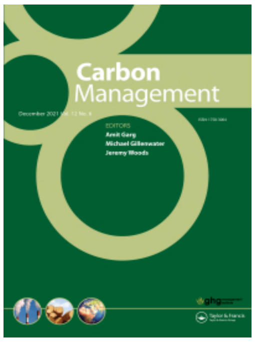

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Soil carbon management and climate change

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Soil carbon management and climate change

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World soils, a large reservoir of reactive carbon, moderate the global carbon cycle, atmospheric chemistry, radioactive forcing and ecosystem services; as such, soil carbon sequestration is important in limiting global warming to 2°C. Among uncertainties are emissions from soils and permafrost, the CO_2 fertilization effect, silicate weathering, the fate of eroded carbon, the efficiency of natural sinks, the permanence of carbon sequestered in soil and measurements of changes in soil carbon over short periods. Adoption of proven technologies can sequester carbon at the rate of 500–1000 kg/ha/year in croplands, 50–500 kg/ha/year in grazing lands, 500–1000 kg/ha/year in forestlands and 5–10 kg/ha/year of pedogenic carbonates in arid lands. Soil carbon is stabilized though deep placement, interaction with clays and the formation of stable aggregates. Adoption of recommended practices can be promoted by payments for ecosystems services. Researchable priorities include understanding trends of principal drivers, quantifying feedbacks related to climate change and impacts on ecosystem services.

Climate is a system consisting of the atmosphere, hydrosphere, lithosphere and the biosphere **(Figure 1)** [1]. Thus, soil moisture (as influenced by infiltration, runoff and evaporation), vegetation and glaciers are part of the climate system. Whereas melting of the glaciers and ice have received considerable attention by the scientific community and the media, the importance of terrestrial ecosystems in general, and of world soils in particular, on the long- and short-term global carbon cycle (GCC) have not received the attention they deserve [2–12].

Rather than global warming, climate change at a rapid pace (while being nonuniform and not benign), may be appropriately called 'global climate disruption' [13]. Some of the feedback processes [14] that moderate the effect of GCC on climate change are not well understood [15]. The importance of these feedback processes include the effects on the marine carbon cycle [16], weathering rates [17] and the terrestrial carbon cycle (TCC). The TCC comprises of the carbon exchange between pools in vegetation and the soil with those in the atmosphere and ocean. World soils are a major component of the terrestrial carbon pool, and have been a net source of GHGs since the beginning of agriculture [18].

Thus, the objective of this article is to describe the effects of anthropogenic activities on soil carbon dynamics, discuss factors/scenarios that make world soils a source or sink of atmospheric CO_2, CH_4 and N_2O, deliberate on opportunities and challenges of sequestering carbon in soils, and identify research and development priorities.

Terrestrial ecosystems & the GCC

Terrestrial carbon plays an unparalleled role in all terrestrial life, and strongly impacts numerous ecosystems services and human well-being [19]. However, the GCC and its related biogeochemistry are not well understood [18]. There are two components of the GCC; short term and long term. The short-term GCC involves the exchange of carbon between the atmosphere, biosphere, hydrosphere and pedosphere. Carbon is exchanged among these reservoirs over a decadal/centennial scale in near surface and shallow environments through both biotic and abiotic

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Key term

Soil carbon sequestration: The transfer of atmospheric CO_2 into the soil carbon pool as humus or secondary carbonates, such that it is preserved in the soil for a long time.

processes. Principal near-surface processes include combustion/decomposition of biomass, burial of carbonaceous sediments, exchange of CO_2 between the ocean and the atmosphere, and the exchange between the atmosphere and biota [20,21]. In contrast, the long-term GCC involves deep materials/reservoirs within the Earth that may contain more than 90% of the Earth's total carbon pool [22]. The deep processes are not well understood and occur at a millennial time scale. Carbon exchange with deep processes occurs through volcanic eruption, subduction, weathering of silicate minerals, deep life, deep hydrocarbon reservoirs, and so on [23]. There exists large microbial life in both terrestrial and marine environments [24,25]. Pools of carbon in various reservoirs involved in the long-term GCC over the millennial scale are in orders of magnitude larger than those involved in the short-term GCC [20].

