For reprint orders, please contact reprints@future-science.com

Pursuing robust agroecosystem functioning through effective soil organic carbon management

Carbon Management (2013) 4(1), 43–56

Alan J Franzluebbers*

Soil organic matter is a key indicator of many ecosystem functions, particularly in agricultural systems. With carbon as its majority constituent (~58%), soil organic matter is a key variable relating production and environmental responses. However, it is argued that depth distribution of soil organic carbon (SOC) may be more important in understanding how agriculture affects ecosystem services derived from soil than the total quantity of SOC. Conservation agricultural systems lead to highly stratified SOC, which helps to protect soil from erosion and prevent runoff loss of nutrients (i.e., water quality improvement), creates a concentrated organic habitat for nutrient storage and soil biological diversity (i.e., soil quality improvement) and promotes a structurally stable pore network connecting surface and subsurface to avoid negative impacts on soil aeration and GHG emissions (i.e., air quality improvement). A protocol is described to calculate the stratification ratio of soil organic matter fractions from a diversity of sampling procedures, which may be relevant in different ecoregions and conditions of the soil.

Abundant natural resources have provided America, and many other countries, with the wealth needed to support a prosperous economy. However, unlike extractable, nonrenewable natural resources (e.g., coal, oil and minerals), agronomically important natural resources (e.g., air, water and soil) are renewable sources of wealth that rely on stewardship to remain valuable into the future. If we disregard these renewable natural resources, America's wealth will certainly diminish. Poor land management decisions can turn clean air in a region to dusty and polluted skies (remember the Dust Bowl of the 1930s?). Even more far reaching, however, poor land management decisions in many seemingly small isolated situations can change our common global atmosphere and increase the unpredictability of weather events in response to rising GHG concentrations. Similarly, poor land management decisions can lead to local and regional pollution of surface and ground waters. Of equal concern, less than ideal land management implemented across a large region can negatively affect distant ecosystems; for example, hypoxia in the Chesapeake Bay and Gulf of Mexico from cumulative effects throughout the Chesapeake Bay watershed and the vast Mississippi River Basin.

Soil quality can be similarly diminished or rejuvenated with various land management decisions, although local decisions are not as geographically far reaching as they are on air and **water quality** issues. However, soil quality is a key factor in controlling the quality of air and water on a broader scale. This paper addresses the interrelationships among air, water and soil quality, as affected by different agricultural management. It is posited that **soil organic carbon** (SOC) – not simply its content, but its depth distribution in the soil profile – can be used as a key indicator of environmental quality in agricultural systems. A conceptual diagram is described in **Figure 1**, in which air, water and soil quality are directly affected by agricultural management practices and systems. The author's hypothesis is that stratification of SOC will integrate these environmental quality responses into a simple yet robust index that can help guide the development and widespread implementation of sustainable agricultural systems (note: SOC is used here as a broad measure of soil organic matter;

*US Department of Agriculture, Agricultural Research Service, NC State University Department of Soil Science, Campus Box 7619, Raleigh, NC 27695-7619, USA
Tel.: +1 919 515 1973; Fax: +1 919 856 4712; E-mail: alan.franzluebbers@ars.usda.gov

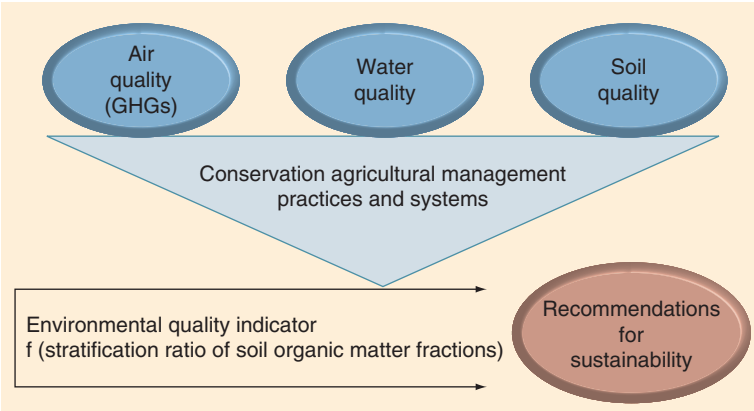

Figure 1. Influence of agricultural management on air, water and soil quality. Illustrates how air, water and soil quality are affected by agricultural management, the results of which influence the environmental component of agricultural sustainability, as indicated by the stratification ratio of soil organic matter fractions.

the stratification index could be calculated with other fractions of organic matter as well).

America's investment in renewable natural resource wealth started with the development and implementation of a variety of **conservation agriculture** approaches. Conservation tillage, cover cropping and recycling of animal wastes as soil amendments on crop and pasture lands are wise steps towards regenerating our natural resources, due to the many benefits they impart of protecting soil from erosion, building organic matter and efficiently utilizing nutrients. However, these components should only be viewed as a beginning, as there are ecologically oriented system level changes needed to transform the nation's agriculture into a regionally appropriate sustainable food production system that simultaneously regenerates its natural resource wealth [1]. Some systems to consider along this continuum of sustainability are conservation agricultural systems, organic agricultural systems, integrated crop–livestock systems, management-intensive rotational grazing systems and perennial-based agricultural systems.

With better understanding and utilization of a robust, simple and quantitative index, the status and trend of a region's renewable natural resource wealth could be efficiently and appropriately characterized with time. This would contribute to the sustainability of agriculture, particularly the first component of the following four goals [2]:

- Enhance the natural resource base and environment;
- Make farming financially viable;
- Contribute to the well-being of farmers, farm workers and rural communities;
- Provide abundant, affordable food, feed, fiber and fuel.

Furthermore, extensive quantification of this environmental quality indicator could help contribute to the recommendation by the National Research Council [2]: *"Sustainability is best evaluated not as a particular end state, but rather as a process that moves farming systems along a trajectory toward greater sustainability on each of the four goals … Finding ways to measure progress along a sustainability trajectory is an important part of the experimentation and adaptive management process … Yet, there are no agreed-upon standards regarding which indicators to use under different conditions … Developing consistent and effective indicators would facilitate assessment of the sustainability of farming practices or systems. Understanding the relationships between sustainability indicators and the outcomes they are meant to represent is a priority for future research."*

Utilization of this environmental quality indicator also fits within the goals outlined in Janzen *et al.* to intensify our research efforts in understanding the functioning of robust and resilient ecosystems from the vantage point of the future, which certainly will require that agricultural systems have high environmental integrity amidst a burgeoning human population demanding more food [3]. In addition, a more systems-oriented approach to understanding agriculture and the environment in its complexity of interactions is needed.

Key terms

Soil quality: Ability of soil to achieve inherent soil functions; for example, to physically support plant growth, receive and store water, cycle nutrients efficiently, foster a thriving soil biological community, and decompose natural and xenobiotic compounds.

Water quality: Condition of water flowing through or over a landscape; negatively affected by chemical or biological contamination from land management activities.

Soil organic carbon: Living and nonliving carbon in soil that contributes as a food source for soil biological activity, as a chemical structure to store a wide diversity of nutrients, and as a physical component of soil that controls water and gas flow into and out of soil.

Conservation agriculture: Environmental approaches to agricultural production that recognize the appropriateness of multiple soil and water conservation practices to build a sustainable system within a particular region. Three key principles of conservation agriculture are minimizing soil disturbance, maximizing soil surface cover and stimulating biological activity.

Balance between production & environmental quality

Striking a balance between food/fiber/feed production and conservation of natural resources is needed to achieve long-term sustainability in agricultural systems. During the 20th century, American agriculture shifted focus several times from production-oriented to conservation-oriented approaches. Tillage-intensive agriculture expanded throughout the Great Plains during the early part of the century but, when combined with the severe droughts of the 1930s, a major conservation movement developed that placed emphasis on soil conservation. The chemical-intensive agriculture that developed mid-century to overcome the low food supply during World War II resulted in vast water

pollution, eventually placing greater emphasis on water quality protection. Toward the end of the 20th century, several factors led to the development of conservation tillage systems, which conserve water, use less energy and reduce soil erosion. Some of these factors included increasing competition for water between municipal–industrial–agricultural sectors, the energy crisis of the 1970s that magnified machinery operating expense and ongoing, widespread soil erosion that required abatement. Current high oil prices and government incentives to develop biofuels from agricultural products have caused another production-oriented stimulus. Concern over potential soil and water degradation with expanded biofuel production has been raised [4,5].

Development and widespread utilization of a few environmental quality indicators would help moderate extreme fluctuations between production and environmental foci, ultimately leading to a more targeted and efficient path towards truly sustainable agricultural systems.

