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REVIEW

Soil health and carbon management

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Abstract

Soil, a natural four-dimensional body at the atmosphere–lithosphere interface, is organic-carbon-mediated realm in which solid, liquid, and gaseous phases interact at a range of scales and generate numerous ecosystem goods and services. Soil organic carbon (SOC) strongly impacts soil quality, functionality and health. Terms soil quality and soil health should not be used interchangeable. Soil quality is related to what it does (functions), whereas soil health treats soil as a living biological entity that affects plant health. Through plant growth, soil health is also connected with the health of animals, humans, and ecosystems within its domain. Through supply of macro- and micronutrients, soil health, mediated by SOC dynamics is a strong determinant of global food and nutritional security. Soil C pool consists of two related but distinct components: SOC and soil inorganic C (SIC). The SIC pool comprises of primary and secondary carbonates, and the latter consists of calcitic (no net sequestration of atmospheric CO_2) and silicatic (net sequestration). While SOC is highly dynamic, its mean residence time depends on the degree of protection (physical, chemical, biological, and ecological) within the soil matrix. Formation of stable microaggregates and of organo–mineral complexes can protect SOC against microbial processes for millennia. In addition to formation of silicatic type of secondary carbonates, leaching of bicarbonates into the subsoil or shallow water table is also an important mechanism of sequestration of CO_2 as SIC. Numerous soil functions and ecosystem services depend on SOC and its dynamics. Improvements in soil health, along with increase in availability of water and nutrients, increases soil's resilience against extreme climate events (e.g., drought, heat wave) and imparts disease-suppressive attributes. Enhancing and sustaining soil health is also pertinent to advancing Sustainable Development Goals of the U.N. such as alleviating poverty, reducing hunger, improving health, and promoting economic development.

Introduction

Soil, a natural body at the atmosphere–lithosphere interphase, is a dynamic entity and teeming with life. It is essential to recycling of dead and decaying organic matter and storing of plant nutrients, denaturing of pollutants and filtering of water, sequestering of carbon (C) and moderating of climate, and storing of germplasm and provisioning of habitat for biodiversity. It is a medium for plant growth, generates the net primary productivity, and supports all terrestrial life through provisioning of the necessary conditions for its well-being. Soil organic C (SOC) concentration, along with its quality and dynamics, is essential to diverse soil functions and ecosystem services. Thus, soil is an organic-C-mediated realm in which solid, liquid, and gaseous phases interact at a scale ranging from nanometers to kilometers and create dynamic environments conducive to growth and development of plants and other biota. Soil organic matter (SOM), comprising about 45–60% of its mass as SOC, is a principal source of energy for soil microorganisms.

Three principal components of SOM are as follows: (1) plant and animal residues and living microbial biomass; (2) active or labile SOM; and (3) relatively stable

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SOM. The live biomass in a healthy and dynamic soil may be as much as 5 Mg/ha (Mg = megagram = 10^6 g = 1 metric ton). The objective of this article is to describe the relationship between SOC and soil quality, functionality, and health.

Soil Quality, Functionality and Health

Humanity's interest in soil quality and functionality dates back to the dawn of civilization (Brevik and Sauer 2015). Moses outlined soil functionality or quality by asking his followers as they entered Canaan around circa 1400 BC by stating, "See what the land is like and whether the people who live there are strong or weak, few or many. What kind of land do they live in? Is it good or bad? How is the soil? It is fertile or poor? Are there trees or not? Do your best to bring back some fruits from the land" (Numbers 13:18–20). The Book of Oades, dating back to China's Zhou dynasty from 770 to 476 BC, describes landforms, animals and plants, and explains agricultural practices for their management. In 400 BC, Hippocrates provided a list of things regarding the land or ground: "…whether it be naked or deficient in water or wooded and well watered, and whether it lies in a hollow, confined situation, or is elevated and cold…" (Hippocrates, 400 BC, quoted by Brevik and Sauer 2015). Around 60 BC, Columella related human health to soil conditions and described human diseases that may be contracted from marshes (Sylvia et al. 1998). In a Sanskrit manual "Artha Sastra," Chanukya/Kautilya (4th Century BCE) explains to land managers, techniques of improving soil functions by applying manure and other systems of managing soil fertility and conserving water. Ibn-Al-Awwam, a Moorish philosopher of the 12th Century, wrote in the Book on Agriculture (Kitab-Al-Felaha) "the first step in agriculture is the recognition of soils and how to distinguish that which is of a good quality and that which is of an inferior quality. One must also take into consideration the depth of the soil, for it often happens that its surface layer may be black."

During the modern era, soil quality and functionality have received a growing attention since 1970s because of the increasingly affluent world population (Warkentin and Fletcher 1977; Larson and Pierce 1991; Doran et al. 1994, 1996; Karlen et al. 1994; Parr et al. 1992; Lal 1993, 1994, 1997; Smith et al. 1993; Harris and Bezdicek1994, Doran and Jones1996; Doran and Zeiss 2000). Three separate but interrelated terms emerged since 1970s are as follows: soil quality, soil functionality, and soil health. Soil quality is defined as the "fitness for use" (Larson and Pierce 1991), and "capacity of the soil to function" (Karlen et al. 1997). Thus, soil functions, intricately linked with soil quality, depend on specific land use, and include sustaining plant and animal productivity (agricultural land use), forest productivity (silviculture land use), air and water quality in relation to human health and habitation (urban land use), contamination with heavy metals (minelands and urban lands) etc. Important soil functions, of relevance to human well-being and nature conservancy, include: retention and cycling of nutrients, formation and stabilization of soil structure (aggregation), retention and transmission of water, aeration and gaseous exchange, buffering of soil reaction, transformation of compounds, and maintenance of biodiversity. These functions are also termed as ecosystem services provided by soil resources (Daily et al. 1997). However, soil functions are difficult to quantify, and are usually measured through assessment of soil quality indicators, which must be flexible and broad-based to be pertinent to a wide range of soil functions (Andrews et al. 2004). As Edward Demmings (1943) pointed out, important things which cannot be measured must be judiciously managed. Therefore, the question is not – what is there in the soil that can be measured, but what it does which must be quantified. What it does is… soil quality, and it can be measured neither precisely nor directly. Therefore, it is measured indirectly by assessing some soil quality indicators (SQI).

