertile soils. The basis for this statement was derived from the observation that the ratio of soil organic C with conservation tillage-to-conventional tillage was logarithmically greater in soils with inherently lower organic C than in soils with inherently higher organic C content (Figure 4). Therefore on a relative basis, the improvement in soil organic C was proportionately higher in poorer soils.

The potential to sequester soil organic C with conservation tillage in the southeastern USA has been shown to be as high as in other regions of North America, despite the inherently low soil organic matter content from the warm, moist environmental conditions that limits soil organic matter accumulation (Figure 5). Mean soil organic C sequestration rate in cotton production systems was estimated as 0.48 ± 0.56 Mg C/ha/yr from 41 observations throughout the southeastern USA (Causarano et al., 2006). In addition, whether conservation tillage systems employed cover crops or not had a large impact on the rate of soil organic C sequestration in the

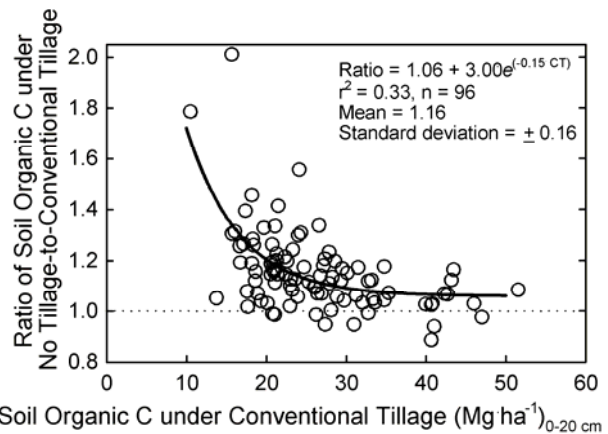


Figure 4. The ratio of soil organic C under conservation tillage-to-conventional tillage as related to the initial soil organic C content under conventional tillage (from Franzluebbers, 2005).

southeastern USA. Soil organic C sequestration rate was 0.28 ± 0.44 Mg C/ha/yr without cover cropping ($n = 40$) and was 0.53 ± 0.45 Mg C/ha/yr with cover cropping ($n = 53$) (difference between cropping systems was $p < 0.01$) (Franzluebbers, 2005). The average ratio of soil organic C with conservation tillage-to-conventional tillage was 1.11 without cover cropping and 1.20 with cover cropping ($p = 0.02$). It has been stated that conservation tillage alone creates an imperfect and incomplete system for conservation agricultural systems (Derpsch, 2007). These soil organic C sequestration data sorted into cover cropping categories support this view.

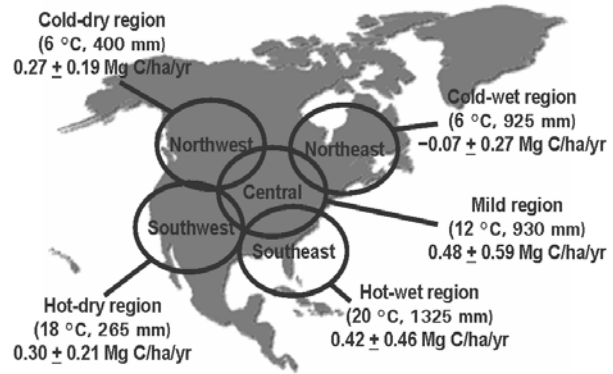


Figure 5. Mean \pm standard deviation of soil organic C sequestration rates in five different regions of the USA and Canada (adapted from Franzluebbers et al., 2006).

Increased cropping system complexity would be expected to create a diversity of crop residue qualities, crop rooting depths and patterns, and possibly greater C inputs. From the few studies available, increasing crop complexity (2.9 ± 0.7 vs. 1.7 ± 0.8 crops/rotation cycle) did lead to 0.22 Mg C/ha/yr greater ($p < 0.001$) soil organic C sequestration in the southeastern USA (Franzluebbers, 2005). Tillage system did not significantly alter this effect, but there was a slight trend ($p = 0.28$) for a greater value under conservation tillage (0.27 ± 0.32 Mg C/ha/yr) than under conventional tillage (0.16 ± 0.35 Mg C/ha/yr). The simple and complex crop rotations in this analysis were near the upper end of cropping intensity (i.e., 0.76 ± 0.26 and 0.88 ± 0.13 , respectively, expressed as a fraction of year in cropping). With data summarized across North America having a wider range in cropping intensity, soil organic C sequestration with conservation compared with conventional tillage increased with increasing cropping intensity (Franzluebbers and Steiner, 2002). Soil organic C sequestration was -0.26 Mg C/ha/yr under no tillage compared with conventional tillage with a cropping intensity of 0.25 (e.g., wheat-fallow), was 0.38 Mg C/ha/yr with a cropping intensity of 0.5 (e.g., continuous sorghum, wheat, or corn), and was 0.62 Mg C/ha/yr with a cropping intensity of 1.0 (e.g., double cropping).