Land is a principal component of the TCC, and the knowledge of carbon exchange between the atmosphere, ocean and land is important [26]. While fossil fuel has been an important source of atmospheric CO_2, especially since approximately 1950 [13], land use and land-use change have been major sources since the dawn of settled agriculture, for 10–12 millennia [27], and have also been a major factor since 1850 [28]. The fraction of the cumulative human-induced CO_2 emission total at present is approximately 25% [28]. The carbon pool in forest biomass is considered to be the so-called 'missing carbon sink' [29], and is important in balancing the global carbon budget [30]. There has been a net CO_2 uptake by land (and oceans) for a 50-year period between 1960 and 2010 [31]. While the southern ocean sink may have stopped growing [32], most land

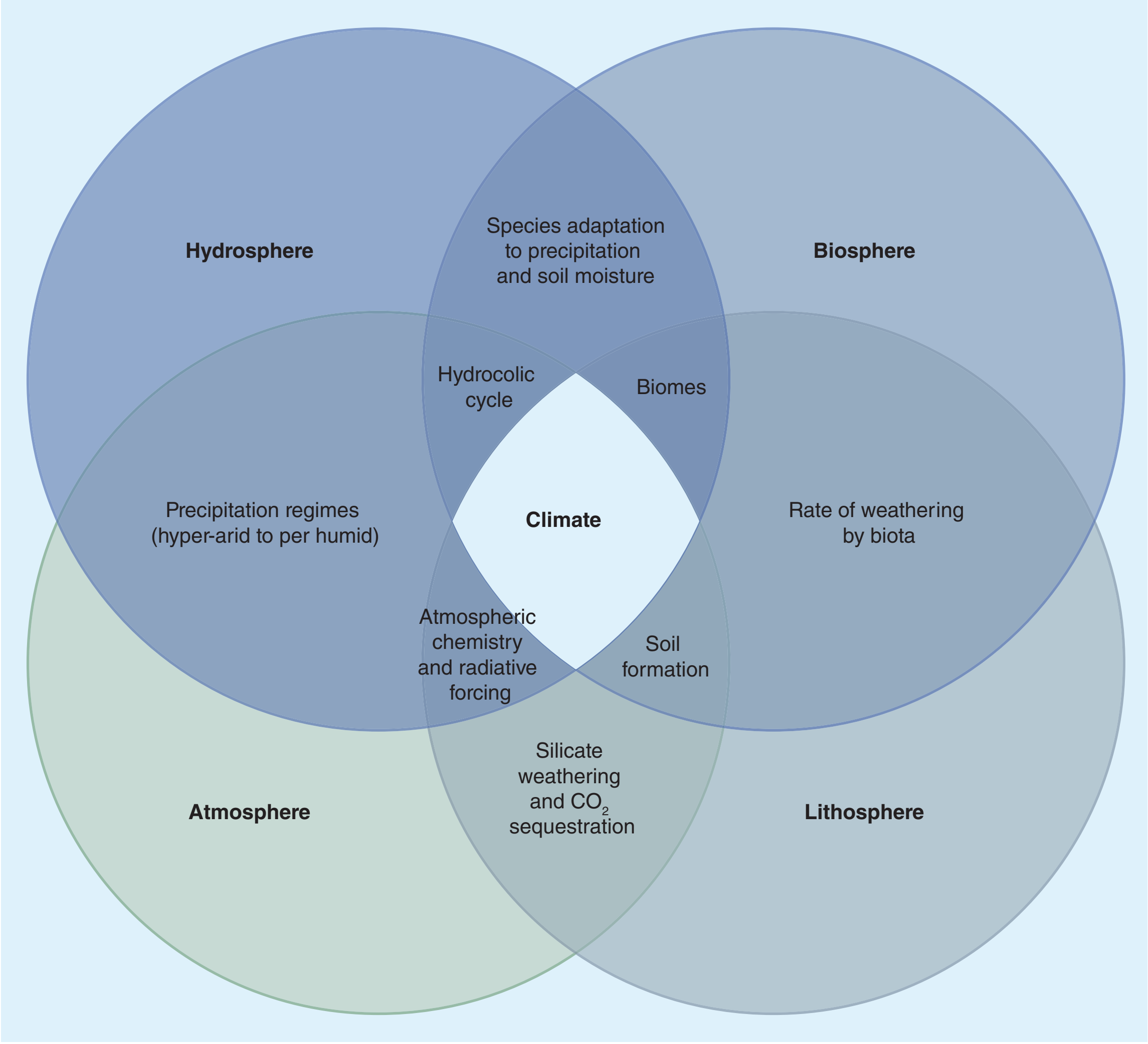

Figure 1. Four components of the climate system and the interactions among them.

regions (especially in the tropics) are a substantial CO_2 sink [33]. Forest carbon storage and its management have an important impact on GCC [34]; thus, there are global consequences of land use [35,36]. However, there are major uncertainties in the terrestrial carbon budget associated with land-use change, probably due to a lack of precise knowledge about the soil carbon pool and its dynamics [37]. The fractional uptake of the annual anthropogenic emission of CO_2 by natural sinks (i.e., ocean, forest, soils) has been progressively declining between the 1960s and 2011 (Figure 2) [38,301].

Geologic sequestration

