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FEATURE

Societal value of soil carbon

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Agriculture is an engine of economic development and is integral to any agenda for addressing global issues of the twenty-first century (e.g., food and nutritional security, climate change, growing energy and water demands, and biodiversity). By 2050, there will be an additional global food demand for cereal production by 1 billion t y^{-1} (1.1 billion tn yr^{-1}) from 2.1 to 3.0 billion t (2.3 to 3.3 billion tn), and 200 million t y^{-1} (220 million tn yr^{-1}) of meat up to 470 million t y^{-1} (518 million tn yr^{-1}) (FAO 2009; Alexandros and Bruinsma 2012). In addition, President Obama announced on June 2, 2014, that the US Environmental Protection Agency would cut carbon (C) emissions from the US power sector by up to 30% and soot and smog pollution by 25% by 2030 relative to 2005 levels (Kintisch 2014). There will also be an additional water demand of 40% by 2030, in which soil-water storage (e.g., green water) will play a crucial role (Rosegrant et al. 2002). Indeed, major concerns of the modern civilization, especially peace and tranquility (Lal 2014), are intricately connected with soil and its quality, sustainable intensification of agriculture, and climate-resilient farming through recarbonization of soil and the terrestrial biosphere.

Soil organic carbon (SOC; concentration and pool) and its dynamics are key determinants of soil quality and for the provisioning of essential ecosystem services (Koch et al. 2012; Stockman et al. 2013). Thus, soil should be appropriately defined as an organic C-mediated realm in which solid, liquid, gaseous, and biological components interact from nanometer to landscape scale to generate ecosystem services essential to all terrestrial life. The objective of this article is to describe the importance of SOC to addressing global issues, especially food security advancement and climate change mitigation and adaptation. The inherent and societal value of SOC is also assessed.

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Table 1

Comparison of environmental indicators in 1992 and 2014 (Brown 2010; Le Quere et al. 2013; Houghton 2003; WMO 2013; IPCC 1990, 2013; UN 2014; FAO 2011, 2014; IFDC 2010; World Bank 2014 ; WHO/UNICEF 2014).

Parameters	1992	2014
Total population (10^9)	5.49	7.24
Urban population (10^9)	2.57	3.88
Energy use (EJ)	365	600
Fossil fuel emission (Pg C)	6.2	10.1
Emission from tropical deforestation (Pg C)	2.18	0.8
Water use (km^3)	0.56	0.70
Fertilizer use (10^6 Mg)	125	190
Per capita arable land (ha)	0.26	0.19
Atmospheric carbon dioxide concentration (ppm)	354	400
Atmospheric methane concentration (ppm)	1,720	1,831
Atmospheric nitrous oxide concentration (ppm)	310	327
Per capita grain production (kg)	359	344
Poverty (10^9; <US\$1.25 d^{-1})	1.9	1.5
Ethanol production (10^9 L)	17	120
Hunger prone population (10^6)	1,000	842
Lack of clean drinking water (people 10^9)	1.32	0.81
Lack of access to sanitation (people 10^9)	2.90	2.60

SOIL RESILIENCE VERSUS SUSTAINABLE DEVELOPMENT

The Earth Summit, United Nations Conference on Environment and Development in Rio de Janeiro from June 3 to 14, 1992, proposed Agenda 21 on Sustainable Development (UN 1992). It is a nonbinding, voluntarily implemented action plan of the United Nations with regards to sustainable development. It is aimed at preparing the world for the challenges of the twenty-first century through sustainable environments and development. Section 4 specifically addresses the strategy of promoting terrestrial resource utilization and appropriate land use practices that contribute to (1) reduction of anthropogenic emissions of greenhouse gases (GHGs); (2) conservation, sustainable management, and enhancement of all sinks of GHGs; and (3) conservation and sustainable use of natural capital and environmental resources (e.g., soils). However, the analysis of data on global resources indicates that the strategy has not been as effective as was envisaged (table 1). For example, percentage increase of some environmentally sensitive parameters in 2014 compared with their value in 1992 is 32% for total population, 39% for urban population, 64% for energy use, 63% for fossil fuel emission of carbon dioxide (CO_2), 35% for fresh water use, and 52% for fertilizer consumption. An increase in atmospheric concentration of GHGs was also observed (by 13% for CO_2, 6.5% for methane [CH_4], and 5.5% for nitrous oxide [N_2O]). It is important to note, however, that absolute number of hunger-prone population decreased by 15.8%, and the number of world poor (<US\$1.25 d^{-1}) decreased by 21%. On the contrary, per capita land area decreased by 37%, and grain consumption decreased by 4.2% (table 1).