Terms soil quality and soil health, while similar, should not be used interchangeably. Soil quality is related to soil functions or what it does, whereas soil health presents the soil as a finite and dynamic living soil resource, and is directly related to plant health. More specifically, soil health is defined as "capacity of soil to function as a vital living system to sustain biological productivity, maintain environment quality and promote plant, animal and human health" (Doran et al. 1996; Doran and Zeiss 2000). In this definition, however, the impact of soil biotic activity and species diversity on climate is overlooked, and yet both are intricately interconnected and this linkage should not be ignored. Soil attributes essential to life include: (1) physical for provisioning of air, water, and gaseous exchange and habitat; (2) chemical for moderating soil reaction and availability and transformation of nutrients; (3) biological for source of energy and food and nutrient cycling; and (4) ecological for hydrological and energy budget, and landscape processes (Fig. 1). These attributes, individually and through interaction, create environments which are conducive to life, and vice versa. Yes, soil health affects life and is in turn affected by its diversity and dynamics.

Soil health is also connected with human health and nutritional security. The soil–human health nexus has also been recognized ever since the dawn of civilization (Brevik and Sauer 2015), and vividly explained by U.S. soil scientists during 1920s (McCarrison 1921) and 1930s (Knight et al. 1938; Albrecht 1945, 1951, 1957). Voisin (1959)

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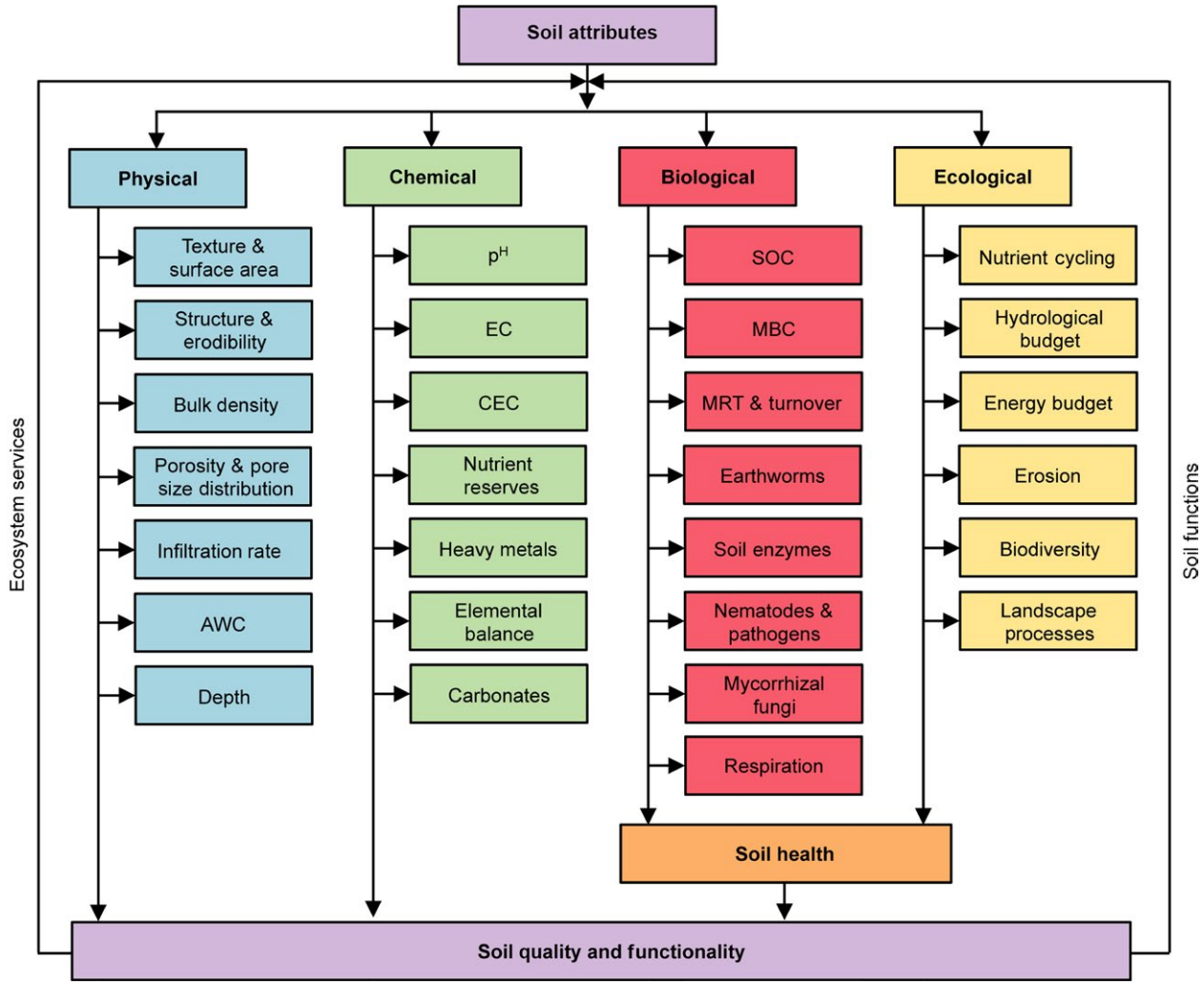

Figure 1. Soil attributes as indicators of soil health (AWC = available water capacity; SOC = soil organic C; CEC = cation exchange capacity; EC = electrical conductivity; MBC = microbial biomass; MRT = mean residence time).

linked cancer to soil health. In British India, Howard (1940, 1947) linked human health to soil health. Being a pioneer in organic agriculture, Sir Albert's work was contemporary to that of Lady Balfour (1943) and that of Rodale (1945). For example, micronutrient deficiencies are an important cause of morbidity and mortality. Children are especially vulnerable to deficiency in Zn, and that of Fe causes anemia in children and nursing mothers. Seventeen micronutrients essential to human health are as follows: Fe, Zn, Cu, Mo, I, F, B, Se, Mu, Ni, Cr, Si, As, Li, Sn, V, and Co. In addition, macronutrients also essential to human health are as follows: N, P, K, Ca, Mg, Na, S, and Cl (Lal 2009). All these micro and macronutrients must be supplied through soil. Thus, the widely recognized truism—the health of soil, plants, animals, people, and ecosystems is one and indivisible. Soil health is defined as — soil's capacity, as a biologically active entity, within natural and managed landscapes, to sustain multiple ecosystem services, including net primary productivity (NPP), food and nutritional security, biodiversity, water purification, and renewability, C sequestration, air quality, and atmospheric chemistry and elemental cycling for human well-being and nature conservancy. This definition of soil health is in accord with that of the Gaia Hypothesis (Lovelock 1979), which states that life creates environment suited to its well-being.