GHG emissions

Agricultural GHG emission (notably CO_2, CH_4 and N_2O) is a topic of much current research, which is deservedly occurring due to the relatively unknown quantitative impacts that various agricultural management systems are exerting on these important gases that can influence direct and indirect components of climate change [6]. Globally, the dominant GHG is CO_2, contributing 77% to radiative forcing. A great deal of research has been conducted for decades on CO_2 emission from soil under various agricultural systems [7–12]. More recently, CH_4 and N_2O emissions have been increasingly researched, although relatively little is still known about the numerous edaphic and biological factors influencing their annual and seasonal variations. CH_4 has a global warming potential on a molar basis compared with CO_2 (100-year time period) of 25 and contributes 14% to radiative forcing, and N_2O has a global warming potential of 298 and contributes 8% to radiative forcing [13]. From the estimated US agricultural burden of 501 Tg CO_2-e in 2008, N_2O emission contributed 46% (mainly nitrogen management of soil) and CH_4 emission contributed 37% (mainly enteric fermentation and manure management), leaving 16% due to CO_2 emission (mainly fossil fuel use and liming, and urea applications to soil) [14].

Emission of GHGs from agricultural systems is highly dynamic, both spatially and temporally. Large temporal variations have been reported on daily, seasonal and yearly time scales. Pulses of N_2O emission have been measured, especially in response to thawing events in springtime [12,15,16], inorganic nitrogen fertilizer application [17,18], manure application [19,20] and incorporation of a legume cover crop [21]. The effect of tillage system on N_2O emissions has been variable, but it appears that one factor controlling the net balance in N_2O emissions between tillage systems is soil aeration. In a review of studies around the world, there was no difference in N_2O emissions between tillage systems in well- or medium-aerated soils, but greater N_2O emissions with no tillage (NT) than with conventional tillage (CT) in poorly aerated soils [22]. Surface accumulation of SOC was likely greater under NT than under CT in aerated soils, but only slightly greater in poorly aerated soils. The current interest in measuring and reporting GHG emissions under a wide diversity of agricultural systems creates an opportunity to associate these responses with changes in the stratification ratio of SOC; depth distribution of SOC and organic matter fractions simply needs to be measured simultaneously.

In agricultural systems, CH_4 is primarily derived from enteric fermentation, paddy rice production and manure storage. However, CH_4 can be emitted from soil under low-oxygen conditions, such as following manure application [20]. In addition, CH_4 can be consumed by soil under conditions of high surface SOC [23]. Therefore, surface SOC can help reduce soil emission of CH_4.

Water quality

In agricultural settings, water quality concerns arise from sediment, nutrient and pesticide runoff from cropland, and fecal-borne pathogen and nutrient runoff from pastureland and livestock operations [24]. A fundamental linkage between soil and water quality has been established through the development and adoption of conservation tillage systems on cropland. Soil and nutrient losses from cropland [25–27] and pastureland [28–30] can be mitigated with sufficient surface residue cover and keeping soil undisturbed. Cropland managed with conservation agricultural systems has led to improved soil quality [31–34] and a reduced quantity of nutrients in water runoff [35,36]. Significant concern remains when fertilizers and animal manures are continually applied to the soil surface, leading to the potential loss of soluble nutrients (nitrogen and phosphorus), which have the potential to deteriorate water quality [36–38].

Water runoff and soil loss have been related to a number of surface conditions and soil properties. Several changes in soil conditions with adoption of conservation tillage can affect soil and water quality simultaneously. Surface residue cover reduces surface sealing, allowing water to infiltrate. Residues also decrease rainfall and runoff energy so that particle detachment and transport are controlled (Figure 2) [39]. Surface residue cover is also a key prerequisite towards improving soil quality under conservation tillage management. Surface soil

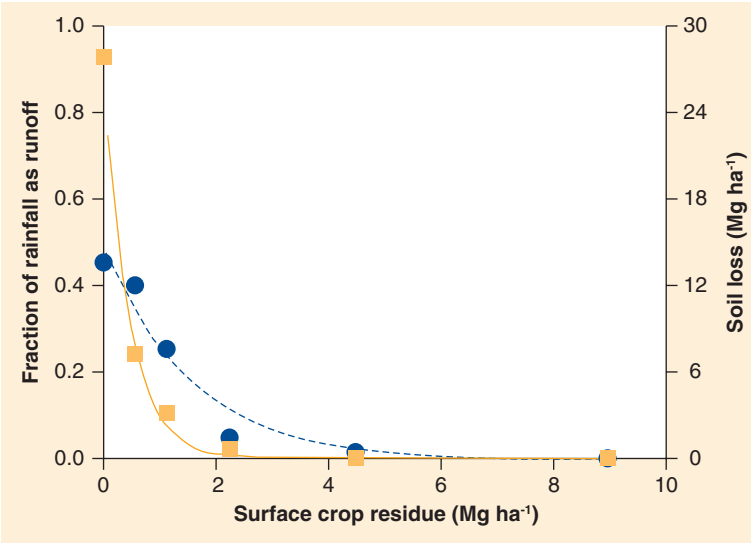

Figure 2. Fraction of rainfall as runoff (dotted line) and soil loss via runoff (solid line) as a function of surface crop residue mass immediately prior to rainfall simulation. Based on well-drained silt loam soil in Indiana, USA. Wheat straw was applied to bare ground. There was 156 mm of rainfall simulated during 3 days.
Reproduced with permission from [92].

roughness, achieved typically with plowing tools, has been shown to positively affect infiltration and reduce water runoff volume and soil loss, at least temporarily [40]. However, continual soil disturbance to create roughness may eventually reduce soil quality by stimulating mineralization of organic matter. Sufficient surface residue cover and lack of inversion tillage leads to enhanced surface SOC content, the effect of which can enhance water-stable aggregation and water infiltration [41,42]. SOC accumulation also leads to greater potential soil biological activity, which assists in improving soil aggregation and creating macropores capable of channeling water quickly from the soil surface to the soil profile [43].

Some negative aspects of surface SOC accumulation have been suggested from continuous macropores that could cause rapid nutrient and pesticide transport to groundwater [44]. Undisturbed soil with frequent surface application of fertilizer and manure can also lead to highly stratified phosphorus distribution in pastures [45], potentially impairing water quality through dissolved phosphorus transport in overland flow [46–48]. These potential detrimental effects of nondisturbance of soil and repeated nutrient applications to the soil surface must be evaluated further within a broader ecosystem context to fully assess their contribution.

Presence of surface residues and high surface SOC are a natural consequence of long-term conservation agricultural management, but the importance of each to water runoff control and water quality protection are not easily separated. On a Typic Argiudoll managed with NT for 15 years in Illinois, USA, removal of surface residue prior to rainfall simulation reduced water infiltration rate [49]. On a Typic Kanhapludult managed with CT and NT for 5 years in Georgia, USA, removal of surface residue reduced infiltration under CT, but had no significant effect under NT [50]. Relative importance of surface residues versus surface SOC may be affected by the scale of investigation, in which contact time of water at the soil surface may be variably controlled (e.g., ponded infiltration versus rainfall simulation versus natural rainfall).

Soil quality

The ability of soil to function effectively as a medium for plant growth, as a regulator of the water cycle and as a reservoir of biota capable of consuming organic matter and emitting gases to the atmosphere, is an essential part of our world. Unfortunately, humans have damaged many of these essential soil functions with aggressive land management activities. Food production, food security and environmental quality (e.g., water quality, climate change and energy use in food production) are linked to the concept of soil quality through management impacts on various soil functions. Unfortunately, moderate to severe degradation of soils (i.e., loss of soil biodiversity, poor soil tilth and unbalanced elemental composition) has and continues to occur with industrialized agricultural production systems. Reports on the state of agricultural land in America suggest that soil sediment, nutrients and organic matter have been lost at rates far exceeding a sustainable level, the result of which has had enormous direct and indirect consequences on the profitability, productivity and environmental quality of agriculture [51–53].

Soil quality is dependent upon intended use; humans derive many valuable services from soil and their activities impact how soil affects the rest of the environment. The use-dependent nature of soil quality is not without debate [54]. Notwithstanding, soil quality has served as a scientific tool for land managers to adaptively manage soil resources for sustainable future use [55]. Land practitioners have been at the forefront to define and assess soil quality, primarily because of their concerns for the health of the environment [56]. Assessment of soil quality has been integral for the development and evaluation of sustainable agricultural systems [57,58].

Assessment of soil quality separates static and dynamic soil properties, because static soil properties reflect inherent characteristics of a particular site (soil texture, mineralogy and classification), which are influenced by geologic history and long-term climatic conditions. In addition, topography, hydrology and climate influence the productivity and environmental quality

of a site somewhat independent of management. Static soil properties have been characterized through periodic samplings with the National Resources Inventory [59]. Static soil properties provide contextual background to evaluate how soil management practices might alter dynamic soil properties.

Soil properties that can change value over relatively short time periods (e.g., months, years and decades) are considered dynamic. Since dynamic soil properties change quickly and dramatically in response to management, they can indicate whether a farm uses agronomically and ecologically sustainable practices.

Sustainable cropping systems will improve soil quality, for example, through diverse crop rotations, minimal use of tillage for weed control and seedbed preparation, and addition of organic amendments such as animal manures, crop residues and compost. Poor management that causes poor soil quality often occurs by starving soil biota from low residue production, allowing erosion from intensive tillage on sloping lands and thwarting opportunities to biologically control pests through lack of cropping system diversity.