The data in table 1, and of numerous other critical parameters, clearly indicate that the goals of Agenda 21 have not been met, and neither have the targets of the so-called Millennium Development Goals (United Nations Development Programme 2000). Yet, the cost of adaptation to climate change can be high (Ahmed and Suphachalasai 2014). Thus, there is a strong need to critically and

Table 2

Impacts of soil organic carbon concentration on soil quality. All qualities function together to provide resilience against climate change and other perturbations.

Soil	Soil parameter
Physical quality	Aggregation and structural stability
	Tilth, resistance to crusting and compaction, and ease of cultivation
	Aeration and gaseous composition in soil air
	Water retention and availability
	Water transmission (infiltration and percolation)
	Heat capacity
	Surface area
	Soil strength/erodibility
Chemical quality	Cation exchange capacity
	Nutrient retention and availability
	Buffer capacity (against pH)
Biological quality	Soil biodiversity
	Food and habitat for soil biota
Ecological quality	Net primary productivity
	Use efficiency of input
	Nutrient cycling and biogeochemical transformations
	Carbon sequestration
	Rate of new soil formation
	Water purification
	Denaturing of pollutants

objectively reexamine the concept of sustainability (Benson and Craig 2014a). The resilience concept may be a better way to address environmental and natural resources challenges in an uncertain future (Showstack 2014) because the realities of anthropocene demands a new approach to environmental governance (Benson and Craig 2014b). The term "sustainable development" as perceived in Agenda 21 refers to a broader goal on strategy toward sustainable development with due consideration to the environment (concerns about climate change) and availability of natural resources (land, water, etc.). The data in table 1 show that neither the anthropogenic emissions have been reduced nor the concentrations of GHGs stabilized. The goals of eliminating hunger, poverty, and malnutrition remain as elusive as ever and merely a mirage.

Therefore, the focus is shifting toward "resilience" of social-ecological systems (SESs) and other innovative concepts because when indicators of climate change and the baseline of 1990 are in flux (moving targets), it is difficult to comprehend what is to be sustained. Agenda 21 assumed possession of both the knowledge about what can be sustained and the human capacity to achieve it. In contrast to maintaining stationarity, the resilience concept acknowledges disequilibrium and suggests techniques of assessing dynamic equilibrium among SESs and how to enhance the capacity to restore their functions (Benson and Craig 2014a, 2014b).

Soil, as a finite but essential resource, is prone to degradation, and risks of disequilibrium are exaggerated by climate change. Therefore, the strategy is to enhance soil's resilience against natural and anthropogenic perturbations (table 2). The key determinant of soil resilience is its SOC concentration, quality, and threshold level for meeting the ever-growing demands (food, feed, fiber, and fuel) of increasingly affluent humanity. Thus, the focus must be on judicious management of SOC concentration and pool.

SOIL ORGANIC CARBON

Soil organic matter (SOM) comprising of approximately 58% of SOC (which is a researchable issue in itself), is the basis of all physical, chemical, biological, and ecological transformations and reactions within a soil. Its importance has been recognized by farmers of all ancient civilizations. Asian farmers were able to cultivate the same field for as long as 40,000 years while maintaining soil fertility by managing SOM through manuring and recycling (King 1911). Sir Albert Howard (1873 to 1947) stated that "the health of soil, plant, animal, and man is one and indivisible." Beginning in 1905, Sir Howard worked as an agricultural advisor in Indore, India, and realized the importance of SOM and recycling biomass to soil quality and productivity (Howard 1929, 1943). Howard strongly believed in the relationship between the rise and fall of civilizations and their agricultural practices and argued that "the real arsenal of democracy is a fertile soil, the fresh produce of which is the birthright of nations" (Howard 1945).

