Will we allow soil carbon to feed our needs?

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Alan J Franzluebbers†

Humans need many things, but unacknowledged by many of us are the intricately critical influences that soil with high organic carbon has on our life support system. Soil is as vital to human survival as air, water and the sun; its protection and enrichment with organic carbon are needed for the future sustainability of our planet. Curiously, the growing possibility of trading carbon in a global marketplace may actually help us to better appreciate the enormous value of soil carbon on how our world functions and how we have the influence to preserve and enhance critical ecosystem functions or continue to degrade them with reckless abandonment. With the expected rise in human population and the need for even more food to be produced on already stressed landscapes, widespread adoption of conservation agricultural systems is necessary to build a more resilient global food production system that can also help to mitigate climate change and improve our relationship with nature.

If Earth is the mother of all living things, then soil must be its womb, bearing richness beyond comprehension. Then too, carbon in soil should be considered the blood energizing the entire body, enabling the Earth to provide a multitude of **ecosystem services**.

We, as human civilization, 'need' many things – not necessarily cell phones to be continuously in contact with our co-workers and friends, not necessarily television to see who will be scoring points, not necessarily watches to know when to drink tea; these are more like desserts after the main course. The main course to feed our 'needs' comes from the ecosystem services supplied by Nature. **Figure 1** outlines the packages of ecosystem services that are essential for the inhabitants of the Earth [1]. Lest we ignore our essential diet derived from the main course, the desserts we pleasure will simply not be satisfying in the future.

Importance of soil

Where would we be if we did not have air, water, soil and the sun? Even without one of these essential ecosystem elements, our survival on Earth would be dismal. Since carbon forms the 'backbone' biochemical structure of all living things, it is intimately associated with the various processes involving air, water, soil, and the sun. One vitally essential process that starts the carbon cycle is photosynthesis, which embodies all four of these elements in a magical moment that occurs every day all over the Earth – photonic energy from the sun is captured within chloroplasts of green plants that encase water imbibed from the soil in a conglomeration of cells structurally arranged to allow oxygen and CO_2 to permeate its boundaries to create a chemical cocktail of carbohydrates that eventually forms the web of life for animals and decaying organisms. Carbohydrates fuel plant growth and their utilization releases CO_2 and water vapor back to the atmosphere. A key carbon pathway in the global carbon cycle is the transfer of carbon resources from living plants to soil organisms through decomposition, which eventually enriches **soil organic carbon** pools.

Soil properties and processes have underlying importance in addressing many global issues facing society during the coming decades [2]. How can we grow food for billions more people without harming the environment even further? How can we manage soils in order to

†USDA–Agricultural Research Service, 1420 Experiment Station Road, Watkinsville GA 30677, USA
Tel.: +1 706 769 5631; Fax: +1 706 769 8962; E-mail: alan.franzluebbers@ars.usda.gov

Key terms

Ecosystem services: Properties and processes of the natural world that contribute to the well-being of plants, animals, and humans in a holistic and global context.

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.

obtain a better balance for the dwindling pools of fresh water between agricultural irrigation and municipal needs? With increasing cost and scarcity of nutrients, how do we preserve and enhance the fertility of our soils while expecting larger harvests? How can we manage land to accommodate for the increasing demand for bio-based energy? How will impending climate change affect the productivity and resilience of our soils and broader environment? How can we better understand and enhance the diversity of organisms within and upon the soil to create more resilient and fructuous ecosystems? How can we better use soils as biogeochemical reactors to recycle wastes, thereby avoiding environmental contamination and maintaining soil productivity? How can we develop a seamless global perspective of lands, but still optimize management practices for local places and cultures? These are all important questions evolving from the relatively unknown world beneath our feet, the quality of which is dependent upon carbon.

What is soil carbon?

Carbon is found in soil as organic matter and carbonate minerals (e.g., $CaCO_3$). Soil organic matter is an assorted mixture of organic compounds, having been processed over varying lengths of time by soil organisms. It may be living (e.g., plant roots, insects, fungi, protozoa or bacteria) or it may be dead, dying or partially decayed. The most abundant constituent of soil organic matter is carbon (50–58%), hence the congruence between soil organic carbon and soil organic matter. Living components of soil organic matter are rather small in percentage (<10%), but play enormously important roles in decomposition, nutrient cycling, plant root zone modification, soil structural manipulation, aggregate stabilization and ecological resilience through underground biodiversity development. The living components of soil have been investigated only scantily compared with other components [3]. Nonliving components of soil organic matter are categorized in different manners according to the complexity of the compounds. A traditional approach has been through a fractionation scheme that first removes relatively large particles of organic matter (>50 μm) and water-soluble organic matter to yield humus. Humus can then be further subdivided into nonhumic biopolymers (e.g., polysaccharides, sugars, proteins, amino acids, fats, waxes, other lipids and lignin), humic acid (soluble in alkaline solution, but precipitate when acidified), fulvic acid (soluble in alkaline solution and remains soluble when acidified), and humin (insoluble in alkaline solution). Another approach for the fractionation of soil organic matter has been based on decomposition rate, where at least three pools of organic matter are characterized on a continuum from readily decomposable to recalcitrant forms through laboratory or field incubations (i.e., active, slow and passive) [4].

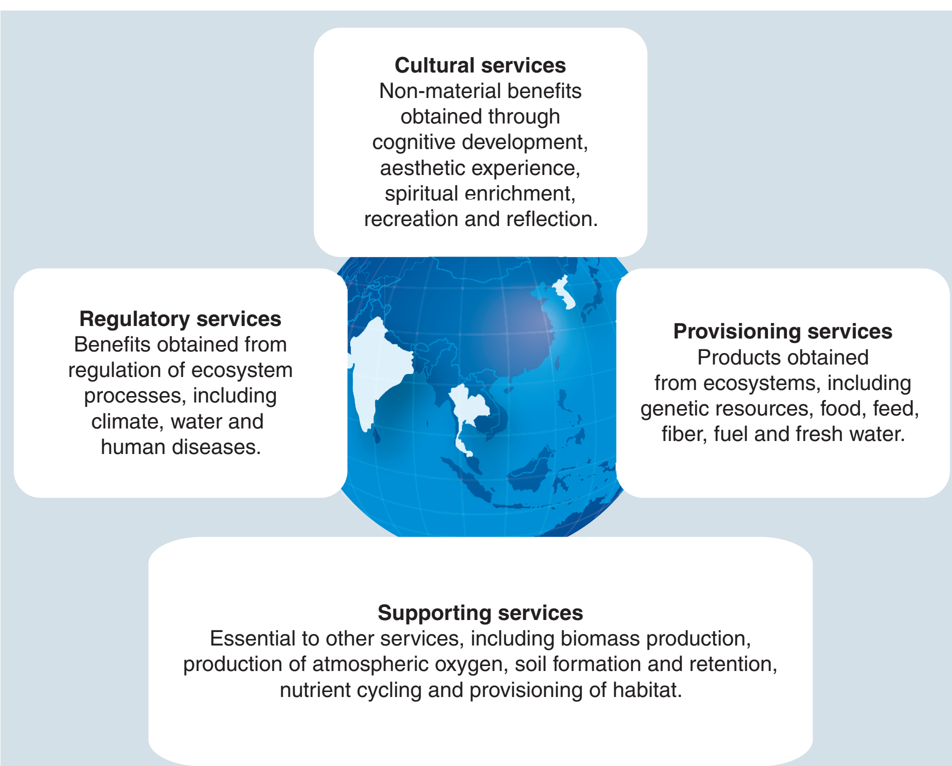

Figure 1. Categories of ecosystem services provided by Nature. Supporting services underlie all other functions and services. Cultural services form the pinnacle in response to effective functioning of supporting, regulating and provisioning services. Adapted from [1].

Soil carbon in a global context

Global plant biomass captures approximately 110 Pg (10^{15} g) C year^{-1} from the atmosphere through photosynthesis. Maintenance and decay of plants and animals occurs simultaneously and returns approximately 110 Pg C year^{-1} as CO_2 to the atmosphere through autotrophic respiration (50 Pg C year^{-1})

and heterotrophic respiration (60 Pg C year^{-1}). Soil to a depth of 1 m stores approximately 1600 Pg C in organic matter; an additional 700 Pg C is stored in soil as carbonate minerals [4]. The atmosphere contains approximately 800 Pg C as CO_2 and has been increasing in CO_2 concentration since the beginning of the 20th Century. Estimates from the first decade of the 21st Century indicate emissions of 7.7 Pg C year^{-1} from the burning of fossil fuels and 1.4 Pg C year^{-1} from deforestation [5]. Sinks for this additional CO_2 in the atmosphere have been 2.3 Pg C year^{-1} in the oceans and 2.7 Pg C year^{-1} to land biomass, leaving behind 4.1 Pg C year^{-1} accumulating in the atmosphere [5].