Fertilization of crops is needed to overcome deficiencies in nutrients supplied by soils, especially in those soils exhausted by years of soil erosion, intensive disturbance with tillage, and continuous harvest of products that remove large quantities of nutrients. Excessive fertilization can also occur when agronomic prescriptions exist without regard for economic and environmental consequences. In a review of data from the southeastern USA, soil organic C generally accumulated with increasing rate of N fertilizer application (Figure 6). The average

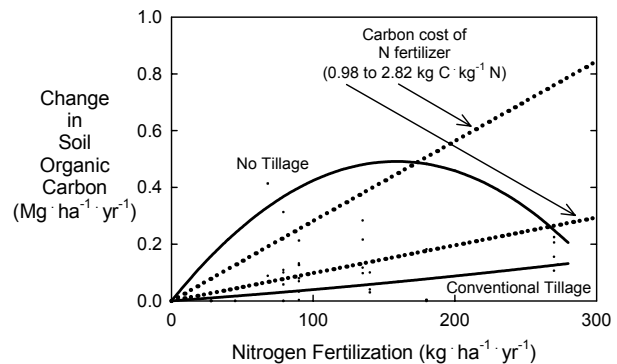


Figure 6. Average change in soil organic C as affected by N fertilizer rate in the southeastern USA (Franzluebbers 2005). Dotted lines represent the lower and upper limits of C cost of N fertilizer manufacture, distribution, and application.

N fertilizer rate to achieve maximum soil organic C sequestration (0.28 Mg C/ha/yr) was 171 kg N/ha/yr (Franzluebbers, 2005), well within the range of values often reported to maximize cereal crop yields. However, when considering the C costs of N fertilizer (i.e., manufacture, distribution, and application), the optimum N fertilizer rate was 107-120 kg N/ha/yr based on C costs of 0.98 [0.86 + 0.08 + 0.04 for production, application, and liming components, respectively (West and Marland, 2002)] to 1.23 kg C/kg N fertilizer (Izaurre et al., 1998). These calculations did not include the global warming potential of N₂O emission that is a near-inevitable consequence of N fertilizer application. With N₂O 296 times more potent than CO₂ and assuming 1.25% of applied N would be emitted as N₂O (IPCC, 1997), then an additional C cost of 1.59 kg C/kg N fertilizer would be an appropriate calculation. Therefore, the baseline settings for the response curves in Figure 6 should be between 0.98 and 2.82 kg C/kg N fertilizer, depending upon system boundaries. Optimum N fertilizer application to maximize C offset should then be reduced to as low as 24 kg N/ha/yr to achieve soil organic C sequestration of only 0.07 Mg C/ha/yr (Franzluebbers, 2005). Other life-cycle system boundaries could also be included to encompass the off-site effects of N fertilization on water quality, biodiversity preservation, rural infrastructure, and policy developments.

Animal manure application to land should promote soil organic C sequestration due to its relatively high C content.

From available data in the southeastern USA, poultry litter application to crop and pasture lands led to significant soil organic C sequestration (Table 2). Conversion of C in poultry litter to soil organic C was 17 ± 15% among studies. Although soil organic C has been shown to increase with animal manure application, very few life-cycle analyses have been conducted to include the on- and off-farm transfers of animal manure, as

well as the impacts on N₂O and CH₄ emissions. Such life-cycle analyses are needed to better understand the production and environmental values of animal manure in a whole-farm system.