Recycling nutrients in the biomass (e.g., manure and compost) has been practiced for millennia in India, China, and other ancient civilizations. In ancient India, Kautilya (Chanakaya), a brahmin and a contemporary of Aristotle, was prime minister (326 to 301 BC) of the Emperor Chandragupta of the Mauryan Empire (326 to 200 BC). The book written in Sanskrit by Kautilya, *Artha Sastra,* has an important section on science of agricultural production and irrigation. Of the 15 books in *Artha Sastra*, chapter 14 in book 2 is entitled "Sitadhyaksha" or the "Superintendent of Agriculture" (Shamasastry 1915, 1961; Waldauer et al. 1996; Nene 2002; Tamboli and Nene 2010; Basu 2014). In the context of environment and ecology, Kautilya stated that sources of hazards pertaining to environment and ecology are human indiscretion and emphasized that a king should protect different types of forests and that water reservoirs (*setu*) be filled with water either from perennial sources or drawn from some other source (Shamasastry 1915). In *Krishi-Parashara* (a text on ancient Indian agriculture in Sanskrit), it is stated that crops grown without manure will not give yield. Kautilya mentioned the use of cow dung, animal bones, fish, milk, and manure to enhance soil fertility (Chaudhuri 1963). Ancient farmers in India believed that manuring is more important than plowing (Aiyar 1952). Green manure (plowing under of sesame) for crops, and liquid manure (*kunapa*) were recommended practices for trees (*surapala*) (Aiyar 1961). The importance of cow dung as a biofertilizer and a reservoir of soil fauna is still highly regarded (Srivastava et al. 2010).

Similar to India, China has a rich ancient literature on agricultural practices and soil management dating back to the dawn of farming. The *Book of Odes* explains agricultural practices dating back from Zhou dynasty (1027 to 771 BC) to 770 to 476 BC (Shi Jing) (Karlgren 1950). A compilation of 305 poems covering ancient life in China, it also describes landforms, animals, and plants. Houji, a legendary Chinese hero (~2100 BC) in the middle reaches of Yellow and Yangtze rivers, is credited with introducing millet (*Pennisetum glaucum*) during the Xia dynasty. He developed the philosophy of agriculturalism in China and was famous for his luxurious crops of beans, rice, hemp, gourds, and millets (Wu 1982; Ho 1976).

In the book *Kitab al-Filaha*, written in the second half of the twelfth century, Ibn Al-'Awwam, a Moorish Arab from southern Spain described 585 plants and explained cultivation of more than 50 different fruit trees. He described soil quality with an important reference to SOM through soil color by stating that "the first step in the science of agriculture is the recognition of soils and of how to distinguish that which is of good quality and that which is of inferior quality…one must also consider the depth of the soil—for it often happens that its surface may be black" (Al-'Awwam 1866).

In the *USDA Yearbook 3: Soils and Men*, Albrecht (1938) stated that "SOM is one of our most important natural resources: its unwise exploitation has been devastating; and it must be given its proper place in any conservation policy as one of the major factors affecting the level of crop production in the future." He also believed in "healthy soils, healthy people, and healthy animals" (Albrecht 1958). As president of Soil Science Society of America in 1938, he stated that "a declining soil fertility, due to a lack of organic material, major elements, and trace minerals, is responsible for poor crops and in turn for poor people." He also related health of teeth to the health of soils (Albrecht 1947) and argued that "health of our nation may be impossible to restore without first restoring the health of our soils."

SOIL ORGANIC CARBON AND ECOSYSTEM FUNCTION

There are several options of mitigating climate change by offsetting anthropogenic emissions and creating net negative balance in the atmosphere (figure 1). Important among these are geo-engineering, reducing emissions, carbonation, and sequestering emissions by abiotic and biotic processes. Carbon sequestration in soil and vegetation is a promising option with numerous cobenefits. Further, SOC is a key parameter for maintaining soil physical, chemical, and biological quality (table 1). Thus, maintaining SOC concentration above the threshold level of ~2% in the root zone is essential (Loveland and Webb 2003; Schjonning et al. 2010; Patrick et al. 2013). It is widely known that increase in SOC concentration in depleted soils increases crop yield (Lal 2006, 2010; Seremesic et al. 2011) and use efficiency of input, and has numerous global benefits (Govers et al. 2012). The magnitude of yield increase depends on soil type, crop, management, antecedent SOC concentration, and the weather during the growing season. By enhancing soil resilience against extreme events and uncertain climate, and improving use efficiency of inputs, SOC-induced improvement in soil quality is critical to ensuring satisfactory crop yields even during a poor growing season. The literature is replete with data on favorable impacts of SOC on soil structure, erodibility, crusting, compaction, water retention, and transmission (Manlay et al. 2007; Feller et al. 2012; Six et al. 2002). In conjunction with activity and species diversity of soil biota, improvement in SOC also creates disease-suppressive soils. Thus, the strategy of removing crop residues for biofuels and cellulosic ethanol production must be critically assessed (Johnson et al. 2010).