Soil quality indicators are often divided into three main classes: chemical, physical and biological. Within each of these classes, a variety of soil properties or processes can be selected to indicate soil functional capabilities. Unfortunately, most commercial soil testing laboratories do not offer suitable biological and physical tests to assess the necessary balance of soil quality indicators. However, minimum datasets for soil quality have been proposed [60,101].

Developing a small set of indicators that can integrate several of these characteristics simultaneously, or through multicriteria relationships, and be applicable across a wide geographic region, would be very valuable for widespread utilization of soil quality assessment and ultimately leading to a more targeted and efficient path towards truly sustainable agricultural systems.

In agriculture, key soil functions characterized by an indicator should be supplying and cycling nutrients for optimum plant growth; receiving rainfall and storing water for root utilization; filtering water passing through soil to protect groundwater quality; storing SOC for nutrient accumulation and mitigating GHG emission; and decomposing organic matter and xenobiotics to avoid detrimental exposures to plants and the environment. Optimizing these soil functions is critical for achieving a balance between production and environmental quality, a necessary step towards sustainable agricultural systems.

Stratification of soil organic matter

Soil organic matter is one of the key attributes of soil quality that is vital to many soil functions, because it is a source of energy, substrate and biological diversity. Content of SOC in any particular soil is determined partly by inherent soil forming factors (i.e., climate, organisms, relief, parent material and time), as well as by management, which alters microclimate and organism influences. For example, Mollisols in temperate climates have inherently greater SOC than Ultisols in subtropical climates. Soil organic matter under native vegetation in these two soil orders would be very different due to the long-term history and climatic conditions that control steady-state inputs and outputs of carbon. Similarly, implementation of the most sustainable agricultural

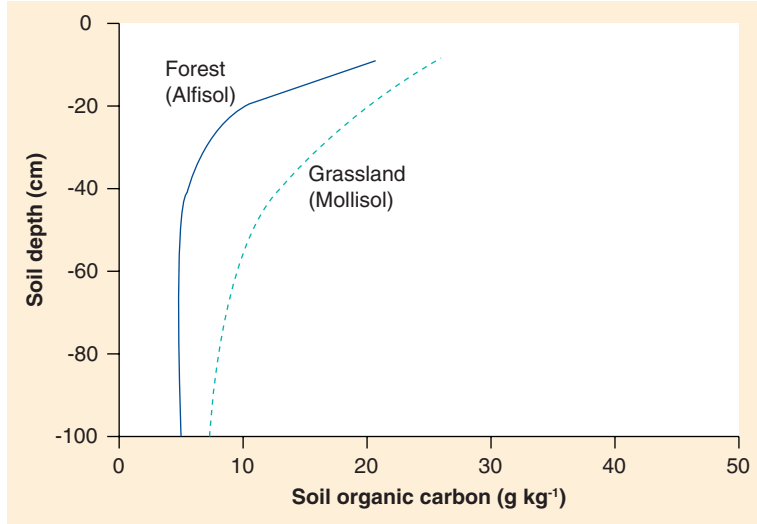

Figure 3. Depth distribution of soil organic carbon in two soils under native vegetation.

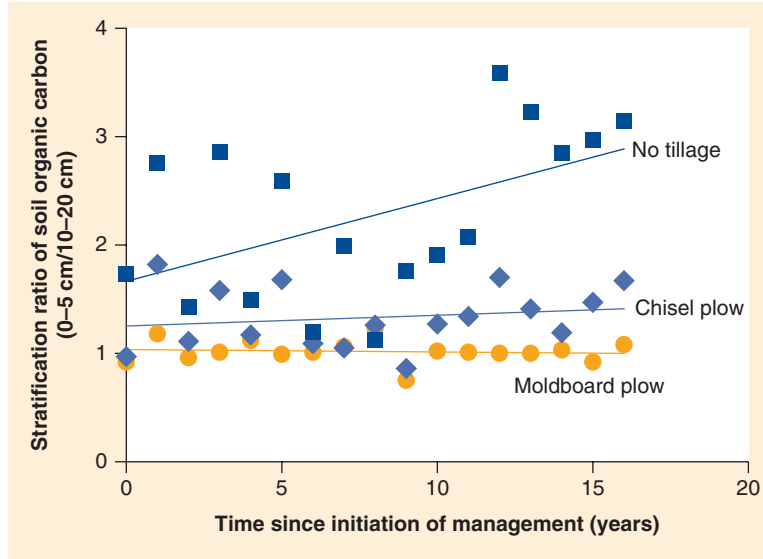

Figure 4. Change in stratification ratio of soil organic carbon with time under different tillage systems in Spain.
Data taken from [62].

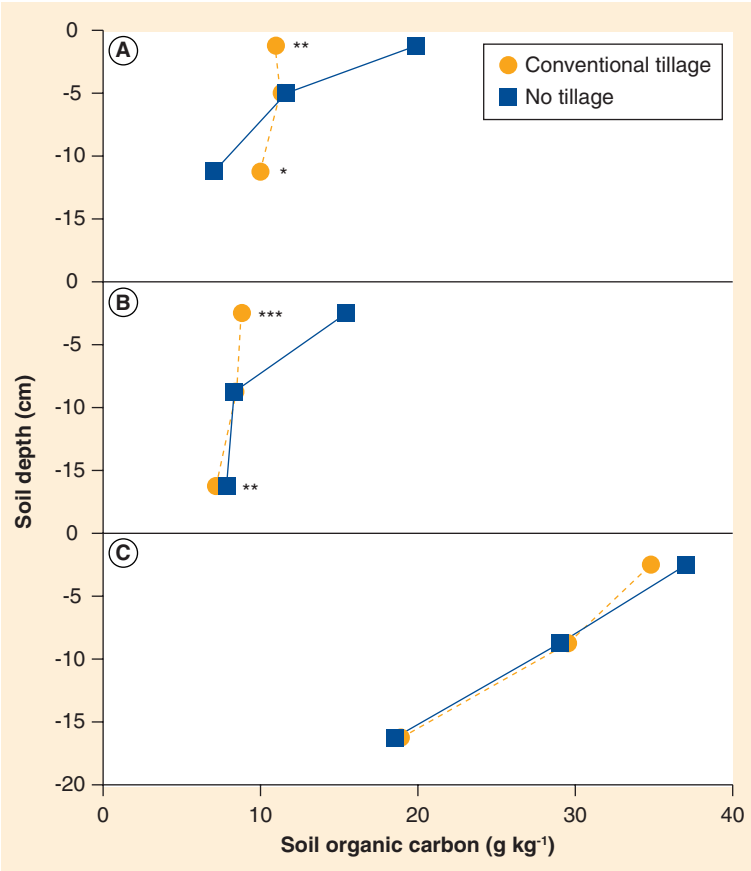

Figure 5. Depth distribution of soil organic carbon under conventional and no tillage in three different ecoregions. (A) Georgia, USA: 1250 mm mean annual precipitation; 16.5°C mean annual temperature; 21 Mg ha^{-1} of soil organic carbon. **(B)** Texas, USA: 980 mm mean annual precipitation; 20°C mean annual temperature; 26 Mg ha^{-1} of soil organic ca rbon. **(C)** Alberta/British Columbia, Canada: 450 mm mean annual precipitation; 20°C mean annual temperature; 61 Mg ha^{-1} of soil organic carbon. *, ** and *** indicate significance of difference between pairs of means within a depth at $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively. Reproduced with permission from [61] © Elsevier (2002).

management system on these two different soil orders would likely result in greater SOC content on a Mollisol than on an Ultisol, but the incremental or proportional change might be greater in the Ultisol, depending on severity of previous degradation. Therefore, the content of SOC itself would not be a robust quantitative indicator of soil or environmental quality. To be able to use SOC as a quantitative soil quality indicator, there is a need to either incorporate individual SOC responses to management within a classified set of soil and climatic conditions (e.g., different soil quality responses in Mollisols, Ultisols, Alfisols in the warm-temperate region, Alfisols in the cool-temperate region, Entisols in the arid region and Entisols in the humid region) or develop a normalization protocol so that SOC responses to management could be compared across a diversity of soil and climatic conditions.

Depth distribution of SOC is proposed as a robust indicator of how agricultural management might affect soil and environmental quality. Depth distribution of SOC can be normalized across soils and climatic conditions by calculating a ratio; that is, SOC concentration near the surface (e.g., 0–5-cm depth) divided by SOC concentration at or below the traditional plow layer (e.g., 20–30-cm depth) [61]. Since SOC at or below the traditional plow layer changes very little due to management, the concentration of SOC at this depth provides a signature value for each soil, depending upon its overarching and unique climate, texture, landscape position, aspect and mineralogical factors. How management changes SOC concentration near the surface relative to each soil's signature value can then be calculated as a key indicator of soil quality (or how management alters soil function).