Assuming a global loss of 20% organic carbon from soils (i.e., 400 Pg from an original level of 2000 Pg) via historical land clearing that caused erosion and oxidation of organic matter [6,7], there is an enormous potential to recapture at least 400 Pg of organic carbon in soil with technological innovations and restoration activities. Assuming that an aggressive global restoration could occur within the next century, nearly all of the current rate of CO_2 increase in the atmosphere (i.e., 4.1 Pg C year^{-1}) could be mitigated through soil restoration (400 Pg C/5 billon ha of agricultural land/100 years = mean soil organic carbon sequestration rate of 0.8 Mg C ha^{-1} year^{-1}; certainly a tremendous goal, but also plausible). Clearly, the potential for soil restoration with organic carbon could have a major impact on the atmosphere; it is our collective willingness to achieve this goal that may be questioned. Obviously, the time required to fully restore soil organic carbon may be longer than a century and the rate of release of fossil fuel-derived CO_2 cannot be considered static. In addition, Lal more conservatively suggested that only 42–78 Pg C might have been lost from soils worldwide [8,9], although estimates have varied from 44 to 537 Pg C.

How does soil carbon affect ecosystem properties & services?

Soil organic carbon is a vital component of ecosystem properties, processes and functions. It has highly relevant physical, chemical and biological features. This wide diversity of features has given soil organic carbon deserved attention as a key indicator of soil quality (i.e., how soil management affects the functioning of soil) [10].

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

- **Physical**
  - Color: the dark color of organic matter alters thermal properties (i.e., absorbing heat);
  - Low solubility: ensures that organic matter inputs are retained and are not rapidly leached from the soil profile;
  - Water retention: directly helps to absorb several times its mass of water and indirectly retains water through its effect on pore geometry and soil structure **(Figure 2)** [11];
  - Stabilization of soil structure: binding of mineral particles to form water-stable aggregates and improve water infiltration into the surface soil.
- **Chemical**
  - Cation exchange capacity: high charge enhances retention of nutrient cations, such as Al, Fe, Ca, Mg and NH_4 **(Figure 3)**;

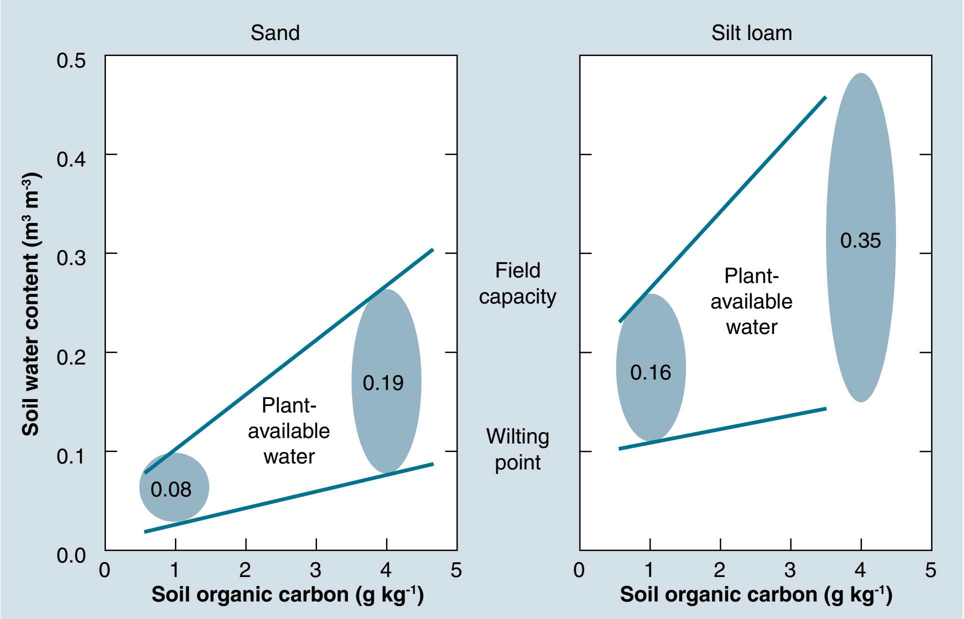

Figure 2. Effect of soil organic carbon concentration on plant-available water in sand soils from Florida and silt loam soils from Iowa, Kansas, Minnesota and Wisconsin, USA. Plant-available water is the difference between field capacity (upper line; calculated as water content following free drainage of saturated soil) and wilting point (lower line; calculated as water content that causes plants to wilt permanently). With four-times greater soil organic carbon concentration, these two different soil types would hold 2.2–2.5-times more water in the same volume. Adapted with permission from data presented in [11].

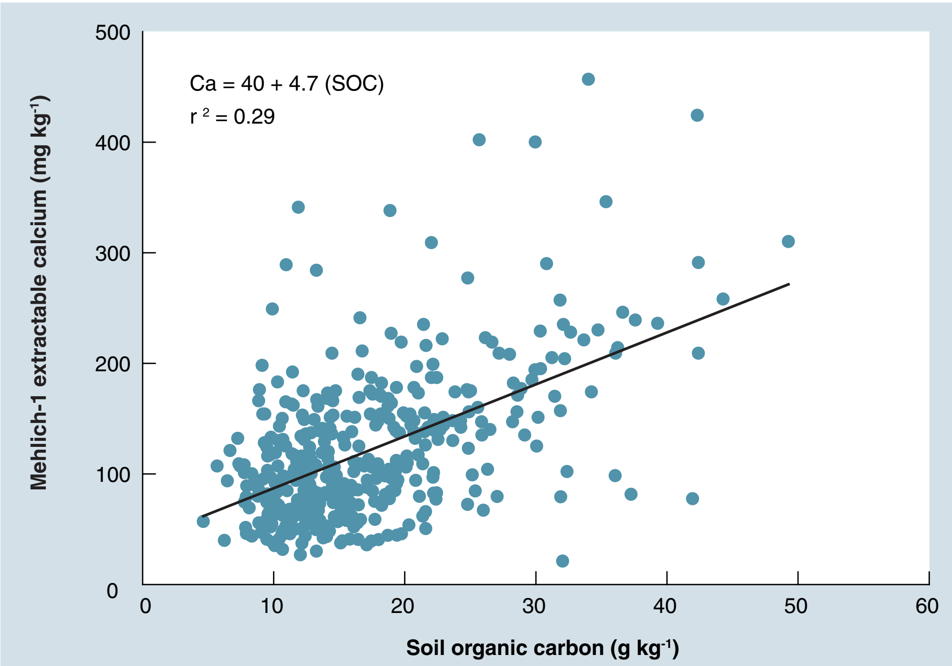

Figure 3. Relationship between concentration of soil organic carbon and extractable calcium in pastures in the Piedmont of Georgia, USA. In general, soil with 10 g kg^{-1} of organic carbon contained only a third as much calcium as soil with 50 g kg^{-1} of organic carbon (87 vs 275 mg Ca kg^{-1} soil). Soil organic matter retains nutrients within various organic structures and these nutrients can be released through mineralization of organic matter.
Data from [AJ Franzluebbers, RL Haney, Unpublished data].

- Buffering capacity and pH effects: avoids large swings in pH to keep acidity/alkalinity in a more acceptable range for plants;
- Chelation of metals: complexation with metals to enhance dissolution of minerals, enhance availability of phosphorus, reduce losses of micronutrients and reduce toxicity;
- Interactions with xenobiotics: alter biodegradeability, activity, and persistence of pesticides and other organic contaminants, such as antibiotics and endocrine-disrupting chemicals.

- **Biological**

- Reservoir of metabolic energy: energy embedded in organic molecules to drive biological processes;
- Source of macronutrients: mineralization of organic matter releases nitrogen, phosphorus, sulfur and other elements (Figure 4) [12];
- Enzymatic activities: both enhancement and inhibition of enzymes are possible by various humic materials;
- Ecosystem resilience: accumulation of soil organic matter can enhance the ability of an ecosystem to recover from various disturbances (e.g., drought, flooding, tillage and fire).