Global climate change is perceived by some as an engineering problem, and fixing the planet by engineering is a feasible option. Some proposed geoengineering techniques (e.g., short-wave climate engineering) have a large mitigation potential [39,40] but are controversial [41] and expensive [302]. However, the strategy of carbon capture and sequestration into geological strata is being vigorously pursued as the so-called 'clean coal technology' to mitigate climate change and permit the use of relatively cheap and abundant fossil fuel in the form of coal [41–43]. With the goal of limiting global warming to a 2°C increase in temperature, there is a finite amount of fossil fuel that can be burned. The maximum amount of fossil fuel that can be burnt to stay within an internationally agreed maximum target of 2°C is much less than the amount that is known to exist as proven reserves, and indeed also less than the amount that business has plans for extraction. Assuming that 4 Pg of fossil carbon burned raises the atmospheric CO_2 concentration by 1 ppmv, the amount of carbon that can be burned is 4× (560–390 ppm) = 680 Pg [44]. The size of the so-called 'carbon pie' is determined by the target of the atmospheric CO_2 concentration stabilization, and on the assumption that 4 Pg of emission equals 1 ppmv of CO_2. It is widely perceived, however, that these assumptions may not be valid [45]. Nonetheless, there is a limit to the amount of fossil carbon that can be burned. Thus, there are numerous scenarios proposed to contain atmospheric CO_2 [46,47]. Some of the wedges proposed by Pacala and Socolow comprise of carbon sequestration in the terrestrial biosphere through phytosequestration in forest and soil carbon sequestration [46].

Carbon sequestration in terrestrial ecosystems

Phytosequestration is a natural process of reducing the atmospheric concentration of CO_2. The annual fluxes of carbon between the atmosphere and land,