Stratification of SOC with depth is common in many natural ecosystems, managed grasslands and forests, and conservation-tilled cropland (Figure 3) [62–68]. The reason why surface SOC is vitally important in natural (and agricultural) systems is because the soil surface accepts nutrients and biochemicals (fertilizers and pesticides) from aboveground vegetation and litter into the soil profile or rejects them as runoff contamination; receives intense impact of rainfall that can either allow rapid infiltration with development of permanent biopores or create surface crusts with disruption of surface aggregates; partitions gas flow into and out of soil; and creates either an oasis of litter (surface residue)-covered soil, providing organic substrates and protected microenvironmental conditions for support of biological diversity or a barren surface devoid of habitat protection.

With time, agricultural soils can become stratified with SOC when they remain relatively undisturbed from tillage (e.g., with conservation tillage and pastures) and when they receive sufficient organic materials supplied to the soil surface (e.g., with cover crops, sod rotations and diversified cropping systems). The stratification ratio of SOC (0–2.5 cm/12.5–20 cm) in an Aquic Hapludult in Maryland, USA, increased from 1.0 under plow tillage to 1.1 with 1 year of NT, and to 1.5 with 3 years of NT [69]. On a Typic Paleudalf in Kentucky, USA, the stratification ratio of SOC increased with time under NT and after 2 years of NT was always greater than under CT [70]. On a Calcic Haploxeralf in Spain, the stratification ratio of SOC (0–5 cm/10–20 cm) increased with time under NT, but remained stable with time under chisel plow and moldboard plow (Figure 4). From a survey of farms in the southeastern USA, the stratification ratio of SOC (0–5 cm/12.5–20 cm) increased from an average of 1.4

under CT to a plateau of 2.8 within 10 years of adopting conservation tillage [71]. During pasture development on a Typic Kanhapludult in Georgia, USA, the stratification ratio of SOC (0–15 cm/15–30 cm) increased from 2.4 at initiation to 3.0 ± 0.7 at the end of 5 years to 3.6 ± 0.6 at the end of 12 years [72,73].

Typically, SOC under long-term conservation tillage systems is stratified with depth as a result of crop residues left at the soil surface, where temperature and moisture fluctuations limit decomposition and result in accumulation of SOC. Early observations indicated greater difference in stratification of SOC between tillage systems in hot–wet–low soil organic matter environments than in cold–dry–high soil organic matter environments (Figure 5). Soils with a low inherent level of SOC could, therefore, be the most functionally improved with conservation tillage, despite modest or no change in total standing stock of SOC within the rooting zone.

Stratification of soil organic matter is not limited to total SOC, but can also occur with particulate organic, microbial biomass, and mineralizable carbon and nitrogen fractions [61]. The degree of stratification of soil organic matter fractions with adoption of conservation agricultural systems will depend upon the inherent level of SOC dictated by climatic conditions; type and intensity of soil disturbance; type of cropping system that determines the quantity and quality of organic carbon inputs; and years of management.

On a Mollic Cryoboralf in Alberta, Canada, the level of soil microbial biomass nitrogen at a depth of 0–10 cm was positively correlated with barley and canola yield, indicating that turnover of labile nitrogen in surface soil organic matter contributed significantly to crop yield [74]. On a Fluventic Ustochrept in Texas, USA, surface-soil nutrients were enhanced following 8 years of NT compared with CT [75]. In another study in Texas, greater stratification of soil nutrients under reduced tillage was associated with significantly greater cotton lint yield [76].

Since the recent development of this concept [61], a large number of research reports from other parts of the world have documented the influence of conservation agricultural management systems on stratification of various soil organic matter fractions. Greater stratification ratio of SOC under NT than under CT has been reported in Georgia, USA [73], Virginia, USA [77], Canada [78], Brazil [79], Argentina [80], China [81], Italy [82] and Spain [83–86]. The stratification ratio of additional soil organic matter fractions has been reported for various other agricultural management comparisons in Georgia, USA [87], Canada [88], China [89] and Spain [90]. These studies provide further evidence to support the concept of stratification of SOC as an indicator of environmental quality. As a result of this vertical redistribution of SOC, a linkage to soil quality (i.e., nutrient cycling [73–76], surface aggregation and hydrologic function [78,89,90], organic matter decomposition [77,79–81,83–88] and soil biological activity/diversity [73,82,83,86]) of the entire soil profile can be firmly established.

However, there is still a large need for rigorous scientifically established relationships in different agroecological regions to further validate the use of the SOC stratification ratio as a simple, robust indicator of environmental quality. The stratification ratio of SOC was highly related to rate of water infiltration and macroaggregation of surface soil in a Typic Kanhapludult in Georgia, USA [91]. Although many water runoff and nutrient transport studies have been conducted throughout the USA, a lack of detailed SOC characterization by depth has occurred [92], which limits robust quantitative validation despite intuitive qualitative association. From limited data available at two sites in Mississippi and Ohio, USA, the stratification ratio of SOC (0–3 cm/7.6–15.2 cm) was strongly inversely related to soil loss during rainfall simulation experiments (Figure 6).

It is not entirely clear whether some fractions of organic matter might be more sensitive to changes brought about by agricultural management systems than others. Active fractions of organic matter may be too sensitive, but total SOC and nitrogen may be too general to reflect the broad diversity of environmental responses (i.e., air, water and soil quality). Particulate organic carbon and nitrogen may be fractions that are

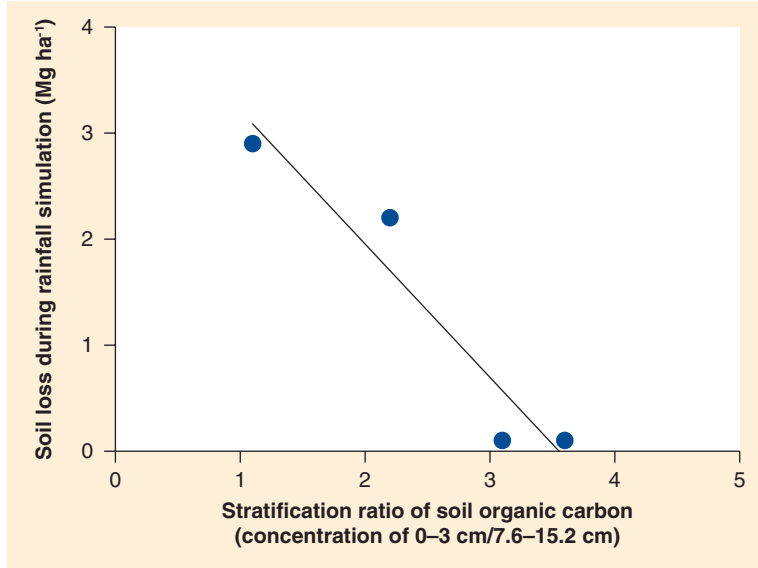

Figure 6. Relationship of soil loss to stratification of soil organic carbon.
r = -0.96.
Data taken from [26].

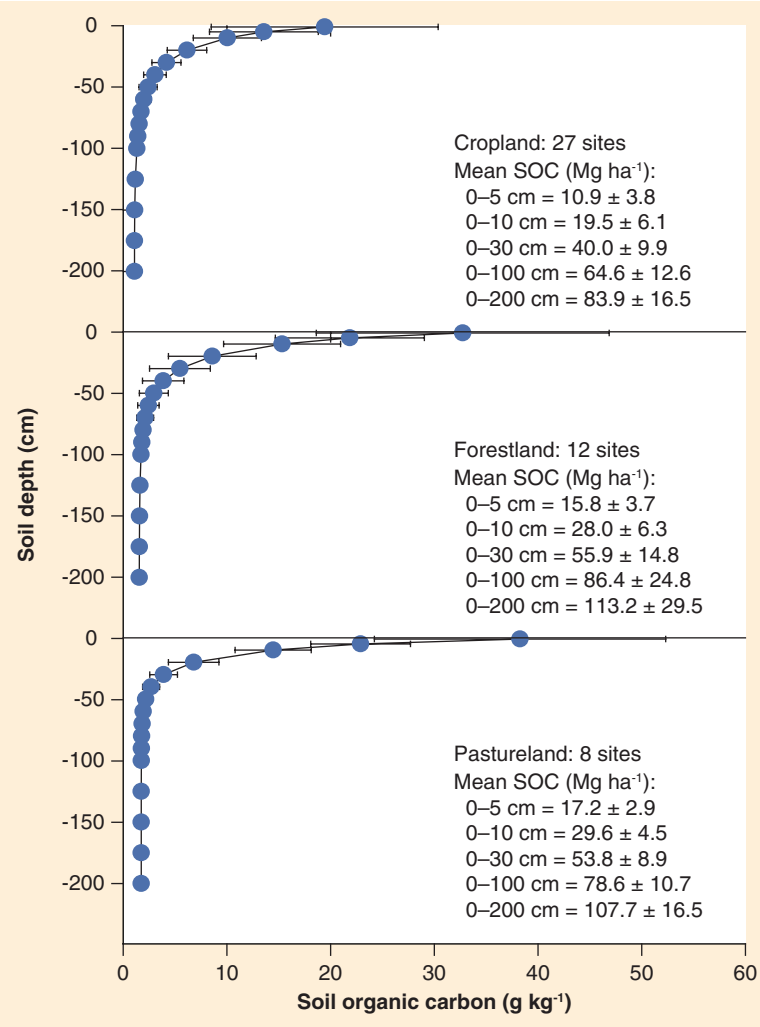

Figure 7. Mean depth distribution of soil organic carbon from Ultisols in Georgia, USA, as affected by land use.
SOC: Soil organic carbon.
Data taken from [95].

stable enough, yet highly responsive to minor differences in management practices, especially regarding tillage type and frequency, residue management, annual cropping versus perennial cropping, cover cropping, animal manure management, alley cropping and so on. Further research on stratification of different organic matter fractions related to production and environmental performance is needed.