Soil Carbon

Soil carbon (C) consists of two related but distinct components (Fig. 2). Soil organic C (SOC) comprises of the remains of plants and animals at different stages of decomposition and of the microbial biomass and their by-products. As a component of SOM (45–60%), SOC is a

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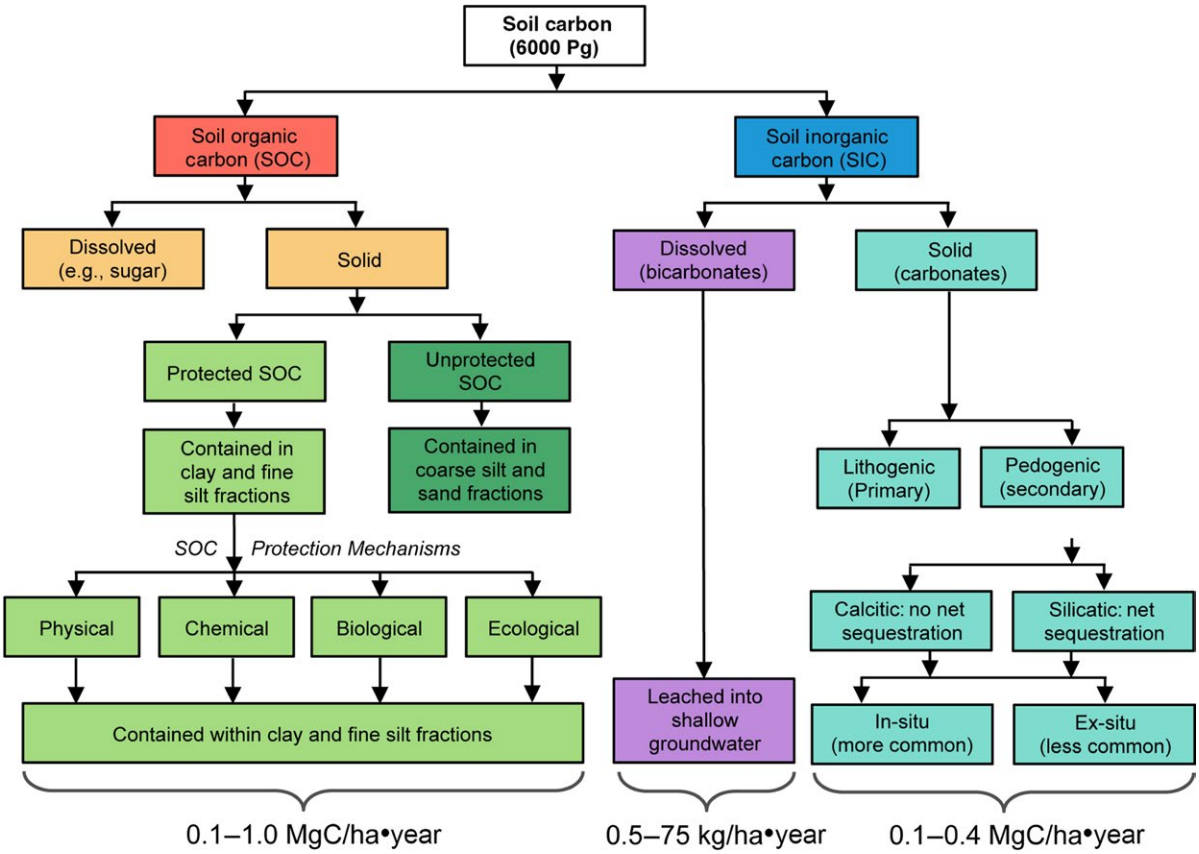

Figure 2. Types of organic and inorganic carbon pools in soil. The numerical values listed on the last line are ranges of sequestration of organic and inorganic carbon in diverse soils and ecoregions. Soil C pool of 6000 Pg is to 3-m depth and comprises of all components.

heterogeneous mixture of organic materials including fresh litter, carbohydrates, and simple sugars, complex organic compounds, some inert materials, and pyrogenic compounds. Dynamics of SOC as a component of the terrestrial C cycle is discussed by Jansson et al. (2010), among others. The SOC is a highly reactive component, and is the basis of numerous pedogenic processes. Because of a high surface area and charge density, it reacts with clay and minerals to form organo–mineral complexes. The mean residence time (MRT) or the rate of its turnover depends on the degree of protection within the soil matrix (Dungait et al. 2012). Among numerous protective mechanisms are physical, chemical, biological, and ecological. Physical mechanisms include encapsulation within stable microaggregates (Six et al. 2000, 2002), formation of organo–mineral complexes, and transfer deep into the subsoil away from the zone of natural and anthropogenic perturbations. Formation of organo–mineral complexes can store SOC for millennia. Chemical protection involves formation of some recalcitrant compounds (von Lützow and Kögel-Knaber 2009), including aromatic and double-bond hydrocarbons and some hydrophobic substances that coat stable aggregates. Biological mechanisms include some microbial exudates that repel other organisms, transfer of SOC into biologically nonpreferred soil spaces (Ekschmitt et al. 2008; Kleber 2010; Kleber et al. 2011; Dungait et al. 2012), and substrate-driven biological rate limitations (Ekschmitt et al. 2005). Ecological mechanisms include coupled cycling of C with other soil constituents (H_2O, N, O, S and microelements), erosion cont rol, and deep translocation through biogeochemical processes (Fig. 2).

The SIC, a dominant form of C in soil of arid and semi-arid regions (rainfall <500 mm/year), consists of carbonates (CO_3^{-2}) and bicarbonates (HCO_3^-) of Ca^{+2}, Mg^{+2}, K^+ and Na^+. Further, SIC comprises of primary or lithogenic carbonates and secondary, or pedogenic carbonates. The SIC consists of elemental C; carbonate-bearing minerals (e.g., calcite, agronite, and gypsum); gaseous CO_2 as a by-product of heterotrophic respiration, and dissolved C as an equilibrium of H_2CO_3, HCO_3^-, and CO_3^{-2} (Jansson et al. 2010). Secondary carbonates are formed through reaction of HCO_3^- and CO_3^{-2} (in solution by dissolution of CO_2) with Ca^{+2} or Mg^{+2}. Formation of secondary carbonates leads to sequestration of atmospheric CO_2.

