

Conceptual basis of managing soil carbon: Inspired by nature and driven by science

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The anthropogenically induced increase of 146% in atmospheric concentration of carbon dioxide (CO_2), from 278 ppm in the preindustrial era (circa 1750) to 405.5 ppm in 2017, is presently increasing at the rate of 2.24 ppm y^{-1} (0.55%) (WMO 2018). This increase, along with those of methane (CH_4 ; from 722 ppb to 1,859 ppb by 257% and increasing at the rate of 0.38% or 6.9 ppb y^{-1}) and nitrous oxide (N_2O ; from 270 ppb to 330 ppb at the rate of 0.27% or 0.93 ppb y^{-1}) has already caused $\sim 1^\circ\text{C}$ (1.8°F) increase in global temperature since the Industrial Revolution (IPCC 2018) with dire consequences as exemplified by the increase in frequency of extreme events throughout the world. However, there is still a chance to implement the Paris Climate Agreement proposed at the Paris Climate Conference (COP21) in 2015 and limit the global warming to 1.5°C (2.7°F). To achieve this limit, however, the world must identify noncarbon (C) fuel sources and simultaneously adopt techniques of removing CO_2 from the atmosphere or implement negative emission technologies (NET). Carbon sequestration in soil is an important NET option with numerous cobenefits of enhancing agricultural production, improving water resources, and strengthening biodiversity (Lal 2010).

Carbon sequestration in the terrestrial biosphere, with a technical cumulative C sink capacity of 155 Pg C (158.6×10^9 tn C) in vegetation and 178 Pg C (182.1×10^9 tn C) in soil by 2100 (Lal et al. 2018), is equivalent to drawdown of atmospheric CO_2 by 156 ppm. Of the total drawdown potential, drawdown through sequestration of soil organic C (SOC) is ~ 84 ppm of CO_2 . However, the large C sink capacity of the terrestrial biosphere must be accompanied by a complete moratorium on fossil fuel combustion by 2050, another 32 years from now. To limit the global warming to

1.5°C (2.7°F), the atmospheric concentration of CO_2 at 405.5 ppm in 2017 must not exceed 560 ppm by 2050. Whereas the cumulative emissions from fossil fuel combustion between 1960 and 2017 is estimated at 350 Pg C (358.1×10^9 tn C), additional emissions until 2050 must not exceed 328 Pg C (335.6×10^9 tn C) as described below and shown in figure 1:

$$(560 \text{ ppm } \text{CO}_2 - 405.5 \text{ ppm } \text{CO}_2) \div (\text{Pg C}/0.47 \text{ ppm } \text{CO}_2) = 328 \text{ Pg C.} \quad (1)$$

The present rate of fossil fuel combustion of 9.9 Pg C (10.1×10^9 tn C) in 2017 (Le Quéré et al. 2018) must decline to 0 by 2050 with the maximum cumulative C emission of 328 Pg (figure 1). Thus, the objective of this article is to describe the processes and practices of soil C sequestration to limiting the global warming to 1.5°C (2.7°F).

SOIL CARBON POOL

The soil C pool consists of two related but different components: the SOC pool and the soil inorganic C (SIC) pool, which strongly impact the global C cycle (GCC). The SOC pool, derived from the decomposition of the remains of plants and animals and the by-products of microbial processes, is estimated at 1,505 Pg ($1,539.8 \times 10^9$ tn) to 1 m (3.28 ft) depth (Batjes 1996). In addition, Cryosols (frozen soils or the permafrost) may contain as much as 1,672 Pg C ($1,710.6 \times 10^9$ tn C) (Jungkunst et al. 2012). The SIC pool consists of carbonates derived from the weathering of parent rocks (lithogenic or primary carbonates) and those formed from the dissolution of CO_2 in soil air to form a weak carbonic acid and its reaction with the bases brought in from outside the system (pedogenic or secondary carbonates). The magnitude of the SIC pool is estimated at 940 Pg C (961.7×10^9 tn C) to 1 m (3.28 ft) depth (Monger et al. 2015). The SIC pool also consists of bicarbonates in groundwater estimated at 1,404 Pg C ($1,436.4 \times 10^9$ tn C); there is a strong flux of CO_2 into the groundwater (Kessler and