A remaining issue in the development of the stratification ratio of SOC as an indicator of environmental quality is determining the sensitivity of various depth increments and selecting an optimum set of depth increments for predicting environmental quality responses. Using multiple sampling depths from a diverse soil survey report in Georgia, USA, depth distribution of SOC could be described with a mathematical expression of the form [93]:

$$SOC = a + b \bullet \exp(-c \bullet D)$$

Equation 1

Where SOC is an output value (g kg^{-1}), a is a derived constant representing the minimum concentration of SOC deep in the profile (g kg^{-1}), b is a derived constant representing the peak SOC concentration from accumulation nearer the soil surface (g kg^{-1}), c is a derived constant representing a decay coefficient controlling the magnitude of decline in SOC concentration with depth (cm^{-1}), and D is an input parameter representing the midpoint of a sampling increment (depth [cm]). Using this mathematical description, SOC (or any other measured soil organic matter fraction) can be calculated at any formulated optimum depth and subsequently used in a calculation of the stratification ratio.

Mean SOC distribution from multiple profiles of the Southern Piedmont region land use systems is shown in Figure 7. Although definitive depths have not been recommended for calculating the stratification ratio, it is clear that the numerator should be focused within the surface 10 cm and the denominator should be focused within some reasonable subsurface layer within 10–50 cm depth. The subsurface depth of choice may be determined by historical management and actual availability of data, but typically would be near the bottom of the traditional plow layer (e.g., 20–40-cm depth). Using the dataset from Figure 7 as an example, the stratification ratio calculated from SOC concentration at 2.5 cm (midpoint of 0–5 cm sampling) divided by that at 30 cm (midpoint of 20–40 cm sampling) was 4.8, 6.3 and 9.2 under cropland, forestland and pastureland, respectively. Although these data were not statistically comparable due to the nature of their derivation, a reasonable least significant difference of 1.5 can be projected onto these comparisons from previous work [91]. Greater ratio with undisturbed soil under forestland and pastureland was expected. When using SOC concentration at 5 cm divided by that at 30 cm, the stratification ratio was 4.1, 5.2 and 7.2 under cropland, forestland and pastureland, respectively, suggesting that statistical differences only occurred between pastureland and other land uses. When using SOC concentration at 10 cm divided by that at 30 cm, the stratification ratio was 3.1, 3.6 and 4.4 under cropland, forestland and pastureland, respectively. When using SOC concentration at 15 cm divided by that at 100 cm, the stratification ratio was 9.7, 7.0 and 5.3 under cropland, forestland and pastureland, respectively. Clearly the land use trend on stratification became contrary to that nearer the surface when probing too deep into the profile and, therefore, too deep samplings are not needed and should be avoided when

interpreting the effect of management on the stratification ratio. Management will affect the surface 10–30 cm of soil most dramatically in the short term and, therefore, focus on studies with contrasting management duration <50 years should be on the surface approximately 30 cm.

Equation 1 allows for calculation of the stratification ratio at any point along a continuum of soil profile data, assuming that a representative distribution of SOC concentration has been sampled; for example, from greater than three sampling points within the surface 40 cm and more points if sampled to deeper depths. The alternative calculation method is to simply use a standardized set of sampling depths, for example, 0–5 or 0–10 cm for surface samples and 12.5–20, 15–30, 20–30 or 30–40 cm for subsurface samples. Calculations of SOC based on sampling of 0–10 cm divided by 20–30 cm resulted in a stratification ratio of 3.0, 3.8 and 5.3 for cropland, forestland and pastureland, respectively [93], with least significant difference of 1.9.

One soil order and drainage condition that had SOC concentration data not fitting the typical depth distribution function well was Spodosol in the Flatwoods major land resource region of the Atlantic Coast of Georgia, USA (Figure 8). Depletion of SOC in the eluviated upper soil layer and deposition in the subsequent illuviated lower layer caused this nonconformance. However, all other soil orders (Alfisols, Entisols, Inceptisols, Mollisols and Ultisols) produced very reasonable associations ($r^2 > 0.9$) [93]. Thus, although the stratification ratio may not be universally applicable, there are a large number of soils that the relationship shows excellent potential to monitor the progress of soil condition with improved surface soil management.

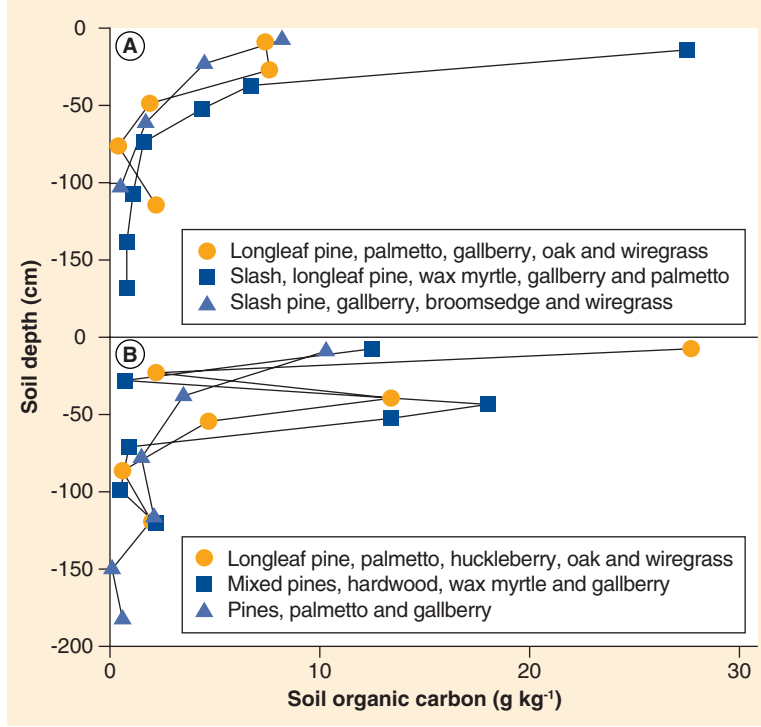

Figure 8. Depth distribution of soil organic carbon from Spodosols in Georgia, USA, as affected by drainage class. (A) Three somewhat poorly drained profiles: Ridgeland (sandy, siliceous, thermic Oxyaquic Alorthods). **(B)** Three poorly drained profiles: Leon (sandy, siliceous, thermic Aeric Alaquods). Soils in **(A)** are better drained than soils in **(B)**. **(A)** and **(B)** are differentiated by soil drainage class, resulting in two different responses: typical stratified distribution for better aerated soils and atypical SOC distribution of varying concentration for poorly aerated soils.
Data taken from [95].

Building ecosystem resilience with stratified soil organic matter

Change in SOC is an important indicator of land use sustainability – declining SOC leads to poor plant performance, loss of soil through erosion, and the ever increasing need for external inputs to subsidize the lack of nutrients, soil biotic diversity and poor soil condition for root development. Land with aggrading SOC leads to robust plant production, opportunities to resist natural degradative forces and limit the return of plant-fixed carbon back to the atmosphere. A review of the many positive benefits of SOC content on various attributes of soil, plant production and environmental quality was described in Franzluebbers [38]. Although the stock of SOC may be more important to storage of nutrients and retention of water, it appears that stratification of SOC may be more important for developing a stable surface structure to resist loss of soil and nutrients in runoff and accumulate a robust surface habitat that encourages efficient nutrient cycling and strong microbial linkages with underlying roots. As an example, soil from two sides of a roadway (Typic Kanhapludults) that had been managed consistently different for 25 years (one containing 9.4 Mg C ha^{-1} and the other containing 18.9 Mg C ha^{-1}) were uniformly mixed and tested repeatedly for water infiltration [91]. The time required for 2.8 cm of water to infiltrate averaged 7.3 min for the high-carbon soil managed under NT and 10.2 min for the low-carbon soil managed under CT. However, if the soils were left intact (stratification ratio of 0–3 cm/6–12 cm of 1.4 for the low-carbon soil and 5.7 for the high-carbon soil), time required for infiltration was 3.4 min for the high-carbon soil and 12.9 min for the low-carbon soil. The positive effect of SOC was essentially doubled when SOC was stratified than when uniformly distributed.