NUTRIENTS REQUIRED TO CONVERT BIOMASS CARBON INTO SOIL ORGANIC CARBON

The process of biochemical transformation of biomass (crop residues, plants, and animal wastes) into SOC requires additional nutrients, especially nitrogen (N), phosphorus (P), and sulfur (S) (figure 2). Most residues of cereals have a wide ratio of C:N (100), C:P (200), and C:S (500) compared with that of SOC at 12, 50, and 70, respectively. Using these data and assuming the C concentration in cereal residues and the humification efficiency of ~40%, Himes (1997) estimated that sequestration of 10,000 kg (22,000 lb) of biomass C as SOC would require 62,000 kg (137,000 lb) of oven dry residue consisting of 28,000 kg (62,000 lb) of C and 833 kg (1,836 lb) of N, 200 kg (441 lb) of P, and 143 kg (315 lb) of S. This will produce 17,241 kg (38,010 lb) of humus. Without the availability of these essential nutrients, SOC concentration does not always increase even with long-term

Figure 1

Strategies of mitigating climate change. CSS = carbon capture and storage.

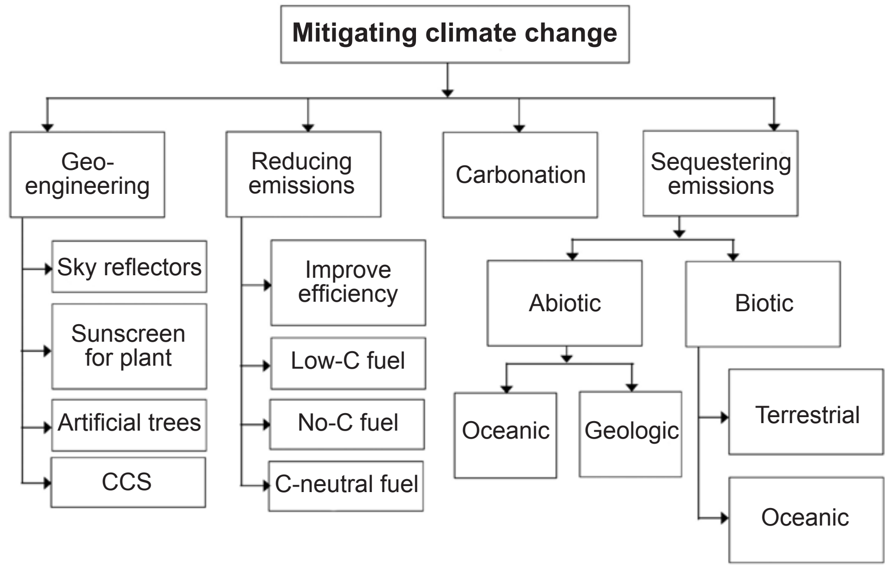
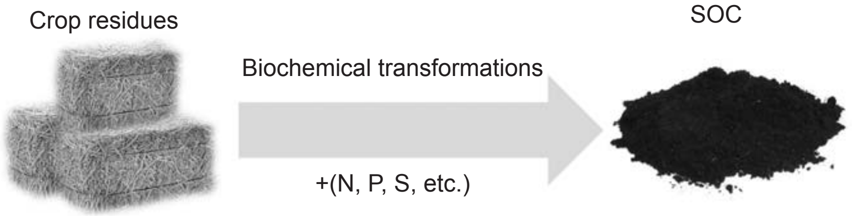


Figure 2

Nutrients required for biogeochemical transformation of biomass carbon (C) into soil organic carbon (SOC). The data on the amount of nitrogen (N), phosphorus (P), and sulfur (S) are from Himes (1997).