Soil formation is a geologically time consuming process driven by the influences of CLORPT [13]:

- Climate: whereby temperature and moisture alter chemical reactions;
- Organisms: whereby plant roots penetrate and deposit residues, animals burrow and create cavities, and bacteria feed upon organic remains;
- Relief: whereby the shape and direction of land surface affect sunlight and moisture exposure;
- Parent material: whereby the underlying bedrock provides different minerals that contribute the chemical and physical conditions of soil;
- Time: whereby different numbers of millennia allow the other factors to take place.

These same factors have a large influence on soil organic matter formation and its capacity to sustain ecosystem functions. It may have taken nature 200 years to form 1 cm of soil, but it took humans about that same amount of time to enable nature to erode the entire Southern Piedmont landscape (a region of hilly land southeast of the Appalachian Mountains from Alabama to Virginia in the USA) when previously forested land was denuded and covered only intermittently with a sparse cotton crop; the process of which eventually removed 18 cm of soil from the entire 17 Mha of land [14]. It is small wonder that soils of the southeastern USA are considered poor and infertile when more than 30 Mg C ha^{-1} would have been lost from the upper soil horizon (calculation of author based on presumed mean soil organic carbon concentration of 12 g C kg^{-1} soil and bulk density of 1.4 Mg m^{-3} in surface 18 cm of soil).

Soil organic carbon accumulates predominately in the upper horizons of soils. Without disturbing soil with tillage, soil organic carbon accumulates as plant residues cover the soil and slowly decompose following intermittent precipitation events (Figure 5) [15]. Protection of the soil surface with plant residues and high soil organic carbon concentration is important for getting rainfall to infiltrate soil (i.e., lower runoff) and keep the soil surface from washing away (i.e., lower soil loss). By helping to control soil erosion and alter the water cycle, soil organic carbon supports and regulates ecosystem services.

With the adoption of inorganic fertilizer application in the 20th Century, the nutrient supplying capacity of soil organic matter became widely underappreciated. Application of inorganic fertilizer can overcome nutrient deficiencies, even in poorly structured soils with low organic matter. However, within a particular soil, the level of organic carbon can have a profound influence on the capacity of the soil to produce food, feed, fiber and fuel (Figure 6) [16]. When soils are maintained with high surface-soil organic carbon rather than depleted with accelerated oxidation from repeated tillage operations, productivity can also be enhanced due to non-nutrient attributes of soil organic matter (Figure 7) [17].

Accumulation of plant residues and organic carbon in the soil surface is also extremely important for protecting the off-site quality of surface waters in nearby streams and lakes. With increasing surface residue and soil organic C, the percentage of rainfall as runoff declines, soil loss declines, and nutrients lost in runoff declines (Figure 8) [18].

In ancient times, soil was thought to be at its best when cultivated with implements to release the nutrients stored within organic matter. Lessons from the American frontiers have informed us that preservation of soil organic matter without soil disturbance is a far better goal for preserving the quality of soil for future generations [19]. The key to sustaining fertility is to match nutrient requirements of crops with various amendments, whether these come from inorganic or organic sources, such as commercial fertilizers, animal manures, nitrogen-fixing green manures, or various industrial or rurally derived composts. The European-influenced culture of clean, bare soil as a vision of agrarian charm has rightfully been replaced in America with the modern vision of crop residue-blanketed fields protected from the fierce elements of wind and water that can be both bane and blessing for the American landscape.

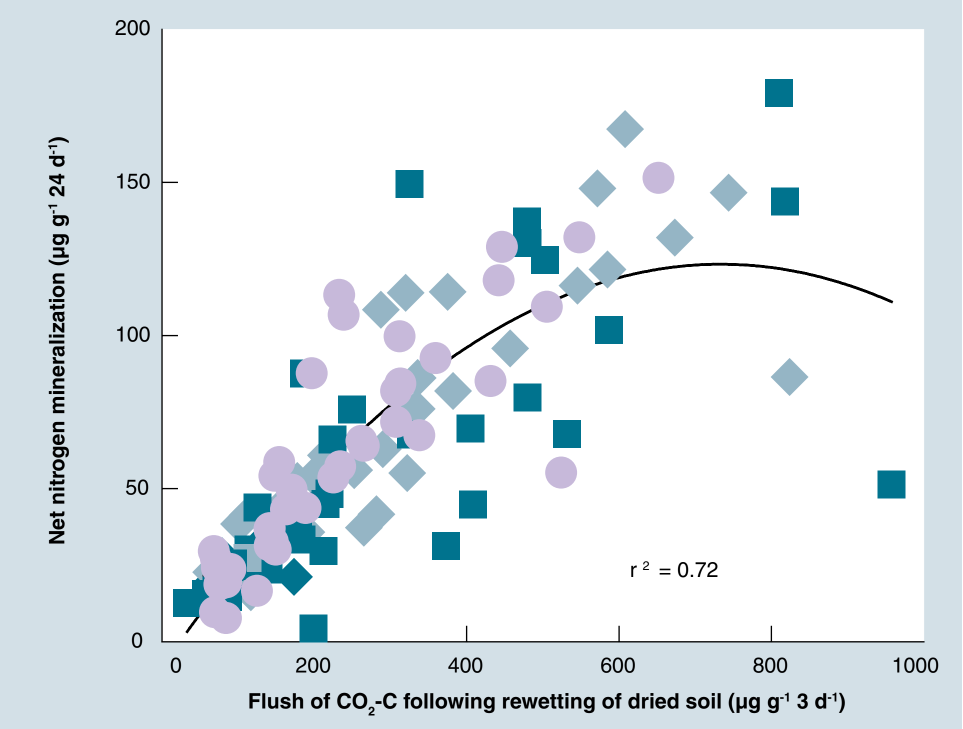

Figure 4. Relationship between the most active fraction of soil organic carbon (i.e., the flush of CO_2 evolved from soil immediately after rewetting) and the amount of nitrogen released into soil solution. The initially linear phase of the relationship indicates that a steady supply of inorganic nitrogen is made available from the decomposition of easily decomposed organic matter. The peak phase of the relationship and the subsequent decline indicates that immobilization of nitrogen into the rapidly growing microbial biomass can occur with excessively reactive carbon substrates. Symbols represent different levels of silage harvest intensity (◊ = low, □ = medium and ○ = high).
Adapted from [12].

Can management increase the stock of soil organic carbon?

As seen from how agricultural land use affects depth distribution of soil organic carbon in Figure 5, management is an important factor in altering soil organic carbon concentration. In the business world of carbon accounting and trading, stock change in soil organic carbon needs to be calculated from the change in soil organic carbon concentration, the change in bulk density of soil, the soil depth of inference, and the time period of evaluation. Stock changes in soil organic carbon at the field level are typically reported in Mg C ha^{-1} $year^{-1}$ (1 Mg = 10^6 g), while stock changes at the farm, county, regional, national or global level can be simply upscaled to various units of Tg C $year^{-1}$ (1 Tg = 10^{12} g), Pg C $year^{-1}$ (1 Pg = 10^{15} g), or Gt C $year^{-1}$ (1 Gt = 10^{15} g). If conversion to CO_2 equivalence (CO_2e) is desired, then a factor of 3.67 should be multiplied by the value of carbon in order to account for molecular weight differences (i.e., 1 Mg C ha^{-1} $year^{-1}$ = 3.67 Mg CO_2-e ha^{-1} $year^{-1}$).

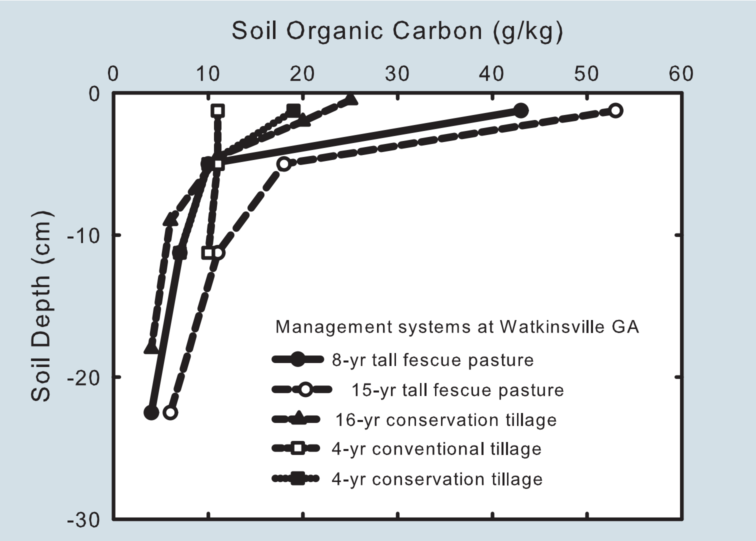

Figure 5. Depth distribution of soil organic carbon concentration by agricultural land management system in the Piedmont of Georgia, USA. Soil organic carbon is often uniformly distributed within the tillage zone (15-cm depth in conventional tillage system). With many years of undisturbed soil using conservation tillage to grow crops, soil organic carbon increases at the surface and declines with depth. Even greater increases in surface soil organic carbon can occur with perennial pastures that are not disturbed by tillage, that have a diversity of plants growing in the spring, summer, and autumn, and that have a large portion of the plant biomass grazed by animals and a portion of that harvested biomass subsequently returned to the soil in undigested form via animal manure. Reproduced with permission from [15].