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Secondary carbonates deposition can be of diverse morphological shapes such as rinds, coats, sheets, pendants, opal, etc. (Blank and Fosberg 1990). The rate of SIC sequestration through formation of secondary carbonates can be 0.12–0.38 MgC/ha.year to 160 cm depth by irrigation and fertilization (Bughio et al. 2015). However, leaching of bicarbonates into the subsoil or shallow water table and its reprecipitation can also be high (Lal 2008; Barta 2011; Ma et al. 2014; Monger et al. 2015). The pool of C in groundwater is 1404 Pg (petagram = 10^{15} = 1 billion metric ton = 1Gt) and the flux of bicarbonates can be as much as 2.1–7.4 g C/m^2.year, with a global flux of C into the groundwater at 0.2–0.36 PgC/year as bicarbonates. (Monger et al. 2015).

Dynamics of soil C pool can have a strong impact on atmospheric chemistry and the global C cycle (Lal 2004). For example, if it were possible to increase soil C pool globally by 4% to 3-m depth, it would cause a drawdown of atmospheric CO_2-C by 240 Pg, the amount equivalent to the reduction of >100 ppmv of CO_2. However, the logistics of achieving such an increase even over a decadal scale are insurmountable at the present level of scientific advances (Lal 2016). Nonetheless, the "4 per Thousand" program proposed at the COP21 in Paris in 2015 is a step in the right direction. Through improvements in soil health and the attendant pedospheric processes, sequestration of C in the soil solum has numerous ancillary benefits to human and nature. As Dyson (2008) stated, "if we control what the plants do with the carbon, the fate of the carbon in the atmosphere is in our hands."

Soil Functions and Ecosystem Services

Among numerous soil functions (Table 1) are those which form critical basis of all terrestrial life. The linkage between soil health and ecosystem services is depicted in Figure 3. Soil health impacts: (1) growing food through plants and animals by storage and availability of plant nutrients, cycling, and transformation of elements and delivering macro- and micronutrients when needed; (2) storing water in the root zone to increase plant-available water capacity, denaturing, and filtering of pollutants, and appropriately using blue and gray/black water for mitigating drought stress and recycling nutrients; (3) moderating of climate through sequestration of C in the soil and biota, buffering against sudden/abrupt fluctuations in moisture and temperature regimes, and regulation of gaseous emissions (CO_2, CH_4, N_2O) into the atmosphere; (4) providing habitat and energy source to biota, especially the microbiota, and the storehouse of germplasm; and (5) providing industrial raw materials (e.g., clay, peat, minerals), and of antibiotics for human and animals and of other pharmaceuticals, and of organisms which create disease-suppressive soils (Fig. 2). Indeed, soil health is the engine of economic development. It impacts quality and magnitude of renewable water resources, adaptation/mitigation and stabilization of climate, production of biomass and net and ecosystem productivity, and the above and below-ground productivity.

Soil Organic Carbon and Soil Health

Quantity, quality, and dynamics/turnover of SOC are critical to soil health (Lal 2014). Threshold level of SOC in the rootzone is 1.5–2.0%. Maintenance of SOC pool at above the threshold/critical level is essential to: (1) soil structure and aggregation which govern soil tilth and aeration; (2) water retention and use efficiency which control tolerance to drought, heat wave, and abrupt climate change; (3) nutrient retention and use efficiency which moderate nonpoint source pollution, water quality, and toxic algal blooms; (4) rhizospheric processes which influence elemental transformations and creation of disease-suppressive soils; and (5) gaseous emissions (e.g., CO_2, CH_4, N_2O) which moderate atmospheric chemistry and regulate climate change. Above all, numerous soil-related constraints to agronomic productivity (Fig. 3) can also be alleviated through enhancement and sustainable management of the SOC pool. Among these constraints are as follows: (1) inherent soil properties

Table 1. Soil functions related to soil quality.

Soil quality	Specific attributes	Soil functions
Physical	Texture, structure, depth, hydraulic conductivity, infiltration rate, aeration, surface area, bulk density	Water retention, transmission, filtration of pollutants, water cycling and renewability, foundation for civil structures, gaseous exchange
Chemical	Cation exchange capacity (CEC), p^H, nutrient reserves, electrical conductivity	Cycling of elements, elemental transformation, buffering, leaching
Biological	SOC, microbial biomass C (MBC), species diversity, soil enzymes, respiration rate	Decomposition of waste, denaturing of pollutants, moderation of climate, carbon sequestration, habitat for biota, energy for soil organisms
Ecological	Soil depth, mineralogical composition, water storage and renewability	Production of biomass or NPP, moderation of climate, medium for plant growth, archive of planetary/human history and paleoclimate.

SOC, soil organic carbon; MBC, microbial biomass carbon; CEC, cation exchange capacity; NPP, net primary productivity.

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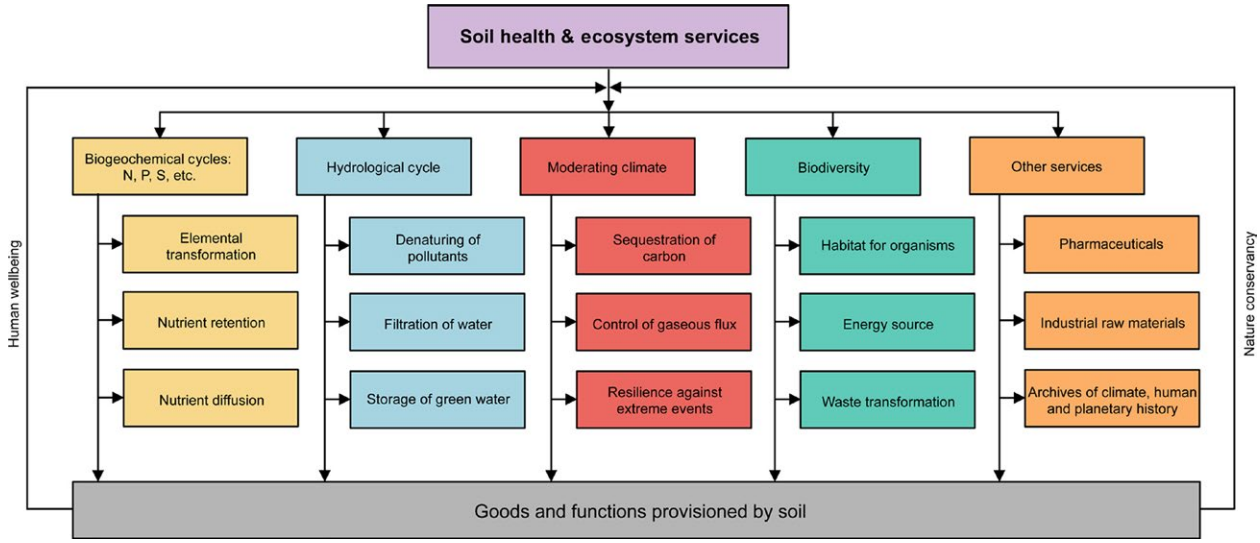