Perennial forages should be considered a vital component of conservation agricultural systems. Modern industrial agricultural systems have increasingly separated crop and livestock enterprises to pursue perceived efficiencies within each, yet there are a number of excellent reasons to integrate the two enterprises (Russelle et al., 2007). Greater integration of crops and livestock enterprises could impart major benefits to the environment and to development of sustainable agricultural systems by (1) more efficiently utilizing natural resources, (2) exploiting natural pest

Table 2. Summary of the effect of poultry litter application to crop and grazing land on soil organic C in the southeastern USA (Franzluebbers, 2005).

Response	Soil organic C (Mg C/ha)	
	Without manure	With manure
2-year studies (n=6)	19.8 ± 8.9	19.6 ± 8.4
11 ± 8-year studies (n=8)	30.6 ± 11.4	36.8 ± 10.6
Soil organic C sequestration for all (Mg C/ha/yr)	0.26 ± 2.15	
Soil organic C sequestration for >2-year studies	0.72 ± 0.67	

control processes, (3) reducing nutrient concentration and consequent environmental risk, and (4) improving soil structure and productivity (Franzluebbers, 2007).

Perennial forages also offer substantial potential to rehabilitate degraded soils resulting from long-term cultivation. Greater soil organic C accumulation under pastures than under annual crops can occur due to longer growing periods, more extensive root system, and less soil disturbance. Comparing cropping and pasture systems in Georgia, soil organic C near the soil surface was greater under pasture than under conservation-tilled cropland, which was greater than under conventional-tilled cropland (Figure 7). Across the southeastern USA, soil organic C sequestration during 15 ± 17 years of pasture was estimated as 1.03 ± 0.90 Mg C/ha/yr (Franzluebbers, 2005). In a recent survey of 29 farms in the Piedmont and Coastal Plain regions of the southeastern USA, soil organic C sequestration under pasture compared with conventional-tillage cropland averaged 0.53 Mg C/ha/yr at a depth of 0-5 cm ($p < 0.01$), 0.17 Mg C/ha/yr at a depth of 5-12.5 cm ($p < 0.01$), and 0.05 Mg C/ha/yr at a depth of 12.5-20 cm ($p > 0.05$) for a total of 0.74 Mg C/ha/yr to a cumulative depth of 0-20 cm (Causarano et al., 2008).

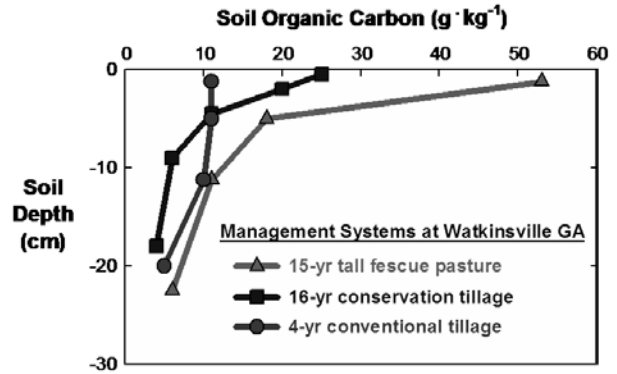


Figure 7. Depth distribution of soil organic C under conventional tillage, conservation tillage, and pasture (adapted from Schnabel et al., 2001).

CARBON SEQUESTRATION DETECTION LIMITATIONS

Soil organic C is most often measured in field experiments or land-use surveys, which can introduce several limitations for detection of significant changes with time or among management systems. When field data are not available, various models have been employed to simulate the effects of management on potential soil organic C sequestration. This section describes some of these approaches and their limitations for use in monitoring and verification of soil organic C sequestration.

When two management systems have been practiced for a long period of time, researchers have an opportunity to sample soils to various depths and make an evaluation of differences in soil organic C due to management. Underlying assumptions must be made as to whether conditions at the beginning of management were similar, such as similar soil, landscape position, climatic condition, previous management history, etc. These comparisons are often unreplicated or have limited field replication, such that subsampling within large blocks of land are needed for pseudo-replication (Franzluebbers et al., 2000). Pseudo-replication