Conservation agricultural systems have great potential to sequester soil organic carbon, which would help mitigate greenhouse gas emissions contributing to climate change and increase soil productivity and avoid further environmental damage from unsustainable use of inversion tillage systems – issues that threaten water quality, reduce soil biodiversity and erode soil around the world. Conservation agricultural systems have three guiding principles that can be globally applied:

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

Key terms

Conservation tillage: Method of plant production that leaves more than 30% residue cover after planting to control erosion and build soil organic carbon; includes minimum tillage, reduced tillage, ridge tillage, direct seeding and no tillage.

Conservation agriculture: Environmental approach to agricultural production that recognizes 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.

Impacts from **conservation tillage** cropping on soil organic carbon sequestration have received a great deal of research attention during the past couple of decades owing to the expansion of this technology throughout the world. Derpsch and Friedrich have estimated that **conservation agriculture** is practiced on 105 Mha throughout the world, with 26.6 Mha in the USA, 25.5 Mha in Brazil, 19.7 Mha in Argentina, 13.5 in Canada and 12.0 in Australia [20]. Globally, conservation agriculture is practiced on only approximately 7% of cropland, suggesting that major expansion of conservation agricultural production is still possible.

Significant soil organic carbon sequestration has occurred with adoption of conservation tillage by farmers in the southeastern USA **(Figure 9)** [21]. Most notable changes in the stock of soil organic carbon with adoption of conservation tillage occur in the surface 5 cm. This dramatic change in surface-soil organic carbon is a result of crop residues that lie at the surface (blanketing the soil surface with protection from wind and water erosion), undergoing slow decomposition to form stable soil organic matter in immediately underlying soil. The combination of crop residue cover and high surface-soil organic carbon is an ideal habitat for a diverse range of organisms, including earthworms, beetles, ants, springtails, nematodes, fungi and bacteria [22].

The type of cropping system can also affect the quantity of carbon fixed and subsequently available for soil organic carbon accumulation. In a review of 147 studies across the southeastern USA, the rate of soil organic carbon sequestration was greater in cropping systems with winter cover crops (0.55 ± 0.06 Mg C ha^{-1} $year^{-1}$, n = 87) than in cropping systems without winter cover crops (0.30 ± 0.05 Mg C ha^{-1} $year^{-1}$, n = 60) [23]. Winter cover crops can provide 2–4 Mg C ha^{-1} $year^{-1}$ additional above-ground carbon input, plus the same magnitude of below-ground carbon input, whch can contribute to formation of soil organic matter. Obviously, the highly conducive environment for decomposition in the southeastern USA requires a large input of plant biomass for significant changes in soil organic carbon to occur. From cropping systems in South-Central Texas, USA (20°C and 978 mm mean annual temperature and precipitation respectively), the fraction of carbon input from above- and below-ground sources that was sequestered as organic carbon in the surface 20 cm of soil was estimated to be 0.09 ± 0.04 g g^{-1} under conventional tillage and 0.22 ± 0.02 g g^{-1} under no tillage [24]. Higher retention rates could be expected in colder and drier climates and lower retention rates could be expected in warmer and wetter climates. In addition to the quantity of organic matter input controlling soil organic carbon content, tillage, crop rotation and cover cropping can alter the quality of soil organic matter, thereby affecting nutrient cycling, aggregation and hydraulic processes [25,26].

Cropping systems with greater amounts of time when soil is covered and plants are growing have greater opportunities to fix carbon and subsequently store carbon in soil organic matter. With increasing cropping intensity, soil **microbial biomass carbon** (and soil organic carbon) increased, irrespective of whether soil was tilled or not **(Figure 10)** [24]. With an effect on soil organic carbon sequestration similar to that of cover cropping, crop rotations with multiple-season sequences, high biomass production, and plant diversity offer producers additional opportunities to reduce the risk of crop failure due to extreme weather events and build resilience with farm production diversification.

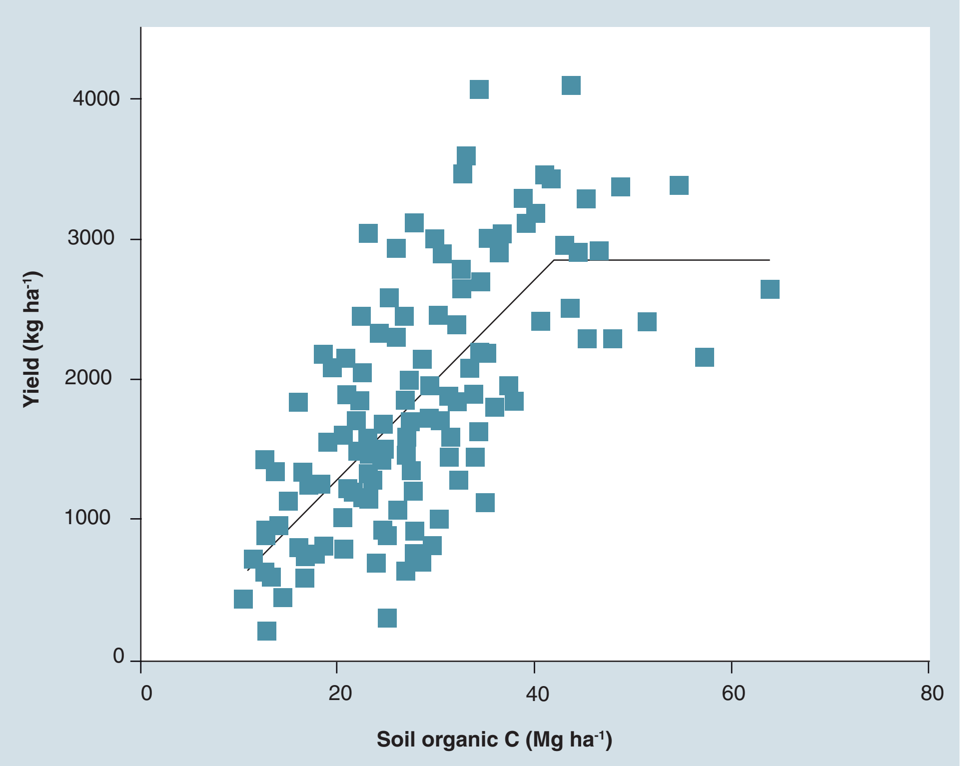

Figure 6. Wheat grain yield as a function of soil organic carbon content from 134 farmer trials in the Pampas region of Argentina. With degraded soils having soil organic carbon content of 10 Mg C ha^{-1}, 3-year average wheat grain yield was only 20% of that achieved in high-quality soils with 40 Mg C ha^{-1} (600 vs. 2800 kg ha^{-1}). Soil with 40 Mg C ha^{-1} could be expected to contain 4000 kg ha^{-1} of nitrogen, while a soil with only 10 Mg C ha^{-1} could be expected to contain only 1000 kg ha^{-1} of nitrogen. Assuming 2.5% release of nitrogen each year through mineralization of organic matter, then high-quality soil would be expected to release 100 kg ha^{-1} of nitrogen, while low-quality soil would be expected to release only 25 kg ha^{-1} of nitrogen.
Reproduced with permission from [16].

Perennial pastures have great potential to sequester soil organic carbon, because land is left relatively undisturbed for several years to several decades. The magnitude and rate of change in soil organic carbon will depend on climatic conditions, soil type and condition of land prior to establishment. Perennial pastures often contain a diversity of forages that grow during different parts of the year, and, therefore, offer extended root-growing opportunities for depositing carbon in soil. In addition, although perennial pastures are often grazed by ruminant animals, a significant amount of carbon contained in ingested plant material is actually returned to the soil as manure [14]. Soil organic carbon sequestration with the establishment of perennial pastures in the southeastern USA is highly significant **(Figure 11)** [21]. Compared with sequestration of soil organic carbon under conservation-tillage cropland, perennial pastures offer greater quantities and increased depth accumulation of soil organic carbon. Management-intensive pasture approaches may be able to sequester even greater quantity and depth distributions of soil organic carbon, assuming a robust forage mixture with deep-rooting capabilities and abundant and diverse supply of nutrients via various organic amendments [27].