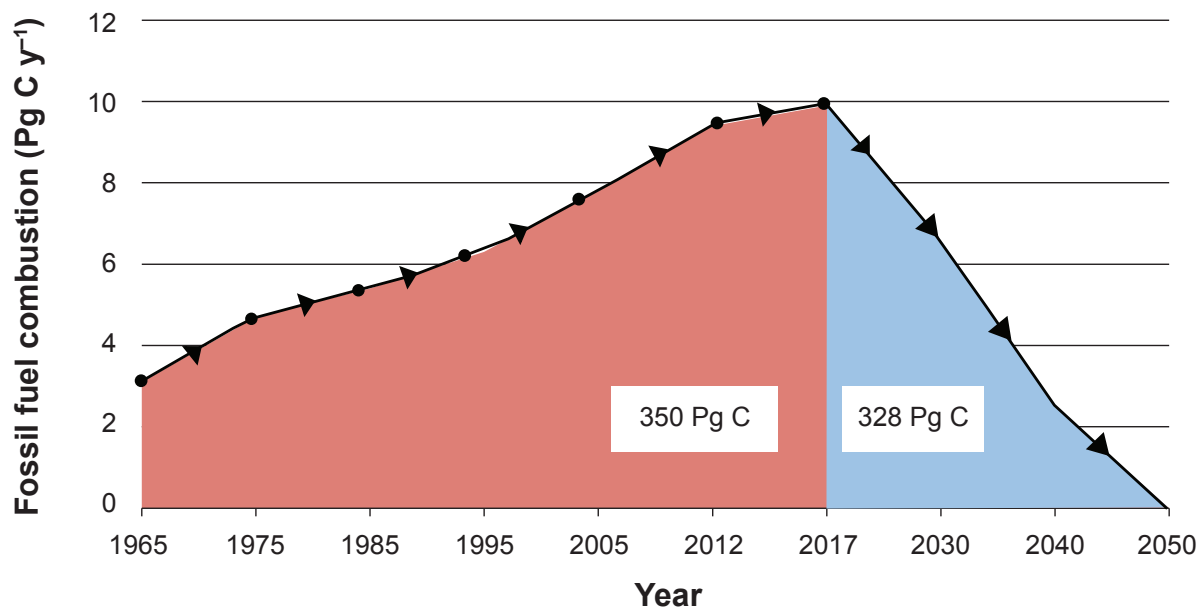
Harvey 2001). Altogether, the SIC pool is about 2,344 Pg C ($2,398.1 \times 10^9$ tn C) to 1 m (3.28 ft) depth (Monger et al. 2015). Recalibration of the nonflat earth for terrain and topsoil may increase the estimates of soil C stock to 8,580 Pg C ($8,778.2 \times 10^9$ tn C) (Blakemore 2018). With such a large C pool, in comparison with that of the atmosphere (820 Pg [838.9×10^9 tn]) and the biotic pool (620 Pg [634.3×10^9 tn]), a small emission from the soil C pool can easily overwhelm the atmospheric pool and aggravate the process of global warming. On the contrary, even a small increase in the soil C pool through storage of biomass C can have a strong drawdown impact on atmospheric concentration of CO_2 . Thus, thoroughly understanding and judiciously managing the largest terrestrial C pool (Scharlemann et al. 2014) is of a critical importance to limiting global warming to 1.5°C (2.7°F) and also meeting other demands of the growing and increasingly affluent world population.

Historic land use and the widespread adoption of extractive farming practices, coupled with the severe problem of erosion and other degradative processes, have depleted the SOC pool of agro-ecosystems by as much as 135 Pg C (138.2×10^9 tn C) (Lal 2018a). On the contrary, restoration of degraded soils through conversion to a restorative land use and adoption of recommended management practices can create a positive soil C budget. Through a widespread adoption of NET, therefore, world soils are a viable option for adaptation and mitigation of anthropogenic climate change. The schematic in figure 2 shows that 80 Pg C (81.8×10^9 tn C) was emitted between 1960 and 2017 from land use change (Le Quéré et al. 2018). However, adoption of the restorative land use and recommended management practices can potentially create a drawdown of about 333 Pg C (340.7×10^9 tn C) between 2020 and 2100 or reduction in atmospheric CO_2 by ~ 156 ppm through sequestration of C in the terrestrial biosphere (Lal et al. 2018).