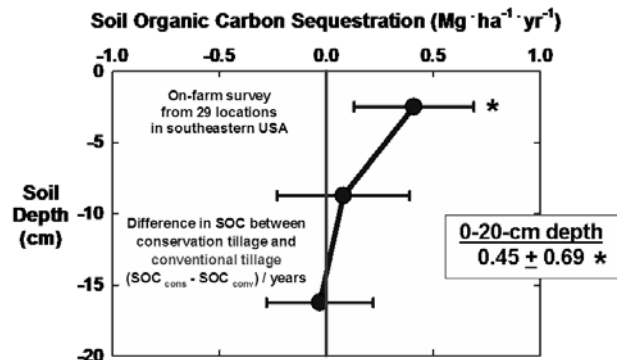


Figure 8. Difference in soil organic C sequestration between conservation-tillage and conventional-tillage cropland from multiple farms in the southeastern USA (adapted from Causarano et al., 2008).

can be effective at representing within field variations, especially if known variations in fields can be adequately described and categorized, such as through intensive soil survey and clustering of zones within a field (Terra et al., 2005), and subsequent sampling of characteristic zones. For example, in response to known long-term animal behavior patterns, soil was sampled in several zones within minimally replicated pastures resulting in between paddock-to-within paddock variation of 0.90 ± 0.64 , suggesting that within-paddock sampling provided equally independent estimates of variation as between-paddock sampling (Franzluebbers et al., 1999). When possible, sampling of multiple paired fields within a region can provide valuable results. For example, Causarano et al. (2008) demonstrated that conservation-tillage cropland sequestered significantly greater soil organic C than conventional-tillage cropland (Figure 8). There were small effects of increasing clay content and increasing temperature on soil organic C content, but these effects did not interact significantly with management system.

The field survey approach described in the previous paragraph relies on relative difference between two or more management systems. This is effective for comparative purposes to describe the effect of an improved management system against “business as usual”. However, we do not know if “business as usual” (in many cases, conventional tillage) might actually be eroding, maintaining, or increasing in soil organic C. Therefore, sampling of soil organic C along several points in time would be a more rigorous approach, especially if two or more management systems can also be compared. Figure 9 describes scenarios that could lead to different interpretations of how effective a conservation agricultural system might be in terms of soil organic C sequestration. In all three scenarios, soil organic C sequestration under conservation agriculture (when calculated as a change with time) was 0.15 Mg C/ha/yr. However in relative comparison with a conventional system, the soil organic C sequestration rate could have been realistically increased to 0.25 Mg C/ha/yr in Scenario A, because soil organic C declined by 0.10 Mg C/ha/yr under conventional agricultural practices following degradation from a previously elevated condition. In Scenario B (the most often presumed condition), soil organic C sequestration under conservation agriculture would have been effectively the same as that observed without comparison with conventional agriculture, because soil organic C under conventional agriculture was at a steady-state condition. In Scenario C, soil organic C sequestration under conservation agriculture would have to be adjusted to 0.05 Mg C/ha/yr, because the conventional system was improved by other practices similar to that under conservation agriculture, which sequestered soil organic C at 0.10 Mg C/ha/yr.

When reliable field data are not available for certain management conditions or particular soil types and environmental conditions, process-based modeling can provide

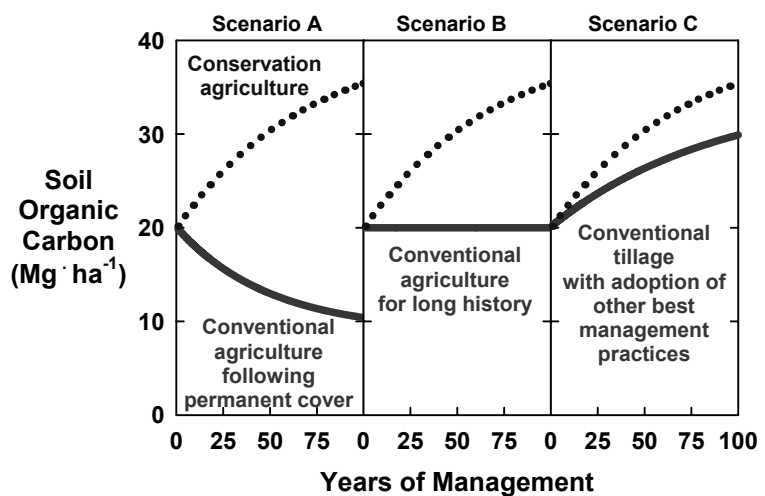


Figure 9. Hypothetical examples of soil organic C content under conservation agriculture and three different baseline conditions of conventional agriculture.