Some researchers have recently become concerned with the apparent lack of significance in soil organic carbon content between conservation agricultural systems and conventional systems [28–30]. Although conservation and conventional systems promote soil organic carbon accumulation in different layers of the rooting zone, which could lead to differences in soil organic carbon sequestration depending upon the depth of sampling **(Figure 5)**, it is the random variation in soil organic carbon concentration with depth that is of critical concern. Soil organic carbon concentration is often highest near the soil surface and declines with depth, while its relative variation often increases with increasing soil depth **(Figure 12)** [31]. Experimenters' ability to detect a statistically significant difference in soil organic carbon content between two land

Key term

Microbial biomass carbon: Small fraction of the soil organic carbon pool composed of bacteria, fungi and actinomycetes that control nutrient cycling though decomposition and mineralization of organic matter.

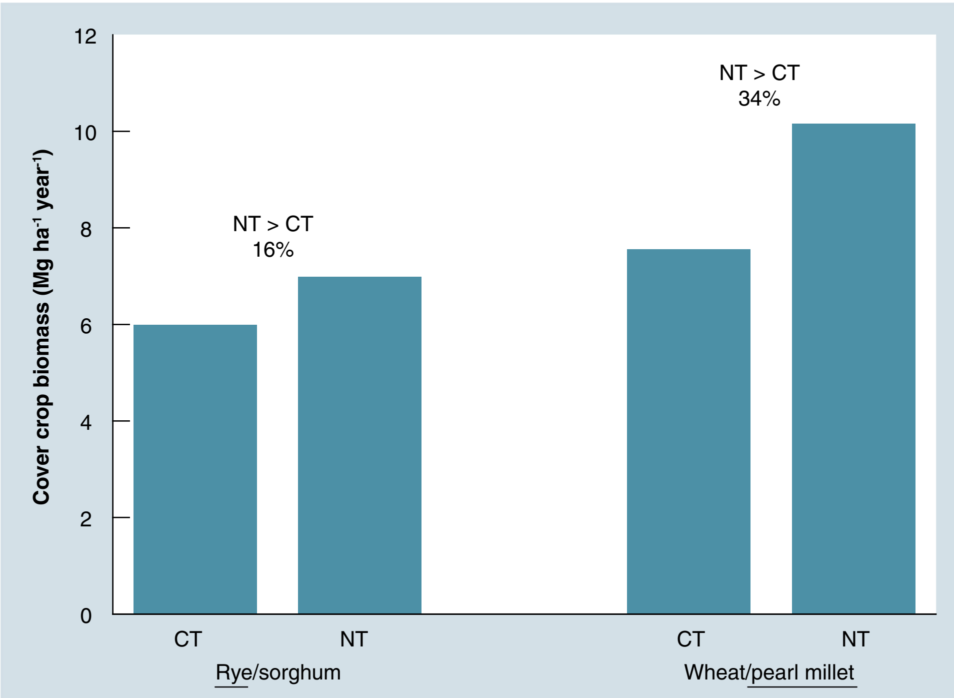

Figure 7. Above-ground biomass production of rye (in rye/sorghum cropping system) and pearl millet (in wheat/pearl millet cropping system) under CT and NT on a Piedmont soil in Georgia, USA. Winter cover crop production of rye was the average over 3 years and summer cover crop production of pearl millet was the average of over 4 years. Each cropping system followed a 20-year period of perennial pasture, which resulted in a high accumulation of soil organic matter. Although nutrients were released from stimulation of soil organic matter decomposition with CT during the initial 3–4 years, greater cover crop biomass production occurred with NT than with CT due to non-nutrient-related physical and/or biological factors. Therefore, preservation of soil organic matter with NT was more important for subsequent production than stimulation of nutrient release with CT.
CT: Conventional tillage; NT: No tillage.
Data from [17].

management systems is several-fold greater in the surface 10 cm of soil than in a deeper zone (e.g., 70–100 cm). Assuming a goal of achieving a 25% increase in soil organic carbon during 10 years of management, a total of seven samples would have to be collected and analyzed to meet the goal of +5.0 Mg C ha^{-1} in the surface 10 cm of soil, with a starting value of 20 Mg C ha^{-1} and coefficient of variation of 25%. By contrast, a total of 37 samples would have to be collected and analyzed in order to meet a goal of +2.5 Mg C ha^{-1} in the 70–100 cm zone of soil with a starting value of 10 Mg C ha^{-1} and coefficient of variation of 75%. The goal of achieving a 25% increase in soil organic carbon in the surface 10 cm within 10 years of management is reasonable (i.e., 0.5 Mg C ha^{-1} year^{-1}), but it is likely that it would take 25 years to achieve a 25% increase in soil organic carbon in the 70–100 cm zone (i.e., 0.1 Mg C ha^{-1} year^{-1}). Therefore, if sampling is too deep, statistical significance of soil organic carbon sequestration between two management systems will almost never be achieved within typical field experiments evaluated for below 10 years and outreach programs to promote best management practices for sequestration of soil organic carbon will be misinformed and misled. Furthermore, soil organic carbon is much easier to manage at the surface than deeper in the soil profile.

Determining the actual change in soil organic carbon with the adoption of an improved management practice, set of management practices or a complete management system is no trivial matter. Although measurement of soil organic carbon and its change with time in response to a particular management approach is common practice in a research agenda, it would be impractical within a measurement, monitoring and validation (MMV) protocol owing to the enormous resources needed in skilled labor hours to determine the sampling approach, collecting the large number of soil samples to achieve representativeness and sheer cost of numerous analyses. An alternative approach for MMV would be to use a model (or even a set of different models) to estimate the change in soil organic carbon. Modeling has the advantages of being a powerful and relatively inexpensive tool for estimating soil organic carbon in a large number of scenarios. Skilled technical labor is still needed to run models and continually check for potential discrepancies with actual data. Robust, process-based models would be best to describe a broad range of unique conditions, but simpler index-type models could also be used if a minimum number of management choices were evaluated. There are many different process-based and index models that could currently be used to estimate soil organic carbon, including CENTURY [32], Rothamsted carbon model (ROTHC) [33], denitrification and decomposition model (DNDC) [34], introductory carbon balance model (ICBM) [35], CQESTR [36], and soil conditioning index (SCI) [37]. However, a key determinant to their success, is sufficient testing and modification to suit the expected diversity of experimental conditions. If, for example, a widely tested model were used in a unique ecological condition, simulations may not be accurate on a specific project basis, but would probably be precise enough over a bundling of projects across a region. Critical in the use of models to estimate soil organic carbon (and certainly this is the only practical approach, rather than direct measurements) is that a large research support structure justifies the validity of the model under all of the ecological conditions in which the model might be used. Therefore, a great deal of up-front and robust research is needed when selecting a particular model for wide-scale implementation.

Who will benefit from increased soil organic carbon?