Figure 3. Soil health and ecosystem services for human well-being and nature conservancy.

(endogenous) related to the parent materials and soil formation; (2) environmental factors (exogenous) related to climate, landscape, and other biotic and abiotic factors; (3) water-related issues which influence the drought-flood syndrome; and (4) the human dimensions that affect availability and access to inputs, along with social, cultural, and environmental issues. Improvement in soil health through SOC enhancement can address these issues. Similar to soil quality, soil health also cannot be measured directly. Thus, there are key soil attributes which can be used as surrogates to develop soil health indicators (Fig. 4).

Soil Health and Sustainable Development Goals

Sustainable Development Goals (SDGs), launched by the U.N. in September 2015 as a continuation of the Agenda 21 and the Millennium Development Goals, are aimed at improving the environment, conserving nature, and enhancing human well-being. This is also called "Agenda 2030." Sustainable management of soil health is critical to advancing several SDGs (Table 2), especially those related to alleviating poverty (#1), ending hunger (#2), improving health (#3), clean water (#6), economic growth (#8), and climate action (#13). Implementation of "4 per Thousand" initiative proposed at the Paris Climate Summit in November/December 2015 highlights the importance of sequestering C in soil at the aspirational rate of 0.4%/year to 40-cm depth (Lal 2016). It is an important mechanism of advancing SDG #2, 6, 8, 13, and 15 (Table 2).

Technological Options to Manage Soil Health

Sustainable management of SOC is critical to enhancing and managing soil health. Thus, management of soil health involves management of SOC pool. The SOC pool can be enhanced by technological options that create a positive C budget (Fig. 5). Important among these are conservation agriculture (CA), integrated, and diverse cropping/farming systems, use of organic amendments and those options that restore soil/ecosystem functions. Among numerous soil properties (Fig. 4), it is pertinent to identify site-specific indicators of soil health. Thus, key soil properties (e.g., physical, chemical, biological, ecological) must be identified to develop an appropriate soil health index. Soil biological properties (MBC, enzymes) are among the most dynamic characteristics, which have a rapid response to landuse, landuse change, and soil/crop/animal management (Cardoso et al. 2013). Appropriate indicators of soil health may be those attributes that can enhance the following functions (Kibblewhite et al. 2008): (1) C transformations; (2) nutrient cycles; (3) soil structure maintenance; and (4) regulation of pests and disease. These functions are moderated by a range of biological processes moderated by diverse soil organisms under specific ambient environment.

Soil Health and Disease-Suppressive Attributes

Soil is a living system. Soil's capacity to perform these functions depends on: a range of biogeochemical processes

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Figure 4. Global soil-related constraints to agronomic productivity.

Table 2. Advancing sustainable development goals through management of soil health.

Goal #	Objective	Impact of soil health
1	No poverty	Increase farm income
2	End hunger	Enhance quantity and quality of food
3	Good health	Produce nutritious food
5	Gender equality	Improve crop productivity of women farmers
6	Clean water and sanitation	Improve water quality
8	Economic growth	An engine of economic development
10	Reduce inequalities	Enhance and sustain farm productivity
12	Responsible consumption	Reduce input of water, nutrients and energy by decreasing losses
13	Climate action	Sequester C and mitigate climate change
15	Life on land	Increase activity and species diversity of soil biota

that occur in the soil, and the functionality of soil biodiversity (Smith et al. 2015). Increasing MBC and soil biodiversity (e.g., rhizobacteria, fungi) also leads to a greater suppression of crop pathogens and pests (Baker and Cook 1974; Larkin and VanAlfen 2015). Robust microbial communities can lead to either general suppression or specific suppression of diseases (Janvier et al. 2007). Thus, depending on microbial communities, soil may range from conducive to suppressive.

Mechanisms of disease-suppressive attributes include (Janvier et al. 2007): (1) slow establishment and persistence of pathogens; (2) lower severity of diseases; and (3) ineffectiveness of pathogens. General principles of enhancing soil health, and thus disease-suppressive attributes, include the following: (1) improve SOC pool; (2) adopt CA; (3) increase soil biodiversity; (4) diversify land use and maintain a live vegetable cover; (5) use organic amendments such as mulch, compost; and (6) adopt integrated nutrient management options. A judicious management of chemical fertilizers, in conjunction with the use of organic amendments, is also important to enhancing soil health (Singh and Ryan 2015). However, total disease control cannot be achieved by techniques which improve soil health (Fig. 5), but the incidence of soil-borne diseases can be reduced. Soil health improvement may not strongly influence the