Interestingly, the stratification ratio of SOC may also be highly predictive of the stock of SOC, at least in some regions. From a land use survey in the southeastern USA [70], the stock of SOC to a depth of 20 cm was related in a nonlinear manner with the stratification

ratio (0–5 cm/12.5–20 cm) of SOC [94]. In the dataset of 267 soil profiles from Ultisols collected from 1954 to 1986 throughout Georgia, USA [95], the stratification ratio of SOC was not well related to SOC content at 0–30, 0–60, 0–100 or 0–200-cm depths. One reason for the lack of congruency in this dataset may have been the focus on subsurface profile conditions rather than near-surface conditions. The midpoint of the upper soil layer sampled was at a depth of 9 ± 3 cm, which indicated that adequate characterization of the surface soil condition may have been missed. The dataset did have 6 ± 1 depths sampled throughout the profile and the deepest sample had a midpoint of 140 ± 37 cm. In other soils in cold wet climates, stock of SOC may not change with conversion from CT to NT [96–98]. Soil may become stratified with NT in this climate, but measurable stock of SOC may not change due to a variety of mechanisms, including sequestration of carbon in unsaturated clayey subsoil and cold conditions that limit decomposition of disturbed soil. Under such conditions without change in stock of SOC, soil functioning may still be increased with stratified SOC, particularly considering high surface residue and SOC in protecting against erosion and water runoff, improving aggregation and providing biological habitat.

Perhaps the strongest evidence for improved ecosystem function from concentrated SOC at the soil surface comes from soil erosion control and water and nutrient runoff abatement. However, the sequestration of SOC associated with stratified SOC provides good evidence of its effect on controlling GHG emissions. Further work is needed to quantify relationships with N_2O and CH_4 more specifically under a variety of conditions. Concentrated SOC at the surface may also

Executive summary

Background
- Striking a balance between food/fiber/feed production and conservation of natural resources is needed to achieve long-term sustainability in agricultural systems.
- It is posited that soil organic carbon (SOC) – not simply its content, but its depth distribution in the soil profile – can be used as a key indicator of environmental quality in agricultural systems.

Balance between production & environmental quality
- Achieving a balance between agricultural production and conservation of natural resources is a necessary goal to achieve sustainability in agricultural systems.
- Development and widespread utilization of a few environmental quality indicators would help moderate extreme fluctuations between production and environmental foci, ultimately leading to a more targeted and efficient path towards truly sustainable agricultural systems.

GHG emissions
- Agricultural GHG emissions (CO_2, CH_4 and N_2O) is a topic of much current research, which is deservedly occurring due to the relatively unknown quantitative role that various agricultural management systems are exerting on these important gases that can influence direct and indirect components of climate change.

Water quality
- A fundamental linkage between soil and water quality has been established through the development and adoption of conservation tillage systems on cropland.
- Presence of surface residues and high surface SOC are a natural consequence of long-term conservation agricultural management, but the importance of each to water runoff control and water quality protection are not easily separated.

Soil quality
- Developing a small set of indicators that can integrate several of these characteristics simultaneously or through multicriteria relationships, and be applicable across a wide geographic region, would be very valuable for widespread utilization of soil quality assessment and ultimately leading to a more targeted and efficient path towards truly sustainable agricultural systems.

Stratification of SOC
- Content of SOC in any particular soil is determined partly by inherent soil forming factors (i.e., climate, organisms, relief, parent material and time), as well as by management, which alters microclimate and organism influences.
- With time, agricultural soils can become stratified with SOC when they remain relatively undisturbed from tillage (e.g., with conservation tillage and pastures) and when they receive sufficient organic materials supplied to the soil surface (e.g., with cover crops, sod rotations and diversified cropping systems).
- A remaining issue in the development of stratification ratio of SOC as an indicator of environmental quality is determining the sensitivity of various depth increments and selecting an optimum set of depth increments for predicting environmental quality responses.

Building ecosystem resilience with stratified soil organic matter
- Change in SOC is an important indicator of land use sustainability – declining SOC leads to poor plant performance, loss of soil through erosion and the ever increasing need for external inputs to subsidize the lack of nutrients, soil biotic diversity and poor soil condition for root development.
- There are several unique opportunities with the diversity of long-term experiments around the world to explore potential relationships among production and environmental responses with stratification ratio of soil organic matter fractions.

limit mobility of unwanted heavy metals from solid waste applications to agricultural soil. In two soils in Germany, copper and zinc were in greater concentration near the surface with NT management, a result highly reflective of that of SOC [99]. It was postulated that availability of these metals would be limited by high SOC concentration, effectively reducing mobility despite occurrence at the surface and susceptible to overland flow characteristics.

Large, statistically significant differences in production and environmental quality responses from similar soils managed differently are only realistically derived from long-term experiments. There are hundreds of long-term soil experiments that have been established, although some have not been able to continue due to funding restrictions, personnel turnover and so on [102]. Relatively few have a complete catalogue of continuous production and environmental responses within and among years, and even fewer have collected detailed soil profile measurements. However, there are several unique opportunities with the diversity of long-term experiments around the world to explore potential relationships among production and environmental responses with the stratification ratio of soil organic matter fractions. This research needs to be explored.

Future perspective

Although the enormous complexities of social, environmental and biophysical factors affecting agriculture are appreciated, the stratification ratio of SOC could be used as a relatively simple, robust indicator of environmental quality. By calculating and utilizing the stratification ratio of SOC, a more balanced approach to production and environmental quality of agricultural systems can be expected to be delivered to stakeholders. Producers, agricultural consultants and scientists will appreciate a simple, robust environmental quality indicator that can help evaluate the diversity of conservation agricultural management approaches unique to a locale for the development of truly sustainable agricultural systems.

Acknowledgements

Appreciation is extended to S Knapp for technical assistance in previous research and to the Agricultural Research Service USA scientists involved with and supporting the cross-location research project of GRACEnet (Greenhouse Gas Reduction through Agricultural Carbon Enhancement network).

Financial & competing interests disclosure

This article was prepared as part of official duties with the US Department of Agriculture, Agricultural Research Service. The author has no other relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript apart from those disclosed.

No writing assistance was utilized in the production of this manuscript.

References

Papers of special note have been highlighted as:

- ▪ of interest
- ▪▪ of considerable interest

1 National Research Council. *Toward Sustainable Agricultural Systems in the 21st Century*. Committee on 21st Century Systems Agriculture, The National Academies Press, Washington, DC, USA (2010).

2 Reganold JP, Jackson-Smith D, Batie SS *et al.* Transforming US agriculture. *Science* 332, 670–671 (2011).

▪ **Synthesis document calling for the rejuvenation of agricultural research to explore sustainable production systems.**

3 Janzen HH, Fixen PE, Franzluebbers AJ *et al.* Global prospects rooted in soil science. *Soil Sci. Soc. Am. J.* 75(1), 1–8 (2011).

4 Wilhelm WW, Johnson JMF, Hatfield JL, Voorhees WB, Linden DR. Crop and soil productivity response to corn residue removal: a literature review. *Agron. J.* 96, 1–17 (2004).

5 Simpson TW, Sharpley AN, Howarth RW, Paerld HW, Mankin KR. The new gold rush: fueling ethanol production while protecting water quality. *J. Environ. Qual.* 37(2), 318–324 (2008).

6 Liebig MA, Franzluebbers AJ, Follett RF. *Managing Agricultural Greenhouse Gases: Coordinated Agricultural Research through GRACEnet to Address our Changing Climate*. Academic Press, San Diego, CA, USA (2012).

7 Kucera CL, Kirkham DR. Soil respiration studies in tallgrass prairie in Missouri. *Ecology* 52, 912–915 (1971).

8 Buyanovski GA, Wagner GH, Gantzer CJ. Soil respiration in a winter wheat ecosystem. *Soil Sci. Soc. Am. J.* 50, 338–344 (1986).

9 Rochette P, Desjardins RL, Pattey E. Spatial and temporal variability of soil respiration in agricultural fields. *Can. J. Soil Sci.* 71, 189–196 (1991).

10 Franzluebbers AJ, Hons FM, Zuberer DA. Tillage-induced seasonal changes in soil physical properties affecting soil CO_2 evolution under intensive cropping. *Soil Till. Res.* 34, 41–60 (1995).

11 Franzluebbers K, Franzluebbers AJ, Jawson MD. Environmental controls on soil and whole-ecosystem respiration from a tallgrass prairie. *Soil Sci. Soc. Am. J.* 66, 254–262 (2002).

12 Johnson JMF, Archer D, Barbour N. Greenhouse gas emission from contrasting management scenarios in the northern Corn Belt. *Soil Sci. Soc. Am. J.* 74, 396–406 (2010).

13 IPCC. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the IPCC*. IPCC, Geneva, Switzerland (2007).

14 Council for Agricultural Science and Technology. *Carbon Sequestration and Greenhouse Gas Fluxes in Agriculture: Challenges and Opportunities. Task Force Report No. 142*. Council for Agricultural Science and Technology, Ames, IA, USA (2011).