Farmers and landowners are the primary beneficiaries of soil with higher organic matter content, because they are rewarded with better tilth, higher nutrient-supplying capacity, improved capacity of soil to withstand drought and store water in the rooting zone, more resilient soil to perturbations from the environment, and abundant biological diversity to support vigorous plants and sustained ecosystem services. However, despite all the benefits that greater soil organic carbon provides to farmers and landowners, there are still a multitude of additional beneficiaries to all of society – the local engineering department that does not have to clear the ditches of sediment; recreational and professional fishermen who have unpolluted water so that they can catch an abundant supply of fish; highway drivers who can see the road rather than fight the dust blowing around from barren fields; taxpayers who do not have to pay for dredging waterways; emergency management officials who do not have to clean up and make disaster payments to overcome flooding, silting and drought; and consumers who can enjoy high quality food without pesticide contamination

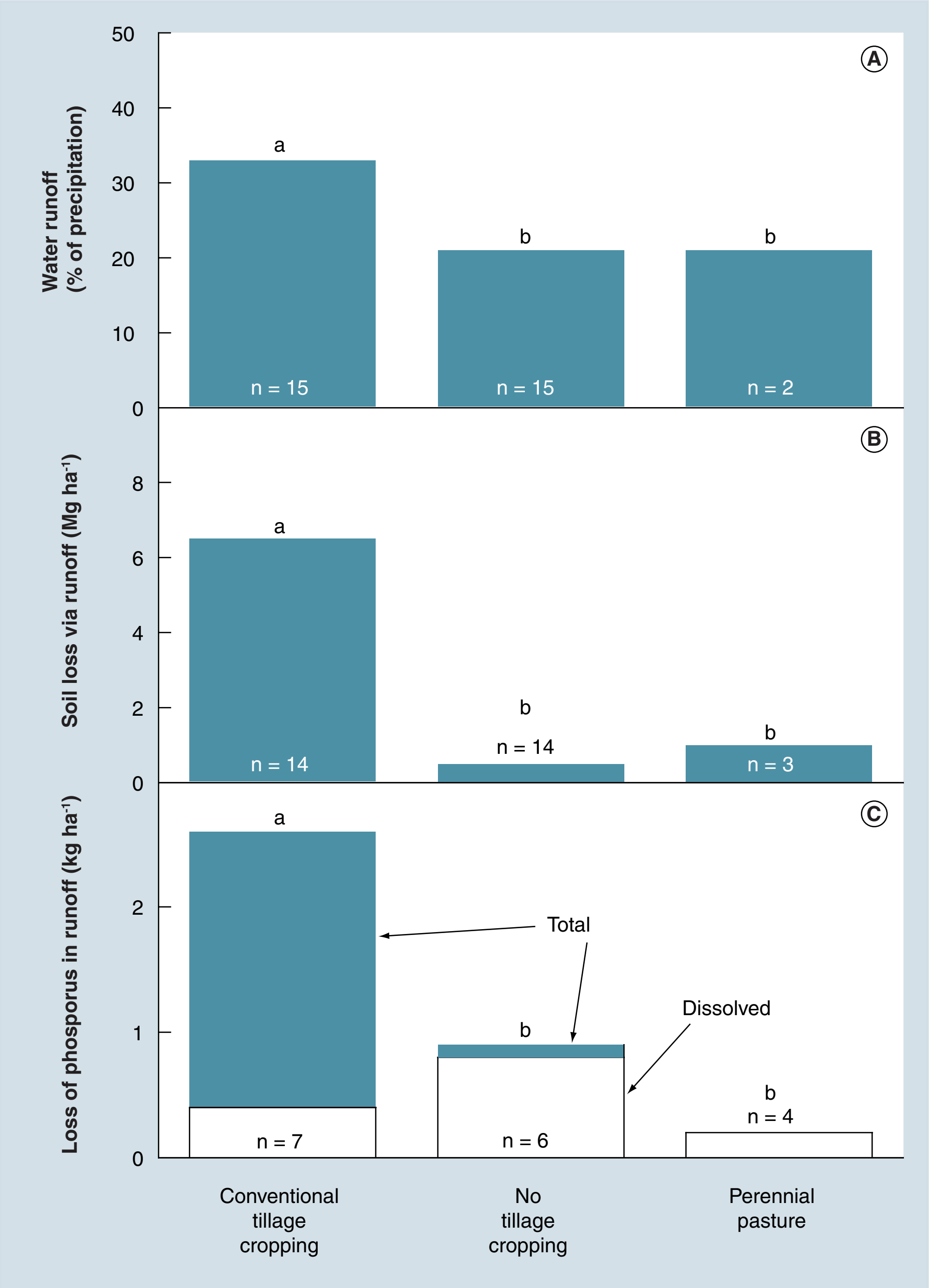

Figure 8. Summary of how agricultural land use affects (A) water runoff volume, (B) soil loss and (C) runoff loss of phosphorus in a variety of studies conducted throughout the eastern USA. Although soil organic carbon was not reported in all studies, presumed soil organic carbon concentration at the soil surface ranged from lowest in conventional-tillage cropping, intermediate in no-tillage cropping and highest in perennial pasture. With increasing soil organic carbon following adoption of conservation agricultural management (i.e., no-tillage cropping and perennial pasture), water runoff is reduced, soil erosion is reduced and nutrient movement into surface water bodies is reduced. With conservation agricultural management, on-site soil quality is enhanced and off-site sedimentation and water quality impairment are greatly reduced.
Data from multiple sources reported in [18].

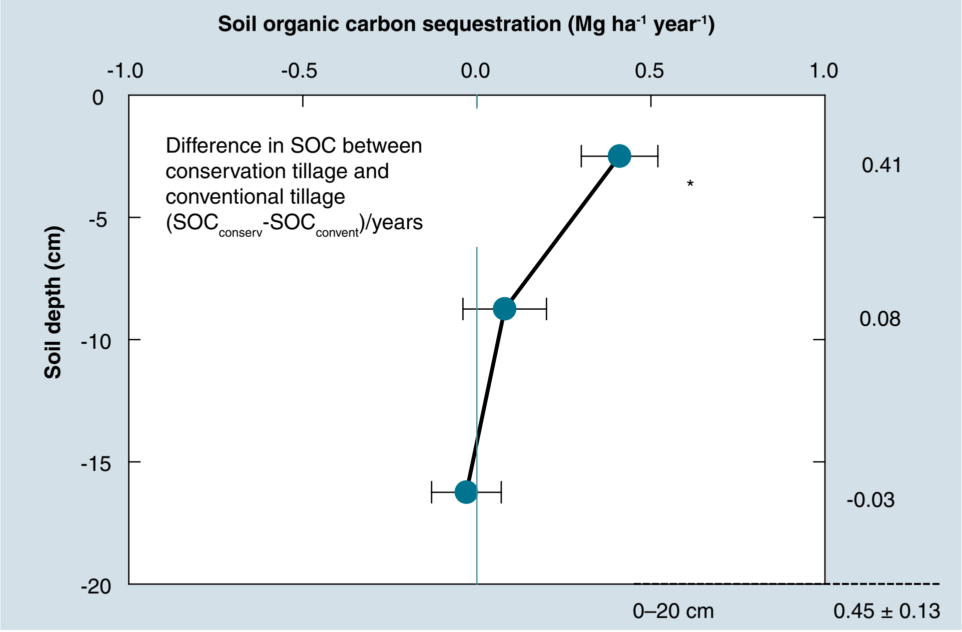

Figure 9. Soil organic carbon sequestration with the adoption of conservation tillage compared with conventional tillage on 29 farms throughout the southeastern USA. Sequestration of carbon occurred primarily in the surface 5 cm of soil. The value of 0.45 ± 0.13 Mg C ha^{-1} $year^{-1}$ represents the mean ± standard error among 29 comparisons throughout the 20-cm sampling depth. Conservation tillage systems were sampled at the end of 12 ± 6 years of continuous implementation in Alabama, Georgia, South Carolina, North Carolina and Virginia (USA). Similar positive response to conservation tillage was observed in soil microbial biomass carbon, potential soil microbial activity and water-stable aggregation.
SOC: Soil Organic Carbon.
Data from [21].

because pests are under better control in fields rich in fertility and resistant to pestilence.

If beneficiaries are expanded outside of the human domain, then the Earth and its ecosystems and ecosystem services are hugely improved with soils having greater soil organic carbon. Agriculture is fundamentally an extractive process serving humankind, but if soils can be managed with conservation agricultural principles (i.e., avoiding disturbance of soil, leaving residues on the surface and diversifying to obtain biological synergies), humankind can become closer aligned with nature. Environmental benefits associated with conservation agriculture include [101]:

- Favorable hydrologic balance and flows in rivers to withstand extreme weather events;
- Reduced incidence and intensity of desertification, which allows ecosystems to rejuvenate following extreme weather events;
- Increased soil biodiversity, which builds resilience to perturbations;
- Less soil erosion resulting in less sediment in rivers and dams and flourishing aquatic ecosystems;
- Potential for reduced emissions of other greenhouse gases, including methane and nitrous oxide, if compaction is avoided, such as with the adoption of controlled traffic-strategies;
- Reduced deforestation owing to land intensification and more reliable and higher crop yield, which creates a more favorable balance between agricultural lands and conservation reserves that are left undisturbed;
- Less water pollution from pesticides, applied fertilizer nutrients, and antibiotics and other pharmaceuticals from irrigation and waste water applications, which keeps aquatic systems healthy and avoids further landscape manipulations to prevent water pollution;
- Less hypoxia of coastal ecosystems, thereby allowing these diverse aquatic systems to properly function in cycling nutrients at the interface of fresh and salt-water ecosystems.