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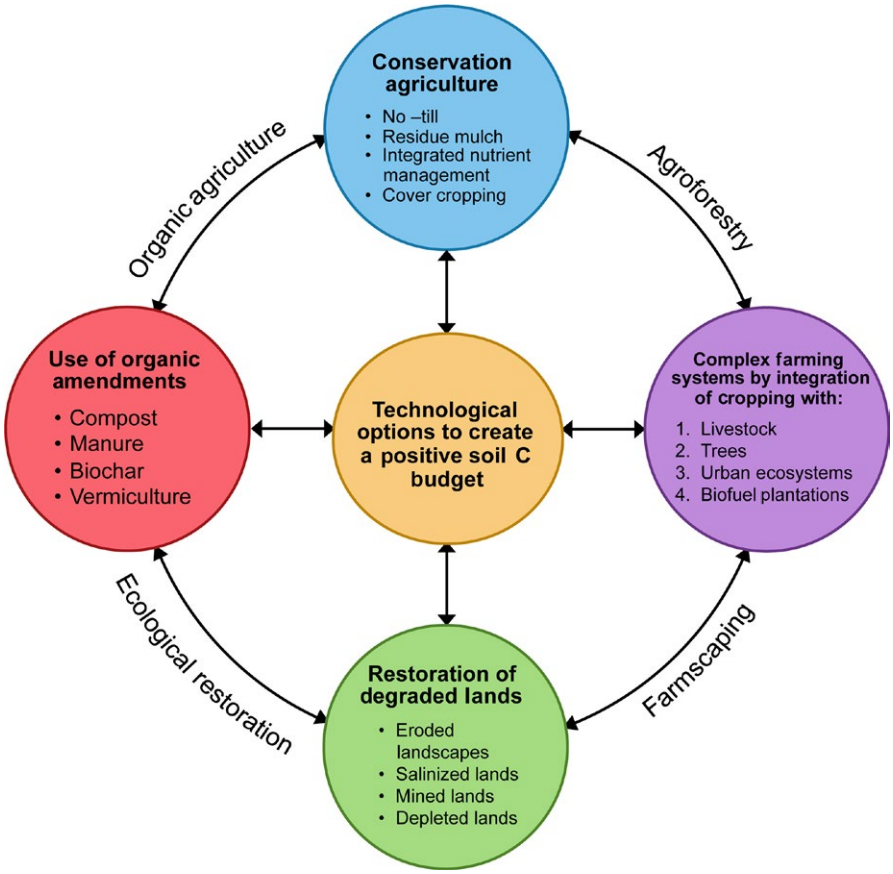

Figure 5. Technological options for soil carbon sequestration.

foliar-borne diseases, but healthy soils support population of beneficial microorganisms and can lead to induced resistance to both soil-borne and foliar disease. Further, plants grown on healthier soils are relatively more resilient and are less susceptible to pathogens (Larkin and VanAlfen 2015). Use of some organic amendments (e.g., compost) can impact disease-suppressive properties. Management of soil through these concepts would do more than just improving plant nutrients, it would also enhance the environment (Ehmke 2013). Healthy soils, with highly diverse and active microbial communities, also are a source of antibiotics for human and livestock (Ness 2015).

Managing Global Soil Carbon Pool

The importance of enhancing and sustaining global soil C (both SOC and SIC) pool is gaining momentum for provisioning of several ecosystem services, but especially to mitigate climate change and advance food security. For example, recommendation of the "4 per Thousand" program at COP21 in Paris in November/December 2015 is indicative of the political significance of this program to address global issues. Therefore, management of soil health is crucial to understanding the dynamics and management of the SOC and SIC pools, and vice versa. In the context of climate change, it is also important to understanding the temperature-sensitivity of SOM decomposition and its effect on the global SOC pool in a warming earth (Zhang 2010). The projected increase in global temperature may also aggravate the risks of positive feedback between elevated CO_2 and SOM decomposition (Wolf et al. 2007). Better understanding of the SOC pool and dynamics in diverse ecoregions may be essential to their judicious management (Scharlemann et al. 2014). Yet, there is a huge potential of SOC sequestration in diverse regions, such as in Europe (Aertsens et al. 2013), USA (Lal et al. 2003), Brazil (Sa et al. 2016), etc. In addition to modeling (Campbell and Paustian 2015), understanding of the SOC pool at the regional-scale (e.g., the U.S. Corn Belt) is also important (Collins et al. 2000). Understanding of such basic processes is critical to the choice of site-specific management through the use of organic amendments (Cooperband 2002), tillage systems (Franzluebbers 2008; Overstreet and DeJong-Huges 2008), appropriate

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systems of intensification of agroecosystems (Liao et al. 2015), or management of irrigated systems (Cochran et al. 2010). Identification of researchable priorities should be based on a thorough analysis of the known and unknowns (Stockmann et al. 2013).

In general, soil health is affected more by the dynamics of SOC than SIC. Yet, formation of secondary carbonates, transport of bicarbonates into the shallow groundwater, and weathering of silicates can also affect atmospheric CO_2 and the global climate change. Management systems (e.g., composting, mulching, manuring, irrigation, limiting) can affect both SOC and SIC pools.

A judicious use of fertilizers implies that they supplement the supply of plant nutrients through natural systems of biological fixation, recycling of biomass and management of soil resources for efficient use in a manner compatible to environmental quality (Lal 2016).

Conclusions

Hayne (1940) stated that, "if we feed the soil, it will feed us," and that "only productive soil can support a prosperous people." Thus, maintaining soil health is essential to human health, ecosystem functions and nature conservancy. However, impact of soil health goes beyond human health, it also has a profound impact on atmosphere, biosphere, and the hydrosphere. The importance of soil health on mitigating climate change, improving water quality, enhancing biodiversity etc. cannot be overemphasized. The environmental consequence of soil health is also determined by the SOC pool, its dynamics and the turnover time, and that of climate change by both SOC and SIC dynamics.

Soil health is more pertinent to global issues now than ever before. Its management is essential to advancing food and nutritional security, critical to mitigating and adapting to changing and uncertain climate, important to reducing nonpoint source pollution, and eutrophication, pertinent to enhancing soil biodiversity, and needed to sustainable intensification of agroecosystems through enhancing use efficiency of inputs (water, nutrients) and reducing losses.

Conflict of Interest

The author is director of the Carbon Management and Sequestration Center, School of Environment and Natural Resources, The Ohio State University, Columbus, OH 43210 USA.

References

Aertsens, J., L. De Nocker, and A. Gobin. 2013. Valuing the carbon sequestration potential for European agriculture. Land Use Policy 31:584–594.

Albrecht, W. A. 1945. Soil fertility and its health implications. Am. J.Orthod. Oral Surg. Orthod. 31:279–286.

Albrecht, W. A. 1951. Pattern of caries in relation to the pattern of soil fertility in the United States. Dent. J. Australia 23:1–6.

Albrecht, W. A. 1957. Soil fertility and biotic geography. Geogr. Rev. 47:86–105.