Elemental Ratio	Cereal Residues	SOC
C:N	100	12
C:P	200	50
C:S	500	70

application of crop residues (Baker et al. 2007; Bissett et al. 2011). Similar calculations were made by Richardson et al. (2014) who estimated that increasing SOC by 1 Mg C ha^{-1} (893 lb C ac^{-1}) into humus requires 73, 17, and 11 kg ha^{-1} (65, 15, and 10 lb ac^{-1}) of N, P and S, respectively. Because nutrients are required both for crop production and C sequestration, Richardson and colleagues suggested the concept of "fertilizing the system" rather than the crop. Thus, there are significant and hidden costs of additional nutrients required for C sequestration.

SOCIETAL AND INHERENT VALUE OF SOIL ORGANIC CARBON

Reducing GHG emissions by 40% to 70% by 2050 necessitates removing CO$_2$ from the atmosphere (or negative emissions) (Benson 2014). In addition to forestry measures (afforestation and reforestation), increasing C in soils has additional cobenefits. The societal value of soil C refers to the monetary equivalent of ecosystem services provisioned by a unit amount of SOC. The range of ecosystem services includes increasing net primary productivity and agronomic yield in the context of food and nutritional security, improving plant available water capacity in the root zone, reducing water runoff and soil erosion, minimizing sedimentation and nonpoint source pollution, offsetting anthropogenic emissions and mitigating/adapting to climate change, denaturing pollutants and purifying water, and enhancing biodiversity. Assessing monetary value of these and other services is a major challenge (Costanza et al. 1997, 1998, 2014). It is indeed difficult to assess the real societal value of SOC. It has been a scientific challenge to assess the time it takes to create 1 cm (0.4 in) of surface soil. Soil is the most "priceless" gift of nature. It is not possible to assess its true worth in monetary terms.

In comparison, the inherent value of SOC can be estimated as the so-called "hidden cost" of all inputs, including crop residues/hay, fertilizers, and labor. Although a useful guide, the inherent cost of SOC must not be confused with its societal value. Just as the monetary value of an animal (human) cannot be computed by summing up the market values of nutrients in blood, bones, and tissues, so also the value of soil or SOC cannot be assessed by adding the monetary equivalent of its constituents (C, N, P, S, etc.). Indeed, life is more than the sum of its innate constituents. While treating SOC as a mixture of compounds, the monetary cost of these inputs must be adjusted for any benefits to farmers in terms of gain in productivity through water conservation and fertility improvement by nutrient cycling.

In continuation of the discussion regarding the inputs of crop residues and nutrients required to sequester 10,000 kg (22,000 lb) of biomass C and transform it biochemically into 17,241 kg (38,010 lb) of humus, monetary costs of residues and fertilizer equivalent (tables 3 and 4) along with those of nutrients are estimated at US$3,384 (table 5). These costs must be adjusted for nutrients returned in the crop residues (table 3 and 4 or about US$22.05 Mg^{-1} [US$20 tn^{-1}] of residues with a total of US$1,367), and the agronomic benefits in crop yields (5% increase due to soil moisture conservation for 6 ha [14.82 ac] for a total gain of 3 Mg [138 bu] of grains with an average price of US$5 bu^{-1} for a total gain of US$690) through soil and water conservation and improvements in soil quality, leaving a net cost of (US$3,384 – US$2,057 = US$1,327) for 10,000 kg C (22,000 lb C) at US$132.70 Mg^{-1} (US$120.40 tn^{-1}) C or US$36.20 Mg^{-1} (US$32.80 tn^{-1}) CO$_2$. Thus, the inherent value of SOC is US$0.13 kg^{-1} (US$0.05 lb^{-1}) C, US$0.075 kg^{-1} (US$0.034 lb^{-1}) of SOM (58% C), and US$0.035 kg^{-1} ($0.016 lb^{-1})of CO$_2$. If only the cost of nutrients (N, P, and S) is considered, the cost of SOC is US$1,028 for 10,000 kg C (22,000 lb C), US$0.10 kg^{-1} (US$0.045 lb^{-1}) of C, and US$0.03 kg^{-1} ($0.013 lb^{-1}) of CO$_2$.