Barriers to adoption of conservation agricultural practices

With so many beneficiaries from increased soil organic carbon, why is this natural resource so greatly underappreciated? Why also are conservation agricultural systems, which help promote soil organic carbon accumulation, largely not widely adopted by farmers? Some reasons are technological, some are programmatic, and some are simply sociological.

Technologically, developing agricultural systems with minimal soil disturbance, maximum soil cover, and heightened diverse biological activity (i.e., the three essential elements of conservation agriculture in a system that can promote soil organic carbon accumulation) is relatively easy. There are underdeveloped regions of the world that do not have access to equipment or financial resources to adopt direct seeding to minimize soil disturbance, apply herbicides rather than use tillage to control weeds, or apply inorganic or organic fertilizers instead of land clearing to create fertile conditions. Adequate machinery and appropriate herbicides were previously a limitation in developed countries, but technological innovations and active networking among farmers and industry representatives overcame many of these technological limitations. Even in nonmechanized agricultural systems, no-till farming can be successfully developed through innovations by farmers and conservation professionals [38].

Programmatically, government policies can have a large influence on adoption of conservation agricultural systems by providing packaged incentives to promote environmental stewardship, maintain productive capacity, and support rural development. Currently, there are only a few examples of government programs specifically designed to support farmers for adopting conservation agricultural systems; currently in the USA there is the Environmental Quality Incentives Program (EQIP) [102] and the Conservation Stewardship Program (CSP) [103] administered by the US Department of Agriculture – Natural Resources Conservation Service (NRCS). Reauthorized in the 2002 Farm Bill, EQIP provides financial and technical assistance to farmers and ranchers who adopt environmentally sound practices on eligible agricultural land. Program practices and activities are carried out in an EQIP program plan that identifies appropriate conservation practices addressing a specific resource concern. Practices are subject to NRCS technical standards adapted for local conditions. National priorities addressed by EQIP are:

- Reduction of nonpoint source pollution, such as nutrients, sediment or pesticides;
- Reduction of groundwater contamination;
- Conservation of ground and surface water resources;
- Reduction of greenhouse gas emissions;
- Reduction in soil erosion and sedimentation from unacceptable levels on agricultural land;
- Promotion of habitat conservation for at-risk species.

A voluntary conservation program, the CSP encourages producers to address resource concerns in a comprehensive manner by:

- Undertaking additional conservation activities;
- Improving, maintaining, and managing existing conservation activities.

The CSP altered how NRCS provides conservation program payments. Instead of using the traditional compensation model that pays a per-acre rental rate or a percentage of the estimated cost of installing a practice, CSP pays for conservation performance – the higher the performance, the higher the payment. Previously the CSP was limited to targeted watersheds, but currently is open to all program-eligible producers throughout the country. Ranking period 2 in 2010 allows for either:

- ‘Enhancement payment’; targeting conservation activities that exceed the sustainable level for a given resource concern used to treat natural resources and greatly improve conservation performance; enhancement practices may be single or bundles, in which a group of specific enhancements when installed as a group address resource concerns synergistically; or

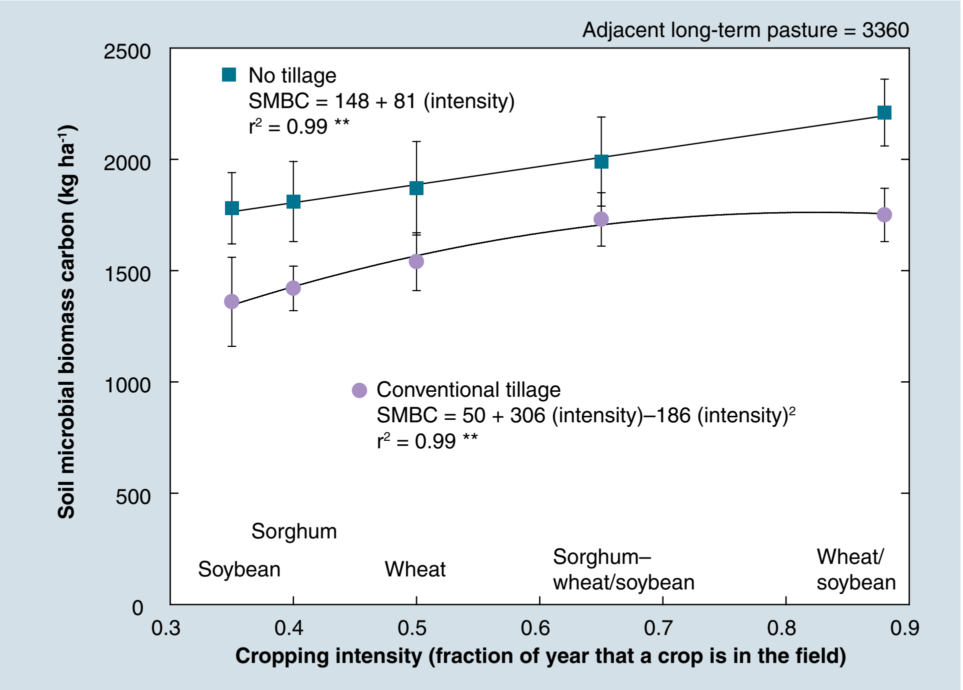

Figure 10. Effect of increasing cropping intensity on soil microbial biomass carbon under conventional and no tillage. Soil microbial biomass carbon is the active portion of soil organic carbon and is highly related to the total amount of carbon in soil. Increasing opportunities exist to feed soil microorganisms and build soil organic carbon with greater cropping intensity. Seasonal variations in soil microbial biomass are denoted in error bars for each cropping system. SMBC: Soil microbial biomass carbon.
Adapted from [24].

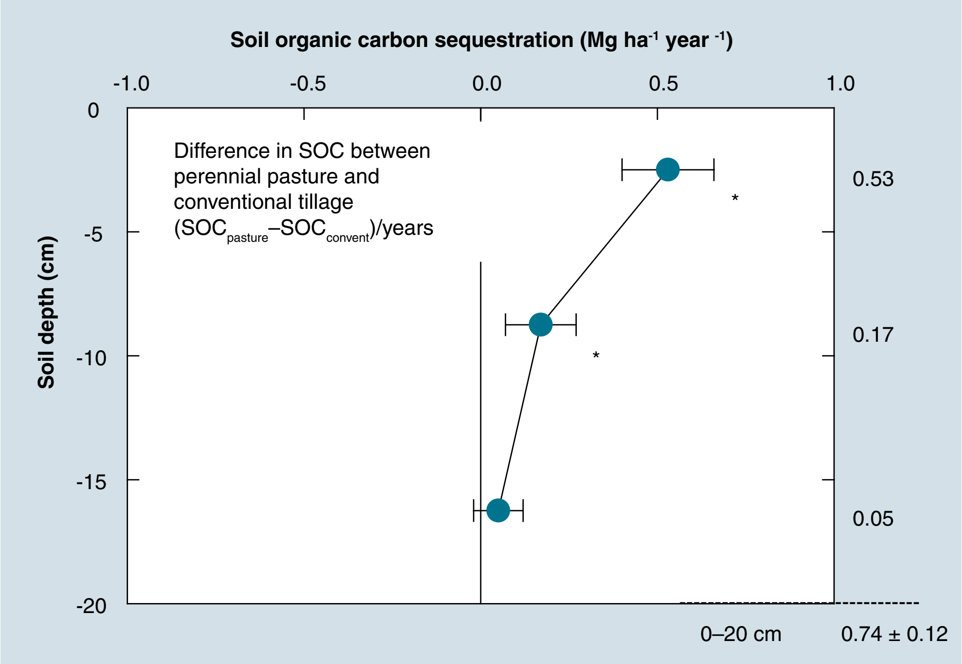

Figure 11. Soil organic carbon sequestration with the adoption of perennial pastures compared with conventional tillage on 29 farms throughout the southeastern USA. Sequestration of carbon occurred primarily in the surface 12 cm of soil. The value of 0.74 ± 0.12 Mg C ha^{-1} $year^{-1}$ represents the mean ± standard error among 29 comparisons throughout the 20-cm sampling depth. Pastures were sampled at the end of 24 ± 11 years of continuous implementation in Alabama, Georgia, South Carolina, North Carolina and Virginia (USA). When comparing these results with those in Figure 9, SOC sequestration with perennial pastures was 64% greater than with conservation-tillage cropping, along with significantly greater accumulation at lower depths.
SOC: Soil organic carbon.
Data from [21].