15 Wagner-Riddle C, Furon A, McLaughlin NL *et al.* Intensive measurement of nitrous oxide emissions from a corn–soybean–wheat rotation under two contrasting management systems over 5 years. *Global Change Biol.* 13, 1722–1736 (2007).

16 Liebig MA, Tanaka DL, Gross JR. Fallow effects on soil carbon and greenhouse gas flux in central North Dakota. *Soil Sci. Soc. Am. J.* 74, 358–365 (2010).

17 Venterea RT, Burger M, Spokas KA. Nitrogen oxide and methane emissions under varying tillage and fertilizer management. *J. Environ. Qual.* 34, 1467–1477 (2005).

18 Venterea RT, Dolan MS, Ochsner TE. Urea decreases nitrous oxide emissions compared with anhydrous ammonia in a Minnesota corn cropping system. *Soil Sci. Soc. Am. J.* 74, 407–418 (2010).

19 Velthof GL, Kuikman PJ, Oenema O. Nitrous oxide emission from animal manures applied to soil under controlled conditions. *Biol. Fertil. Soils* 37, 221–230 (2003).

20 Sistani KR, Warren JG, Lovanh N, Higgins S, Shearer S. Greenhouse gas emissions from swine effluent applied to soil by different methods. *Soil Sci. Soc. Am. J.* 74, 429–435 (2010).

21 Alluvione F, Bertora C, Zavattaro L, Grignani C. Nitrous oxide and carbon dioxide emissions following green manure and compost fertilization in corn. *Soil Sci. Soc. Am. J.* 74, 384–395 (2010).

22 Rochette P. No-till only increases N_2O emissions in poorly-aerated soils. *Soil Till. Res.* 101, 97–100 (2008).

23 Liebig MA, Gross JR, Kronberg SL, Phillips RL, Hanson JD. Grazing management contributions to net global warming potential: a long-term evaluation in the northern Great Plains. *J. Environ. Qual.* 39, 799–809 (2010).

24 Chesters G, Schierow L-J. A primer on nonpoint pollution. *J. Soil Water Conserv.* 40, 9–13 (1985).

25 Holt RF. Crop residue, soil erosion, and plant nutrient relationships. *J. Soil Water Conserv.* 34, 96–98 (1979).

26 Rhoton FE, Shipitalo MJ, Lindbo DL. Runoff and soil loss from midwestern and southeastern US silt loam soils as affected by tillage practice and soil organic matter content. *Soil Till. Res.* 66, 1–11 (2002).

27 Renwick WH, Vanni MJ, Zhang Q, Patton J. Water quality trends and changing agricultural practices in a Midwest US watershed, 1994–2006. *J. Environ. Qual.* 37, 1862–1874 (2008).

28 Barnett AP, Beaty ER, Dooley AE. Runoff and soil losses from closely grazed fescue, a new concept in grass management for the southern Piedmont. *J. Soil Water Conserv.* 27, 168–170 (1972).

29 Jones OR, Eck HV, Smith SJ, Coleman GA, Hauser VL. Runoff, soil, and nutrient losses from rangeland and dry-farmed cropland in the southern High Plains. *J. Soil Water Conserv.* 40, 161–164 (1985).

30 Harmel RD, Torbert HH, Haggard BE, Haney R, Dozier M. Water quality impacts of converting to a poultry litter fertilization strategy. *J. Environ. Qual.* 33, 2229–2242 (2004).

31 Arshad MA, Franzluebbers AJ, Azooz RH. Components of surface soil structure under conventional and no-tillage in northwestern Canada. *Soil Till. Res.* 53, 41–47 (1999).

32 Cambardella CA, Moorman TB, Andrews SS, Karlen DL. Watershed-scale assessment of soil quality in the loess hills of southwest Iowa. *Soil Till. Res.* 78, 237–247 (2004).

33 Liebig MA, Tanaka DL, Wienhold BJ. Tillage and cropping effects on soil quality indicators in the northern Great Plains. *Soil Till. Res.* 78, 131–141 (2004).

34 Bell MC, Raczkowski CW. Soil property indices for assessing short-term changes in soil quality. *Renew. Agric. Food Syst.* 23, 70–79 (2008).

35 Langdale GW, Leonard RA, Thomas AW. Conservation practice effects on phosphorus losses from southern Piedmont watersheds. *J. Soil Water Conserv.* 40, 157–161 (1985).

36 Sharpley AN, Smith SJ, Jones OR, Berg WA, Coleman GA. The transport of bioavailable phosphorus in agricultural runoff. *J. Environ. Qual.* 21, 30–35 (1992).

37 Nichols DJ, Daniel TC, Edwards DR. Nutrient runoff from pasture after incorporation of poultry litter or inorganic fertilizer. *Soil Sci. Soc. Am. J.* 58, 1224–1228 (1994).

38 Franzluebbers AJ. Will we allow soil carbon to feed our needs? *Carbon Management* 1(2), 237–251 (2010).

39 Mannering JV, Meyer LD. The effects of various rates of surface mulch on infiltration and erosion. *Soil Sci. Soc. Am. Proc.* 27, 84–86 (1963).

40 Cogo NP, Moldenhauer WC, Foster GR. Soil loss reductions from conservation tillage practices. *Soil Sci. Soc. Am. J.* 48, 368–373 (1984).

41 Bruce RR, Langdale GW, West LT, Miller WP. Surface soil degradation and soil productivity restoration and maintenance. *Soil Sci. Soc. Am. J.* 59, 654–660 (1995).

42 Franzluebbers AJ, Langdale GW, Schomberg HH. Soil carbon, nitrogen, and aggregation in response to type and frequency of tillage. *Soil Sci. Soc. Am. J.* 63, 349–355 (1999).

43 Shipitalo MJ, Dick WA, Edwards WM. Conservation tillage and macropore factors that affect water movement and the fate of chemicals. *Soil Till. Res.* 53, 167–183 (2000).

44 Addiscott TM, Thomas D. Tillage, mineralization and leaching: phosphate. *Soil Till. Res.* 53, 255–273 (2000).

45 Sharpley AN. Soil mixing to decrease surface stratification of phosphorus in manured soils. *J. Environ. Qual.* 32, 1375–1384 (2003).

46 Pierson ST, Cabrera ML, Evanylo GK *et al.* Phosphorus and ammonium concentrations in surface runoff from grasslands fertilized with broiler litter. *J. Environ. Qual.* 30, 1784–1789 (2001).

47 Pote DH, Kingery WL, Aiken GE, Han FX, Moore PA Jr, Buddington K. Water-quality effects of incorporating poultry litter into perennial grassland soils. *J. Environ. Qual.* 32, 2392–2398 (2003).

48 Harmel RD, Smith DR, Haney RL, Dozier M. Nitrogen and phosphorus runoff from cropland and pasture fields fertilized with poultry litter. *J. Soil Water Conserv.* 64, 400–412 (2009).

49 Bradford JM, Huang C-H. Interrill soil erosion as affected by tillage and residue cover. *Soil Till. Res.* 31, 353–361 (1994).

50 West LT, Miller WP, Langdale GW, Bruce RR, Laflen JM, Thomas AW. Cropping system effects on interrill soil loss in the Georgia Piedmont. *Soil Sci. Soc. Am. J.* 55, 460–466 (1991).

51 National Research Council. *Soil and Water Quality: An Agenda for Agriculture*. National Academy Press, Washington DC, USA (1993).

52 US Department of Agriculture Natural Resources Conservation Service. *America's Private Land: A Geography of Hope*. US Government Printing Office, Washington, DC, USA (1996).

53 Cox C, Hug A, Bruzelius N. *Losing Ground*. Environmental Working Group, Washington, DC, USA (2011)

54 Sojka RE, Upchurch DR. Reservations regarding the soil quality concept. *Soil Sci. Soc. Am. J.* 63, 1039–1054 (1999).

55 Andrews SS, Moorman TB. Introduction. *Agron. J.* 94, 1–2 (2002).

56 Carter MR. Soil quality for sustainable land management: organic matter and aggregation interactions that maintain soil functions. *Agron. J.* 94, 38–47 (2002).

57 Miller FP, Wali MK. Soils, land use and sustainable agriculture: a review. *Can. J. Soil Sci.* 75, 413–422 (1995).

58 Warkentin BP. The changing concept of soil quality. *J. Soil Water Conserv.* 50, 226–228 (1995).

59 Brejda JJ, Moorman TB, Smith JL, Karlen DL, Allan DL, Dao TH. Distribution and variability of surface soil properties at a regional scale. *Soil Sci. Soc. Am. J.* 64, 974–982 (2000).

60 Doran JW, Parkin TB. Defining and assessing soil quality. In: *Defining Soil Quality for a Sustainable Environment*. Doran JW (Ed.). Soil Science Society of America, Madison, WI, USA, 3–21 (1994).

61 Franzluebbers AJ. Soil organic matter stratification ratio as an indicator of soil quality. *Soil Till. Res.* 66, 95–106 (2002).