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Figure 1

The past emission and the designed reduction in the future emission. Past emissions are drawn from Le Quéré et al. (2018).



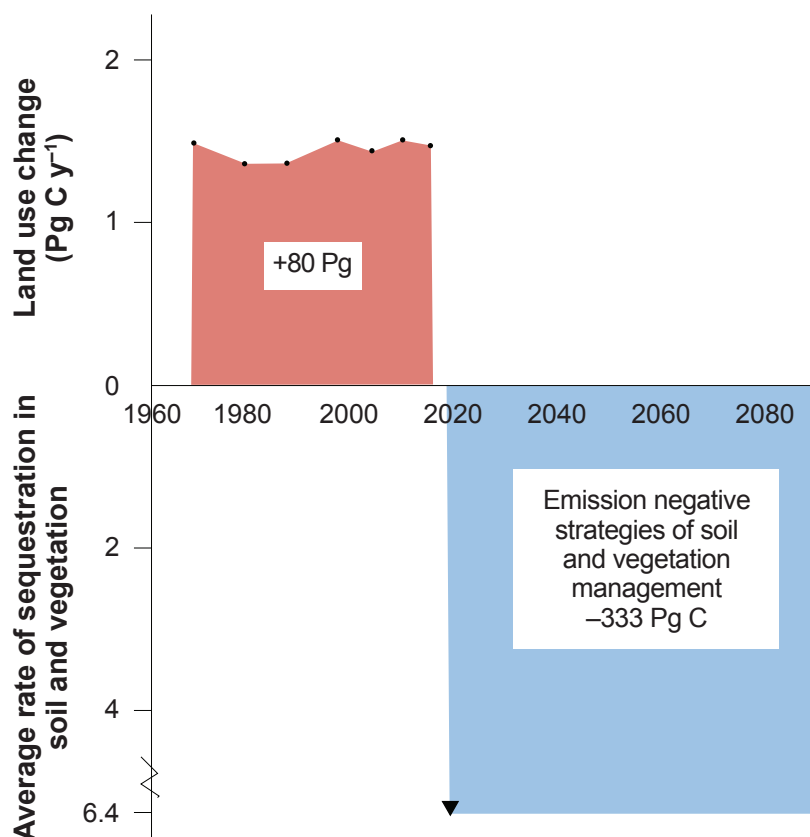
CONCEPTUAL BASIS OF MANAGING THE SOIL CARBON POOL

The NET of C sequestration in the terrestrial biosphere is a natural process. All life on the planet Earth depends on the process of biosequestration of atmospheric CO_2 . Only 0.05% of the 3,800 ZJ (10^{21} J; 3.6×10^{21} BTU) of solar energy is photosynthesized into 123 Pg C yr^{-1} ($1,258 \times 10^9 \text{ tn C yr}^{-1}$) as gross primary productivity. Of this, 60 Pg C ($61.4 \times 10^9 \text{ tn C}$) is respired back and the net primary productivity is 63 Pg C yr^{-1} ($64.5 \times 10^9 \text{ tn C yr}^{-1}$). With losses by erosion, fire, etc., the net ecosystem productivity is merely 3 Pg C yr^{-1} ($3.07 \times 10^9 \text{ tn C yr}^{-1}$) (Jansson et al. 2010). Anthropogenic emissions of 11.3 Pg C ($11.6 \times 10^9 \text{ tn C}$) in 2017, comprising of 9.9 Pg C ($10.13 \times 10^9 \text{ tn C}$) from fossil fuel combustion and 1.4 Pg C ($1.43 \times 10^9 \text{ tn C}$) from land use change (Le Quéré et al. 2018), can be entirely offset through a judicious management of the terrestrial biosphere to increase net ecosystem productivity to $\sim 10\%$ of the annual GDP. Dyson (2008) rightfully stated that “if we control what plants do with carbon, the fate of CO_2 in the atmosphere is in our hands.”