- 'Supplemental payment' when adopting resource-conserving crop rotations that include at least one resource conserving crop (determined by specific State Conservationist), reduces erosion, improves soil fertility and tilth, interrupts pest cycles, and reduces depletion of soil moisture or otherwise reduces the need for irrigation (typically a grass; legume for use as forage, seed for planting, or green manure; legume–grass mixture; or small grain grown in combination with a grass or legume green manure crop).

Since producers are already incentivized to adopt conservation practices, it would seem a relatively small step for them to enter a regulatory carbon market, in which they could provide offsets to industrial emitters that might not meet their cap. Voluntary carbon offsets have been marketed through a currently depressed system implemented by the Chicago Climate Exchange [104]. In addition, the Voluntary Carbon Standard is reviewing protocols for soil carbon sequestration [105]. General lack of confidence in current voluntary markets has depressed prices and there is bated anticipation regarding energy and federal cap and trade legislation, which has no clear programmatic structure as of yet. A piece of pending legislation is the 'American Clean Energy and Security Act of 2009.' Its broad goal is "to create clean energy jobs, achieve energy independence, reduce global warming pollution and transition to a clean energy economy." This legislation has not yet been enacted owing to political differences of opinion in Congress and lack of precedence.

Sociologically, the majority of farmers tend to be quite conservative in their approach. Therefore, unwillingness to change management practices and enroll in untried programs has caused some trepidation and lack of participation. Leadership from key farming organizations will be needed for the process of carbon market trading in the agricultural sector to move forward more quickly than in the past with other programs. Some other sociological issues concerning why farmers do not adopt conservation agricultural systems include tradition or prejudice and having sufficient knowledge and institutional support for adopting practices [20].

Future perspective

Soil organic carbon is an invaluable resource on productive and sustainable farms. Commoditization of carbon in a developing market place, should a regulatory approach be instituted in the USA, will yield a noncompeting value for carbon that farmers can use to further improve the environmental, social and economic well-being of their communities and region. Monetizing the value of carbon may be a necessary future step towards increasing the public's perception of how important soil is for numerous ecosystem services that are currently taken for granted. Marketing carbon stored on agricultural lands will bring renewed vigor and appreciation for land stewardship. Assuming that an average of 0.5 Mg C ha^{-1} $year^{-1}$ can be stored through newly incentivized conservation agricultural systems on 120 Mha of privately owned agricultural land in the USA, this could lead to sequestration of 220 Tg of CO_2 per year, equivalent to 4% of the approximately 5.8 Pg CO_2 emitted in the USA each year.

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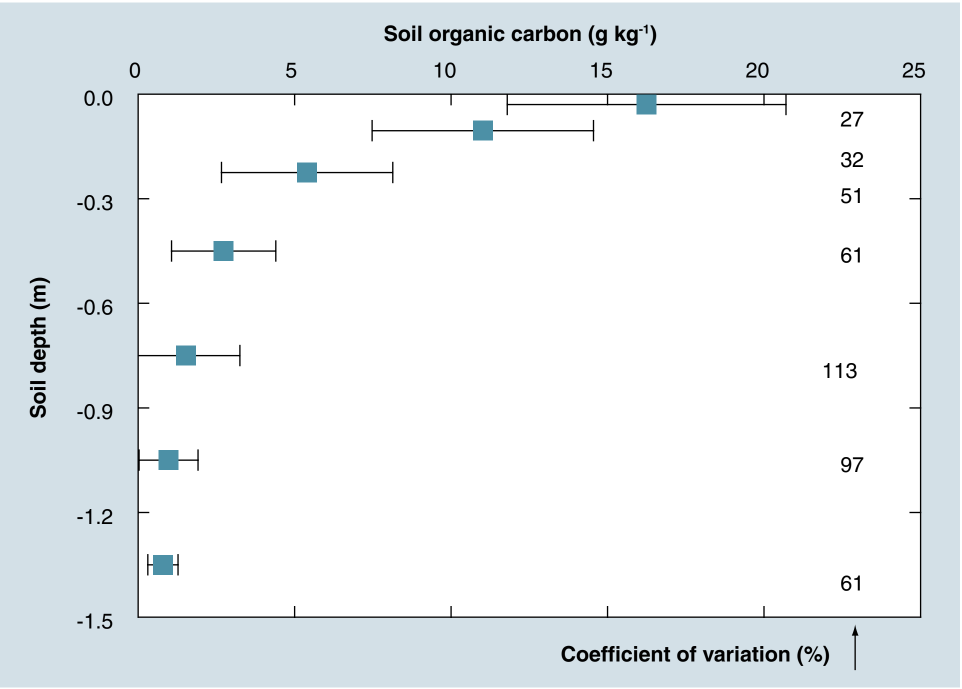

Figure 12. Typical soil organic carbon concentration (mean ± standard deviation among 122 cores within a 15-ha field) and coefficient of variation throughout a 1.5-m soil profile in the Piedmont of Georgia, USA. Soil organic carbon concentration and absolute variation are highest near the soil surface and decline with depth. Relative variation (i.e., the percentage of variation per unit of the mean value; coefficient of variation) increases with sampling depth and makes it very difficult to detect actual changes in soil organic carbon with increasing soil depth. To overcome the large coefficient of variation with increasing depth, researchers must sample a field intensively with either numerous cores or frequent samplings over time; both of which are costly and laborious.
Adapted with permission from [31].

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Executive summary

Importance of soil

- Soil is as vital to human survival as air, water and the sun are; its protection and enrichment with organic carbon are needed for the future sustainability of our planet.
- Many global issues are intricately linked to soil properties and processes, including food availability, fresh water availability, need for external nutrients, production of bio-based energy, climate change, biodiversity and ecosystem resilience, waste recycling, and addressing local issues within a global context.

What is soil carbon?

- Soil carbon is composed of inorganic carbonates and organic matter – living roots, insects and microorganisms as well as dead, dying and partially decayed organic matter.
- Soil organic matter is composed of 50–58% carbon.
- Soil organic carbon is a critical driver for improving physical, chemical and biological processes and properties of soil quality; also, it controls landscape and global level processes of hydrologic function, nutrient cycling, and greenhouse gas emission and mitigation.

Soil carbon in a global context

- Soil carbon is the largest pool of global terrestrial carbon – 1600 Pg (10^{15} g) of carbon stored in soil to a depth of 1 m as organic matter and 700 Pg of carbon stored in soil as carbonate minerals.
- With approximately 4 Pg of additional carbon accumulating in the atmospheric pool (~800 Pg) each year, complete restoration of the estimated 20% loss of soil organic carbon that occurred during the past 200 years of cultivation could fully counteract the current rate of CO_2 accumulation in the atmosphere during the next century.

How does soil carbon affect ecosystem properties & services?

- Soil organic carbon is a key indicator of soil quality, because of its beneficial effects on physical characteristics (e.g., color, solubility, water retention and soil structure), chemical qualities (e.g., cation exchange capacity, buffering, pH, chelation of metals and interactions with xenobiotics), and biological attributes (e.g., reservoir of metabolic energy, source of macronutrients, enzymatic activities and ecosystem resilience).
- Soil organic carbon accumulates predominately in the upper horizon of soil, which is important for water infiltration, nutrient cycling and protection of off-site water quality.

Can management increase the stock of soil organic carbon?

- Loss of soil organic carbon has occurred in the past due to deforestation and cultivation of native ecosystems; great potential exists to replenish soil organic carbon, because of this historic loss.
- Adoption of conservation agricultural systems will sequester soil organic carbon at a generally observed rate of 0.25–1.0 Mg C ha^{-1} $year^{-1}$.
- Conservation agricultural management may include conservation tillage, diverse crop rotations, cover cropping, manure application, and integration of perennial forages and animal grazing with cropping.

Who will benefit from increasing soil organic carbon?

- Increasing soil organic carbon rewards farmers and landowners with better tilth, higher nutrient-supplying capacity, improved resilience to perturbations and weather extremes, and abundant biological diversity to support vigorous plants and sustained ecosystem services.
- Society benefits from cleaner water, cleaner air, and low-cost and healthy supply of food products.

Barriers to adoption of conservation agricultural practices

- Adoption of various conservation agricultural management approaches is a human choice to build a positive relationship with Nature; allowing us to sustain our food production systems and improve the environment into the future.
- Carbon trading may eventually become a marketing tool that helps broaden society's appreciation for the inherent value of soil carbon as a fundamental basis for sustainability.

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