Andrews, S., D. Karlen, and C. Cambardella. 2004. The soil management assessment framework: a quantitative soil quality evaluation method. Soil Sci. Soc. Am. J. 68:1945–1962.

Baker, K. F., and R. J. Cook. 1974. Biological control of plant pathogens. American Phytopathology Society, San Francisco, CA, 433 pp.

Balfour, E. B. 1943. The living soil. Faber and Faber Ltd., London, U.K.

Barta, G. 2011. Secondary carbonates in loess-paleosoil sequences: a general review. Cent. Eur. J. Geosci. 3:129–146.

Blank, R. R., and M. A. Fosberg. 1990. Micromorphology and classification of secondary calcium carbonate accumulations that surround or occur on the undersides of coarse fragments in Idaho (USA). Dev. Soil Sci. 19:341–346.

Brevik, E. C., and T. J. Sauer. 2015. The past, present, and future of soils and human health studies. Soil 1:35–46.

Bughio, M. A., P. Wang, F. Meng, C. Chen, Y. Kuzyakov, X. Wang, et al. 2015. Neoformation of pedogenic carbonates by irrigation and fertilization and their contribution to carbon sequestration in soil. Geoderma 262:12–19.

Campbell, E. E., and K. Paustian. 2015. Current developments in soil organic matter modeling and the expansion of model applications: a review. Environ. Res. Lett. 10:123004. doi:10.1088/1748-9326/10/12/123004.

Cardoso, E. J. B. N., R. L. F. Vasconcellos, D. Bini, M. Y. H. Miyauchi, C. A. dos Santos, P. R. L. Alves, et al. 2013. Soil health: looking for suitable indicators. What should be considered to assess the effects of use and management on soil health? Sci. Agricola 70:274–289.

Cochran, R. L., H. P. Collins, A. Kennedy, and D. F. Bezdicek. 2010. Soil carbon pools and fluxes following land conversion to irrigated agriculture in a semi-arid shrub-steppe ecosystem. Biol. Fertil. Soils 43:479–489.

Collins, H. P., E. T. Elliott, K. Paustian, L. C. Bundy, W. A. Dick, D. R. Huggins, et al. 2000. Soil carbon pools and fluxes in long-term corn belt agroecosystems. Soil Biol. Biochem. 32:157–168.

Cooperband, L. 2002. Building soil organic matter with organic amendments: a resource for urban and rural gardeners, small famers, turfgrass managers and large-scale producers. University of Wisconsin-Madison, Center for Integrated Agricultural Systems, Madison, WI.

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Daily, G. C. 1997. The potential impacts of global warming on managed and natural ecosystem: Implications for human well-being. Abstracts of Papers of the American Chemical Society 213: 12-ENVR.

Demmings, E.. 1943. Statistical adjustment of data. Dover Publications, Oxford, U.K., 261 pp.

Doran, J. W., and M. R. Zeiss. 2000. Soil health and sustainability: managing the biotic component of soil quality. Appl. Soil Ecol. 15:3–11.

Doran, J. W., A. J. Jones, (Eds.), 1996. Methods for Assessing Soil Quality. Soil Science Society of America Special Publication 49: Soil Science Society of America, Madison, Wisconsin.

Doran, J. W., T. B. Parkin, J. W. Doran, D. C. Coleman, D. F. Bezdicek, and B. A. Stewart. 1994. Defining and assessing soil quality. In Doran, J. W., Coleman, D. C., Bezdicek, D. F., Stewart, B. A. (Eds.), Defining Soil Quality for a Sustainable Environment. Soil Science Society of America Special Publication, 35: Soil Science Society of America, Madison, Wisconsin, pp. 3–21.

Doran, J., M. Sarrantonio, M. Liebig, and D. Sparks. 1996. Soil health and sustainability. Adv. Agron. 56:1–54.

Dungait, J. A. J., D. W. Hopkins, A. S. Gregory, and A. P. Whitmore. 2012. Soil organic matter turnover is governed by accessibility not recalcitrance. Glob. Change Biol. 18:1781–1796.

Dyson, F. 2008. The question of global warming. New York Review of Books, 30 June 2010.

Ehmke, T. 2013. Soil health: feature article. Crop and Soils Magazine:4–9.

Ekschmitt, K., M. Q. Liu, S. Vetter, O. Fox, and V. Wolters. 2005. Strategies used by soil biota to overcome soil organic matter stability - why is dead organic matter left over in the soil? Geoderma 128:167–176.

Ekschmitt, K., E. Kandeler, C. Poll, A. Brune, F. Buscot, M. Friedrich, et al. 2008. Soil-carbon preservation through habitat constraints and biological limitations on decomposer activity. J. Plant Nutr. Soil Sci. 171:27–35.

Franzluebbers, A. J. 2008. Soil organic carbon sequestration with conservation agriculture in the southeastern USA: potential and limitations. Available at: http://www.fao.org/ag/ca/CarbonOffsetConsultation/Carbonme

Harris, R., D. Bezdicek. 1994. Descriptive aspects of soil quality health. In Doran, J. W., Coleman, D. C., Bezdicek, D. F., Stewart, B. A. (Eds.), Defining Soil Quality for a Sustainable Environment. Soil Science Society of America Special Publication, 35: Soil Science Society of America, Madison, Wisconsin, pp. 23–25.

Hayne, R. A. 1940. Make the soil productive: We can't grow crops on poor land, Education Series 2, Chicago, IL.

Howard, A. 1940. An agricultural testament. Oxford Univ. Press, London, U.K.

Howard, A. 1947. The soil and health: a study of organic agriculture. Devin-Adair Company, New York, NY.

Jansson, C., S. D. Wullschleger, U. C. Kalluri, and G. A. Tuskan. 2010. Phytosequestration: carbon Biosequestration by plants and the prospects of genetic engineering. Bioscience 60:685–696.

Janvier, C., F. Villeneuve, C. Alabouvette, V. Edel-Hermann, T. Mateille, and C. Steinberg. 2007. Soil health through soil disease suppression: which strategy from descriptors to indicators? Soil Biol. Biochem. 39:1–23.

Karlen, D., N. Wollenhaupt, D. Erbach, E. Berry, J. Swan, N. Eash, et al. 1994. Long-term tillage effects on soil quality. Soil Till. Res. 32:313–327.