The book *The Grapes of Wrath* depicted the ramifications of the Dust Bowl of the

Figure 2

Carbon sequestration in the terrestrial biosphere (data of emission through land use change from Le Quéré et al. [2018], and that of sequestration from Lal et al. [2018]).



1930s (Steinbeck 1939), and subsequent books on the adverse impacts of plowing (Faulkner 1942) and those of pesticides (Carson 1962) provided the conceptual basis of both the urgency and necessity of sustainable management of soil and other natural resources. These concepts were strongly supported by the warnings regarding degradation of soil resources by accelerated erosion and other processes (Whyte and Jacks 1944; Wood 1950; Lowdermilk 1953; Buck 1931; Commoner 1971). The risks of drastic anthropogenic disturbance of the GCC have been highlighted by Roger Revelle since the 1950s (Revelle and Suess 1957; Revelle et al. 1965; Revelle and Munk 1977; Revelle 1982). Revelle and Suess (1957) observed that increase in atmospheric concentration of CO₂ may cause global warming through the Greenhouse Effect, and that the CO₂ concentration should be monitored. The latter led to the start of the Keeling Curve (Keeling et al. 1989). Historic evolution of the scientific movement regarding the close interaction between the terrestrial biosphere and the GCC, and the importance of sustainable management of soil resources and restoration of the environment is outlined in figure 3.

MANAGING SOIL ORGANIC CARBON SEQUESTRATION

Since the onset of the movement on SOC sequestration early 1990s (figure 3), considerable progress has been made in scientific developments (Blankinship et al. 2018). The concept of SOC persistence as an ecosystem property (Schmidt et al. 2011)—based on a balance between decomposition by microbes on the one hand and protection by physical and chemical processes on the other—has been refined (Lehmann and Kleber 2015) in conjunction with the impact of climate (temperature and moisture regimes) on SOC turnover (Lawrence et al. 2015). The importance of physical access to decomposition processes rather than of molecular structure (Dungait et al. 2012; Heckman et al. 2018) along with identification of other protection mechanisms (Six et al. 2002) and the C saturation concept (Castellano et al. 2015) have improved the understanding of the factors governing the mean residence time (MRT) of SOC in soil (Schwendenmann and Pendall 2008). Progress is also being made in measurements and monitoring (Wielopolski et al. 2011), and in understanding the relative importance of sequestration in surface vs. subsoil (Matteodo et al. 2018; Hobbey et al.

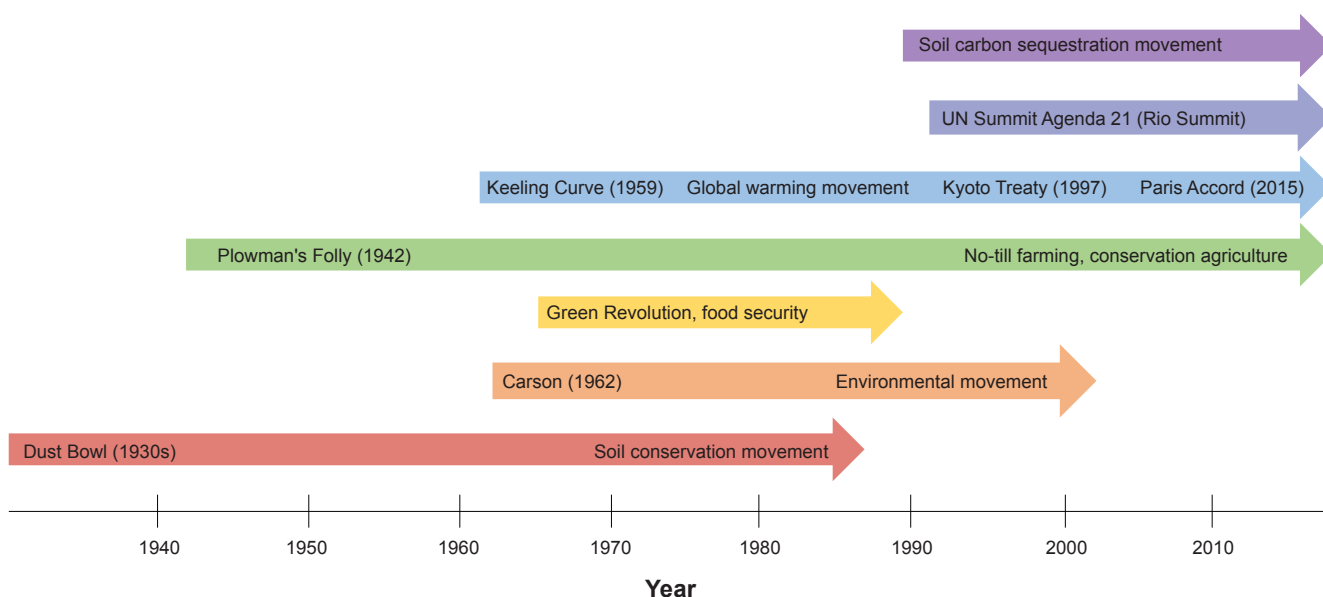
2016; Moni et al. 2010; Wordell-Dietrich et al. 2017), rhizospheric processes (Vidal et al. 2018), microaggregates and SOC turnover (Totsche et al. 2018; Pavithra et al. 2018), nutrient supply (Liang et al. 2019), impact of land use change (Chenu et al. 2018), and of SOC fractions (Poeplau et al. 2018). Despite the progress in science (Lal 2018a) and technologies (Batjes 2018), the scientific knowledge to enhance SOC and SIC pools has not been effectively translated into an action plan at local, regional, national, or global scales.