■■ **Original description rationalizing the calculation of the stratification ratio of soil organic matter.**

62 Lopez-Fando C, Pardo MT. Soil carbon storage and stratification under different tillage systems in a semi-arid region. *Soil Till. Res.* 111, 224–230 (2011).

63 Dick WA. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. *Soil Sci. Soc. Am. J.* 47, 102–107 (1983).

64 Prescott CE, Weetman GF, DeMontigny LE, Preston CM, Keenan RJ. Carbon chemistry and nutrient supply in cedar-hemlock and hemlock-amabilis fir forest floors. In: *Carbon Forms and Functions in Forest Soils*. McFee WW, Kelley JM (Eds). Soil Science Society of America, Madison, WI, USA, 377–396 (1995).

65 Franzluebbers AJ, Stuedemann JA, Schomberg HH, Wilkinson SR. Soil organic C and N pools under long-term pasture management in the southern Piedmont USA. *Soil Biol. Biochem.* 32, 469–478 (2000).

66 Schnabel RR, Franzluebbers AJ, Stout WL, Sanderson MA, Stuedemann JA. The effects of pasture management practices. In: *The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect*. Follett RF, Kimble JM, Lal R (Eds). Lewis Publishers, Boca Raton, FL, USA, 291–322 (2001).

67 Blanco-Canqui H, Lal R, Post WM, Izaurralde RC, Shipitalo MJ. Organic carbon influences on soil particle density and rheological properties. *Soil Sci. Soc. Am. J.* 70, 1407–1414 (2006).

68 Jinbo Z, Changchun S, Shenmin W. Dynamics of soil organic carbon and its fractions after abandonment of cultivated wetlands in northeast China. *Soil Till. Res.* 96, 350–360 (2007).

69 McCarty GW, Lyssenko NN, Starr JL. Short-term changes in soil carbon and nitrogen pools during tillage management transition. *Soil Sci. Soc. Am. J.* 62, 1564–1571 (1998).

70 Diaz-Zorita M, Grove JH. Duration of tillage management effects carbon and phosphorus stratification in phosphatic Paleudalfs. *Soil Till. Res.* 66, 165–174 (2002).

71 Causarano HJ, Franzluebbers AJ, Shaw JN, Reeves DW, Raper RL, Wood CW. Soil organic carbon fractions and aggregation in the southern Piedmont and coastal plain. *Soil Sci. Soc. Am. J.* 72, 221–230 (2008).

72 Franzluebbers AJ, Stuedemann JA. Bermudagrass management in the southern Piedmont USA: VII. Soil-profile organic carbon and total nitrogen. *Soil Sci. Soc. Am. J.* 69, 1455–1462 (2005).

73 Franzluebbers AJ, Stuedemann JA. Early response of soil organic fractions to tillage and integrated crop-livestock production. *Soil Sci. Soc. Am. J.* 72, 613–625 (2008).

74 Soon YK, Arshad MA. Tillage and liming effects on crop and labile soil nitrogen in an acid soil. *Soil Till. Res.* 80, 23–33 (2005).

75 Franzluebbers AJ, Hons FM. Soil-profile distribution of primary and secondary plant-available nutrients under conventional and no tillage. *Soil Till. Res.* 39, 229–239 (1996).

76 Wright AL, Hons FM, Lemon RG, McFarland ML, Nichols RL. Stratification of nutrients in soil for different tillage regimes and cotton rotations. *Soil Till. Res.* 96, 19–27 (2007).

77 Spargo JT, Alley MM, Follett RF, Wallace JV. Soil carbon sequestration with continuous no-till management of grain cropping systems in the Virginia coastal plain. *Soil Till. Res.* 100, 133–140 (2008).

78 Tiessen KHD, Elliott JA, Yarotski J, Lobb DA, Flaten DN, Glozier NE. Conventional and conservation tillage: influence on seasonal runoff, sediment, and nutrient losses in the Canadian Prairies. *J. Environ. Qual.* 39, 964–980 (2010).

79 Sa JCM, Lal R. Stratification ratio of soil organic matter pools as an indicator of carbon sequestration in a tillage chronosequence on a Brazilian Oxisol. *Soil Till. Res.* 103, 46–56 (2009).

80 Quiroga A, Fernandez R, Noellemeyer E. Grazing effect on soil properties in conventional and no-till systems. *Soil Till. Res.* 105, 164–170 (2009).

81 Du Z, Ren T, Hu C. Tillage and residue removal effects on soil carbon and nitrogen storage in the North China Plain. *Soil Sci. Soc. Am. J.* 74, 196–202 (2010).

82 Tabaglio V, Gavazzi C, Menta C. Physico-chemical indicators and microarthropod communities as influenced by no-till, conventional tillage and nitrogen fertilization after four years of continuous maize. *Soil Till. Res.* 105, 135–142 (2009).

83 Alvaro-Fuentes J, Lopez MV, Cantero-Martinez C, Arrue JL. Tillage effects on soil organic carbon fractions in Mediterranean dryland agroecosystems *Soil Sci. Soc. Am. J.* 72, 541–547 (2008).

84 Hernanz JL, Sánchez-Girón V, Navarrete L. Soil carbon sequestration and stratification in a cereal/leguminous crop rotation with three tillage systems in semiarid conditions. *Agric. Ecosyst. Environ.* 133, 114–122 (2009).

85 López-Bellido RJ, Fontán JM, López-Bellido FJ, López-Bellido L. Carbon sequestration by tillage, rotation, and nitrogen fertilization in a Mediterranean Vertisol. *Agron. J.* 102, 310–318 (2010).

86 Melero Sánchez S, Panettieri M, Madejon E, Gomez Macpherson H, Moreno F, Murillo Carpio JM. Implementation of chiseling and mouldboard ploughing in soil after 8 years of no-till management in SW, Spain: effect on soil quality. *Soil Till. Res.* 112, 107–113 (2011).

87 Levi MR, Shaw JN, Wood CW, Hermann SM, Carter EA, Feng Y. Land management effects on near-surface soil properties of southeastern US coastal plain Kandiudults. *Soil Sci. Soc. Am. J.* 74, 258–271 (2010).

88 Carter MR, Gregorich EG. Carbon and nitrogen storage by deep-rooted tall fescue (*Lolium arundinaceum*) in the surface and subsurface soil of a fine sandy loam in eastern Canada. *Agric. Ecosyst. Environ.* 136, 125–132 (2010).

89 Guo Z-B, Yan G, Zhang R-H, Li F-M, Zeng Z-X, Liu H. Improvement of soil physical properties and aggregate-associated C, N, and P after cropland was converted to grassland in semiarid loess plateau. *Soil Sci.* 175, 99–104 (2010).

90 Peregrina F, Larrieta C, Ibanez S, Garcia-Escudero E. Labile organic matter, aggregates, and stratification ratios in a semiarid vineyard with cover crops. *Soil Sci. Soc. Am. J.* 74, 2120–2130 (2010).

91 Franzluebbers AJ. Water infiltration and soil structure related to organic matter and its stratification with depth. *Soil Till. Res.* 66, 197–205 (2002).

92 Franzluebbers AJ. Linking soil and water quality in conservation agricultural systems. *J. Integrative Biosci.* 6, 15–29 (2008).

93 Franzluebbers AJ. Depth distribution of soil organic carbon as a signature of soil quality. *19th World Congress of Soil Science.* 1–6 August 2010, Brisbane, Australia (2010).

- **Development of mathematical relationship for the stratification ratio of soil organic matter described from a large set of soil profiles in Georgia, USA.**

94 Franzluebbers AJ. Achieving soil organic carbon sequestration with conservation agricultural systems in the southeastern United States. *Soil Sci. Soc. Am. J.* 74, 357–357 (2010).

- **Large number of depth distribution relationships summarized for soils in the southeastern USA.**

95 Perkins HF. *Characterization Data for Selected Georgia Soils*. *Special Publication 43*. Georgia Agricultural Experiment Stations, University of Georgia, Athens, GA, USA (1987).

96 Angers DA, Bolinder MA, Carter MR *et al.* Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada. *Soil Till. Res.* 41, 191–201 (1997).

97 VandenBygaart AJ, Yang XM, Kay BD, Aspinall JD. Variability in carbon sequestration potential in no-till soil landscapes of southern Ontario. *Soil Till. Res.* 65, 231–241 (2002).

98 Baker JM, Ochsner TE, Venterea RT, Griffis TJ. Tillage and soil carbon sequestration: what do we really know? *Agric. Ecosyst. Environ.* 118, 1–5 (2007).

99 Dűring R-A, Hoβ T, Gäth S. Depth distribution and bioavailability of pollutants in long-term differently tilled soils. *Soil Till. Res.* 66, 183–195 (2002).

Websites

101 Soil Quality Institute. Soil quality assessment. http://soils.usda.gov/sqi/assessment/assessment.html

102 Duke University. Global inventory of long-term soil-ecosystem experiments. www.nicholas.duke.edu/ltse