These costs are estimates and vary from country to country and year to year depending on the price of fertilizers, grains, stover, and other market forces. The objective of this exercise is not to provide a precise value but to demonstrate the concepts so that inherent or the societal value can be computed on the basis of the hidden costs of the inputs involved.

PAYMENTS FOR ECOSYSTEM SERVICES

Carbon farming is rapidly becoming the new agriculture where C sequestered in soil/trees/wetlands could be traded just as any other farm produce. Alternatively, farmers would be compensated for provisioning of ecosystem services through C sequestration in soil/biomass (Lal et al. 2013). Three mechanisms of compen-

Table 3

Estimation of nutrients contained in crop residues (USDA 2008).

	Nutrient concentration (%)		
Crop	Nitrogen	Phosphorus	Potassium
Corn	0.97	0.10	1.52
Wheat	0.61	0.06	1.17
Sorghum	0.77	0.115	1.01
Rice	0.70	0.09	1.48

Table 4

Price of fertilizer nutrients (AfricaFertilizer.org 2014).

Nutrient	Form	Cost (US\$ Mg^{-1})	Nutrient cost (US\$ kg^{-1})*
Nitrogen	Urea	300 to 500	0.67 to 1.0 (0.84)
	Anhydrous ammonia	400 to 500	0.49 to 0.61 (0.55)
	Ammonium sulfate	120 to 150	0.57 to 0.71 (0.64)
Phosphorous	Mono-ammonium phosphate	400 to 500	1.67 to 2.08 (1.88)
	Di-ammonium phosphate	380 to 500	1.90 to 2.50 (2.22)
	Tri-ammonium phosphate	300 to 390	1.50 to 1.95 (1.73)
Potash	Muriate of potash	300 to 400	0.57 to 0.76 (0.67)
Compound	NPK (16:16:16)	320 to 400	0.67 to 0.83 (0.75)
Sulfur	S	500 to 630	0.50 to 0.63 (0.57)

*Numbers in parentheses are average price per kilogram of nutrient.

Table 5

Monetary cost of converting biomass into soil organic matter/soil organic carbon (C).

Ingredients	Amount (kg)	Price (US\$ kg^{-1})	Total price (US\$)
Residues	62,000*	0.038	2,350
Nitrogen	833	0.67	558
Phosphorus	200	1.94	388
Sulfur	143	0.57	82
		Total	3,384

*Assuming conversions of biomass C at 35%, and C combustion in residues of 45% = (10^4 kg ÷ 0.35) ÷ 0.45 = 62,000 kg.

sating farmers are (1) C credits based on cap and trade, (2) C maintenance fees, and (3) payments for ecosystem services. All of these three mechanisms must consider the inherent value of soil C.

It is the understanding of basic principles governing the value of scientific concepts which leads to innovation and judicious management of natural resources. The human wellbeing depends on appropriate use of science. Humanity is once again grappling with a myriad of strong challenges (e.g., climate change, soil degradation, water scarcity, and food and nutritional security). Successfully addressing these challenges necessitates assigning societal value to critical resources (e.g., SOC). Undervaluing SOC, or other resources such as water, can lead to tragedy of the commons. Not only can the innovations be hindered by undervaluing a resource, but it is prone to exploitation by greed and for making quick returns by cutting corners for short-term gains. Therefore, assigning appropriate societal value to SOC and implementing policies for its judicious management are critical to ecological restoration of our once and future planet (Woodworth 2013) so that soils will always save us (Ohlson 2014).

THE SOIL ICON

Soil is the basis and essence of all terrestrial life. The Gaia hypothesis states that all organisms and their inorganic surroundings on Earth are closely integrated to form a single and self-regulating complete system, maintaining the conditions of life on the planet (Lovelock 1979). Earth-based spirituality and earth wisdom (Kjos 1992) is gaining momentum. Thus, natural resource conservation is increasingly being linked with stewardship and spirituality (Wallace and Clearfield 1997). An icon, with a universal appeal, is needed to enhance awareness about the importance of soil in all daily life. Just as a panda has been used as a symbol of wildlife, a polar bear on an ice patch of global warming, so is an urgent and strong need for a soil icon as a symbol of all terrestrial life and numerous ecosystem functions and services. Such an icon can be a useful education tool for second to twelfth grade students, a promotional poster for media, and an advocacy protocol for policy makers. An example of such an icon, which can be and should be improved, is shown in figure 3 and indicates that all life (microbes, plants, animals, and humans) depend on a healthy soil.