MANAGING SOIL INORGANIC CARBON

Sequestration of SIC, as secondary carbonates and through leaching of bicarbonates, is also an important but much less researched theme (Lal 2009; Zamanian et al. 2016). Yet, SIC is a significant component of the GCC and is a major C constituent in soils of dry climates, which cover about 41% of Earth's land surface (Gao et al. 2017). Furthermore, the MRT of carbonates may be as long as 85,000 years compared with 35 years for SOC, 10 years for vegetation, and 5 years for the atmosphere (Schlesinger 1985, 2002; Monger et al. 2015). Restoration of degraded and desertified lands in dry areas lead to sequestration of SIC as pedogenic

Figure 3

Historical evolution of movements regarding awareness about environmental issues and the importance of soil management.



carbonates. In northwestern China, Gao et al. (2017) observed that the antecedent SIC stock of 32.4 Mg ha⁻¹ (14.45 tn ac⁻¹) to 1 m (3.28 ft) depth increased to 42.5, 49.2, and 68.3 Mg ha⁻¹ (18.96, 21.95, and 30.47 tn ac⁻¹) with afforestation of white poplar (*Populus alba* L.) after 8, 20, and 30 years of establishment probably because of the formation of pedogenic carbonates. Similar observations on SIC under poplar have been reported (Su et al. 2010). Further, formation of secondary carbonates is also closely related to the SOC concentration because of the increase in CO₂ concentration and precipitation of carbonates with cations brought in from outside the system (Monger et al. 2015; Wang et al. 2015; Guo et al. 2016; Zhang et al. 2010). Soil inorganic C is relatively stable with a long MRT.

In addition to the dynamics of SOC and SIC in the surface layer, it is also pertinent to study the changes in both the surface and subsoil with regard to stocks of SOC following afforestation of degraded and desertified lands. Factors affecting SOC and SIC dynamics differ among surface and subsoil layers. Soil moisture and temperature regimes, as moderated by the climate, affect SOC through changes in vegetative growth and the effect on input of biomass-C (Davidson and Janssens 2006). In contrast, land use, afforestation, and drainage affect C dynamics in the subsoil (Tan et al. 2014). Thus, climatic variables and land use can have strong interactive effects on SOC and SIC dynamics in both surface and subsoil layers. Based on a study conducted on a precipitation gradient across the Loess Plateau of China, Han et al. (2018) reported that sequestration of 1 kg SOC m⁻² (0.2048 lb SOC ft⁻²) in the 0 to 0.4 m (1.31 ft) depth by afforestation reduced the SIC by 0.73 kg m⁻² (0.15 lb ft⁻²) but increased it by 1.26 kg SIC m⁻² (0.26 lb SIC ft⁻²) in the 0.4 to 3.0 m (1.31 to 9.8 ft) layer. Han and colleagues hypothesized that the depth distribution and relative sequestration of SOC vs. SIC depend on climate, land use, and the predominant species. Han and colleagues also observed that the total SOC and SIC stocks in 1.0 to 3.0 m (3.28 to 9.84 ft) depth were more than 50% of the stocks in the 0 to 1.0 m (0 to 3.28