some relative indications of potential soil organic C sequestration. Under four management scenarios on three different soil types in the southeastern USA, soil organic C sequestration was estimated with the EPIC v. 3060 model as

(a) -0.03 Mg C/ha/yr under conventional-tillage cotton, (b) 0.39 Mg C/ha/yr under no-tillage cotton with wheat cover crop, (c) 0.49 Mg C/ha/yr under no-tillage cotton-corn rotation with wheat cover crop, and (d) 0.50 Mg C/ha/yr under no-tillage cotton-corn rotation with wheat cover crop for 10 years following bermudagrass pasture for 5 years (Abrahamson et al., 2007).

A simpler predictive model of soil organic C status [i.e., the soil conditioning index (SCI)] produced highly related results to those of EPIC. Across more soils and conditions, a non-linear relationship between soil organic C sequestration predicted by EPIC and the SCI suggests that the simpler SCI could be a valuable, relatively inexpensive, and expedient tool to determine relative soil organic C storage among different agricultural management systems (Abrahamson et al., 2009). However, further research is needed to determine the applicability of all modeling approaches to a wider range of management conditions and environments.

Surface accumulation of soil organic C is a key characteristic of conservation agricultural systems, especially in soils with inherently low soil organic matter content due to coarse soil texture or due to climatic conditions that promote rapid decomposition of organic matter. Although it may be possible to achieve significant soil organic C sequestration with depth in some soils (Fisher et al., 1994), available data from the southeastern USA indicates that soil organic C sequestration is primarily limited to the surface 12 cm of soil (Figures 7 and 8). Baker et al. (2007) argued that if the soil organic C content in the entire rooting profile were accounted (i.e., 0-2 m), the only reasonable conclusion would be that conservation-tillage systems only change the depth distribution of soil organic C not the total amount of C stored in soil. With greater soil depth analyzed, it becomes increasingly difficult to declare significance between treatments or with time due to lower concentrations with depth and greater coefficient of variation. In a 5-year analysis of soil organic C under pastures, coefficient of variation in soil organic C was ~30% in the surface 30 cm, but increased to 60% in the 30-60-cm depth, and even to 100% in the 60-90-cm depth (Franzluebbers and Stuedemann, 2005). Data in Table 2 illustrate the implication of increasing variation with depth on our ability to declare significance of soil organic C sequestration. Assuming an estimate of soil organic C sequestration of 10 Mg C/ha, significance would have been possible only within the surface 30 cm and not below this depth, even if the estimate of soil organic C sequestration would not have changed. More research is needed to quantify soil organic C content within the rooting profile of long-term cropping systems.

Table 3. Soil organic C content and its variation with depth in the soil profile at the end of 12 year of pasture management (Franzluebbers and Stuedemann, 2008).

Soil depth (cm)	Stock of soil organic C	Least significant difference ($p = 0.05$)
	----- Mg/ha -----	
0-15	38.4	6.0
0-30	50.0	8.9
0-60	59.9	11.2
0-90	63.8	11.7
0-120	66.2	12.3
0-150	68.1	12.7

CONCLUSIONS

Conservation agricultural systems create a biologically intensive, yet ecologically protective interface between the soil profile and the atmosphere. Protection of the soil surface from natural physical forces that can cause degradation (i.e., wind, water, and traffic) is needed to allow soils to function to their highest potential. Sequestering organic C in soil, creating a nutrient-rich environment for the proliferation of plants, and allowing water to pass through and be filtered are some critical soil functions that can be enhanced with conservation agricultural systems. Soil organic C sequestration with conservation agriculture in the southeastern USA can be relatively high (i.e., 0.4 to 1.0 Mg C/ha/yr depending on management and soil conditions). Conservation tillage, increased cropping system complexity, cover cropping, animal manure application, optimum fertilization, and rotation of crops with pastures are effective strategies to enhance soil organic C sequestration.

Different types of soil organic C sequestration evaluations have been employed. Each evaluation approach has advantages and disadvantages. Combining field sampling and modeling simulations could provide the most rewarding path forward to get better estimates of soil organic C sequestration across a diversity of conservation agricultural systems. Of particular importance in field sampling is representative sampling, acknowledging variations with depth, and the benefit of repeated sampling at regular intervals.

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