Karlen, D., M. Mausbach, J. Doran, R. Cline, R. Harris, and G. Schuman. 1997. Soil quality: a concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J. 61:4–10.

Kibblewhite, M. G., K. Ritz, and M. J. Swift. 2008. Soil health in agricultural systems. Philos. Trans. R. Soc. B Biol. Sci. 363:685–701.

Kleber, M. 2010. What is recalcitrant soil organic matter? Environ. Chem. 7:320–332.

Kleber, M., P. S. Nico, A. F. Plante, T. Filley, M. Kramer, C. Swanston, et al. 2011. Old and stable soil organic matter is not necessarily chemically recalcitrant: implications for modeling concepts and temperature sensitivity. Glob. Change Biol. 17:1097–1107.

Knight, H. G., C. E. Kellogg, C. P. Barnes, M. A. McCall, B. W. Allin, A. L. Patrick, et al. 1938. Soils and men. USDA Yearbook of Agriculture, Washington, DC.

Lal, R. 1993. Agronomic sustainability of different farming systems on Alfisols in Southwestern Nigeria. J. Sustain. Agric. 4:33–51.

Lal, R. 1994. Methods and Guidelines for Assessing Sustainable Use of Soil and Water Resources in the Tropics. USDA/SMSS Bull. 21, Washington, DC, 78 pp.

Lal, R. 1997. Degradation and resilience of soils. Philos. Trans. R. Soc. Lond. B. 352:997–1010.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627.

Lal, R. 2008. Carbon sequestration. Philos. Trans. R. Soc. B Biol. Sci. 363:815–830.

Lal, R. 2009. Soil degradation as a reason for inadequate human nutrition. Food Sec. 1:45–57.

Lal, R. 2014. Societal value of soil carbon. J. Soil Water Conserv. 69:186A–192A.

Lal, R. 2016. Beyond COP21: potential and challenges of the "4 per Thousand" initiative. J. Soil Water Conserv. 71:20A–25A.

Lal, R., R. F. Follett, and J. M. Kimble. 2003. Achieving soil carbon sequestration in the US: a challenge to policy makers. Soil Sci. 168:1–19.

Larkin, R. P., and N. K. VanAlfen. 2015. Soil health paradigms and implications for disease management. Annu. Rev. Phytopathol. 53:199–221.

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Larson, W. E., and F. J. Pierce. 1991. Conservation enhancement of soil quality. Int. Board Soil Res. Manage. Proc. 2:175–203.

Liao, Y., W. L. Wu, F. Q. Meng, P. Smith, and R. Lal. 2015. Increase in soil organic carbon by agricultural intensification in northern China. Biogeosciences 12:1403–1413.

Lovelock, J. 1979. Gaia: new look at life on earth. Oxford University Press, Oxford, U.K.

von Lützow, M., and I. Kögel-Knaber. 2009. Temperature sensitivity of soil matter decomposition- what do we know? Biol. Fertil. Soils 46:1–15.

Ma, J., R. Liu, L. S. Tang, Z. D. Lan, and Y. Li. 2014. A downward CO_2 flux seems to have nowhere to go. Biogeosciences 11:6251–6262.

McCarrison, R. 1921. Studies in deficiency disease. Hazell Watson and Viney Ltd, London, U.K.

Monger, H. C., R. A. Kraimer, S. Khresat, D. R. Cole, X. J. Wang, and J. P. Wang. 2015. Sequestration of inorganic carbon in soil and groundwater. Geology 43:375–378.

Ness, E. 2015. The hunt for antibiotics in soil. CSA News. doi:10.2136/sh2015-56-5-f.

Overstreet, L. F., and J. DeJong-Huges. 2008. The importance of soil organic matter in cropping systems of the Northern Great Plains. University of Minnesota Extension. Available at: http://www.extension.umn.edu/agriculture/tillage/importance-of-soil-organic-matter/

Parr, J. F., R. I. Papendick, S. B. Hornick, and R. E. Meyer. 1992. Soil quality: Attributes and relationship to alternative and sustainable agriculture. Amer. J. Alternative Agric. 7:5–11.

Rodale, J. I.. 1945. Pay dirt: farming and gardening with composts. Devin-Adair Company, New York, NY.

Sa, J. C. M., R. Lal, C. C. Cerri, K. Lorenz, M. Hungria, P. C. F. Carvalho. 2016. Low-carbon agriculture in South America to mitigate global climate change and advance food security. Catena (accepted).

Scharlemann, J. P. W., E. V. J. Tanner, R. Hiederer, and V. Kapos. 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Manag. 5:81–91.

Singh, B., and J. Ryan. 2015. Managing fertilizers to enhance soil health. IFA, Paris, France.

Six, J., E. T. Elliott, and K. Paustian. 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32:2099–2103.

Six, J., R. T. Conant, E. A. Paul, and K. Paustian. 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241:155–176.

Smith, J., J. Halvorson, and R. Papendick. 1993. Using multiple-variable indicator kriging for evaluating soil quality. Soil Sci. Soc. Am. J. 57:743–749.

Smith, P., M. F. Cotrufo, C. Rumpel, K. Paustin, P. J. Kuikman, J. A. Elliott, et al. 2015. Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils. Soil 1:665–685.

Stockmann, U., M. A. Adams, J. W. Crawford, D. J. Field, N. Henakaarchchi, M. Jenkins, et al. 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric. Ecosyst. Environ. 164:80–99.

Sylvia, D. M., J. J. Fuhrmann, P. G. Hartel, and D. A. Zuberer. 1998. Principles of soil microbiology. Prentice Hall, Upper Saddle River, NJ, 550 pp.

Voisin, A.. 1959. Soil, grass, and cancer. Philosophical Library, New York, NY.

Warkentin, B. 1995. The changing concept of soil quality. J. Soil Water Conserv. 50:226–228.

Wolf, A. A., B. G. Drake, J. E. Erickson, and J. P. Megonigal. 2007. An oxygen-mediated positive feedback between elevated carbon dioxide and soil organic matter decomposition in a simulated anaerobic wetland. Glob. Change Biol. 13:2036–2044.

Zhang, J. 2010. Temperature sensitivity of soil organic matter decomposition and the influence of soil carbon and attributes. [Graduate Theses and Dissertations], Iowa State University, Paper 11234.

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