CONCLUSIONS

As efforts are made to assign value to and manage our soil resources, the following should kept in mind:

- Restoring SOC concentration to above the critical level (~2.0%) in the root zone is essential to ecosystem functions, provisioning of critical services, (e.g., food and nutritional security, resilience to climate change, water quality, biodiversity).
- There are hidden costs of SOC restoration through biochemical transformations of biomass C into residues. These costs include those of crop residues/biomass and nutrients (e.g., N, P, S). The monetary equivalent of inherent cost or societal value of SOC is ~US\$0.133 kg^{-1} (US\$0.060 lb^{-1}).
- With an average sequestration rate of 300 kg C ha^{-1} y^{-1} (267 lb C ac^{-1} yr^{-1}) through adoption of best management practices, farmers should be compensated for provisioning of ecosystem services (climate change mitigation, water quality, biodiversity, etc.) at the rate of US\$40 ha^{-1} y^{-1} (US\$16 ac^{-1} yr^{-1}).
- Humus/SOC is a finite but essential natural capital, and it must be used, enhanced, and restored by land use and management systems that create a positive soil/ecosystem C budget, by decreasing losses (e.g., erosion and decomposition) and increasing input (e.g., crop residues, cover cropping, and manuring) and recommended management practices (e.g., conservation agriculture).

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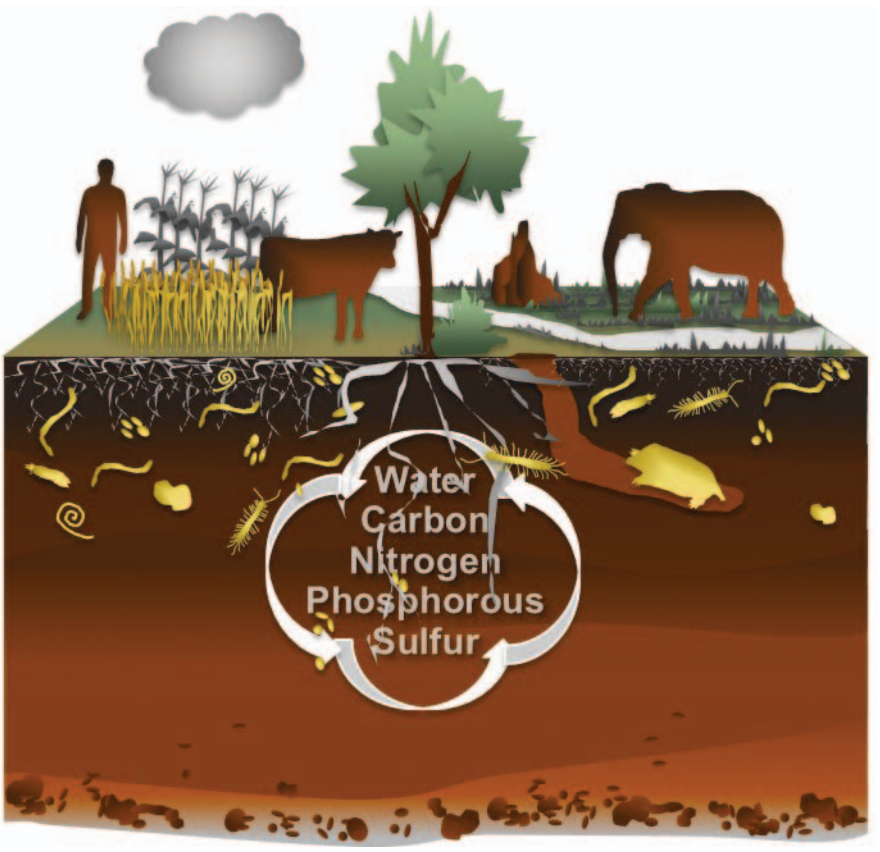
Figure 3

Soil is the essence of all terrestrial life. A possible "soil icon" indicating the life-support services of soil.



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