ft) layer. Additional research needed on SIC dynamics in soils of arid and semiarid regions can be preferably done by the use of isotope technology such as carbon-13 (¹³C), calcium-45 (⁴⁵Ca) and oxygen-18 (¹⁸O) (Bai et al. 2017).

Leaching of bicarbonates into the groundwater is another important mechanism of SIC sequestration. With large SIC stock of 1,404 Pg C (1,436.4 × 10⁹ tn C) as bicarbonates, changes of SIC concentration in the groundwater of as much as 5 mmol L⁻¹ can strongly impact the GCC (Zhu and Schwartz 2011; Monger et al. 2015). Leaching of bicarbonates in the irrigated soils (350 Mha [864.5 × 10⁶ ac] globally) is an important sink that needs to be carefully evaluated. Contrary to the process of the formation of secondary carbonates, sequestration of SIC in the groundwater does not depend on the availability of Ca⁺² and other cations.

TRANSLATING SCIENCE INTO ACTION

There are two necessary prerequisites to using scientific knowledge to enhance the soil C pool. First is the identification of site-specific technologies of land use and soil/crop/animal management. The second is the policy interventions toward adoption of these technologies. Because of the large variation in global agroecosystems (i.e., soil, climate, terrain, crops, farming system, and the human dimensions), there is no single technology that can be universally applicable. With site-specific adaptation, examples of some technologies that can create a positive soil/ecosystem C budget include a system-based conservation agriculture (Lal 2015), agroforestry (Cardinael et al. 2018), organic and inorganic fertilization (Körschens et al. 2013; Wang et al. 2014), controlled grazing (Dlamini et al. 2016), indigenous cyanobacterial application on structurally unstable soils (Nisha et al. 2007), increased activity and species diversity of all biota (Schmitz et al. 2018), legume-based rotations (Sainju and Lenssen 2011), and cover cropping (Olson et al. 2014). The Climate Accord proposed at COP21 in Paris in 2015 also initiated the “4 per Thousand” program of sequestering SOC in world soils at the annual rate of 0.4% per year to 40 cm depth (Chambers et al. 2016). A similar initiative was pro-

posed at COP22 in 2016 in Marrakesh (Lal 2018b). These initiatives are examples of attempts to translate knowledge of soil science into policy. Implementation of these and other initiatives at local, national, and regional levels would be a step in the right direction.

THE POWER OF SOIL CARBON SEQUESTRATION AS EMISSION NEGATIVE

The soil C pool, the largest reservoir of the terrestrial biosphere, has a vast potential to impact the GCC and limit global warming. Despite the suggestions by some to be cautious about the potential of soil to mitigate global warming (Amundson and Biardeau 2018; Schlesinger and Amundson 2018; Cheng et al. 2012), the strong impact on the GCC and numerous cobenefits of SOC sequestration necessitate an urgent action to translate the scientific knowledge into action. The latter would encompass adoption of proven management technologies of soil (i.e., conservation agriculture, biochar, agroforestry, integrating crops with trees and livestock, and recycling biomass), water C harvesting and recycling (through drip subirrigation and other microirrigation systems), livestock (controlled grazing and manure management) and plants (deep root systems and recalcitrant compounds) at local, regional, national, and global scales. A widespread adoption of proven technologies would also involve incentivization of farmers and land managers through payments for provisioning of ecosystem services strengthened by SOC sequestration on the basis of the societal value of soil C (Lal 2014). Soil scientists, in close cooperation with agronomists, foresters, geologists, and extension specialists, must seize the moment by working with policy makers to manage soil as a NET. The soil-centric approach, inspired by nature and driven by science, is also critical to advancing the Sustainable Development Goals of the United Nations or the Agenda 2030.

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