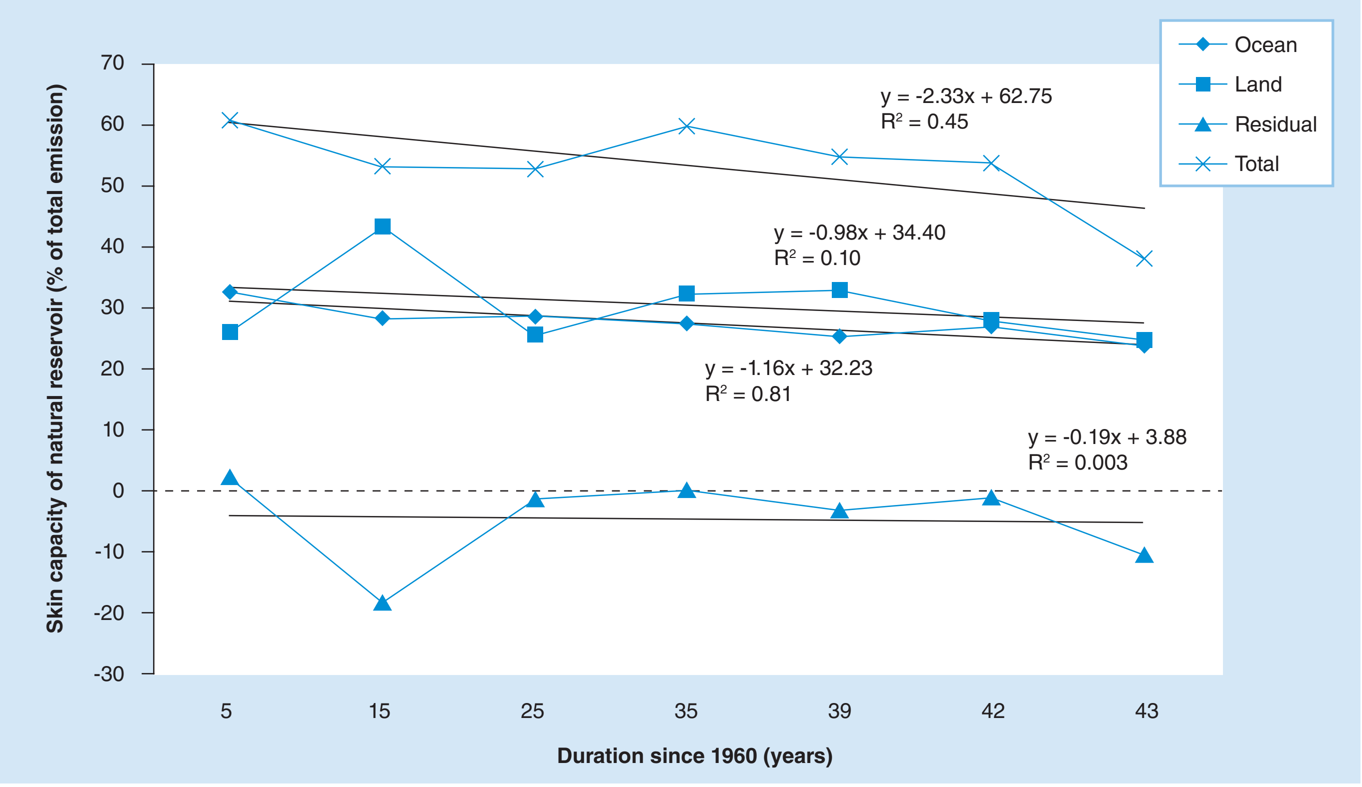

Figure 2. Temporal changes in carbon absorption capacity of natural sink between 1960 and 2011.
Redrawn from [38,301].

and atmosphere and oceans, are 123 and 92 Pg, respectively [48]. The gross primary productivity (GPP) comprises several components:

$$GPP = NPP + Ra$$ (Equation 1)

$$NEP = GPP - [Ra + Rh]$$ (Equation 2)

$$NBP = NEP - Lc$$ (Equation 3)

where Ra is plant respiration, NPP is net primary productivity, NEP is net ecosystem productivity, Rh is heterotrophic respiration, NBP is net biome productivity, and Lc is loss of carbon by harvesting, fire, erosion, and so on. The GPP of 123 PgC/yr is reduced by 60 PgC/yr as plant respiration (Ra), leaving a net primary productivity (NPP) of approximately 63 PgC/yr. Of this, the net ecosystem productivity (NEP) is approximately 10 PgC/yr because of the heterotrophic metabolism (Rh) of approximately 53 PgC/yr [48]. The magnitude of Rh has been estimated to be as high as 68 ± 4 PgC/yr [49]. The amount of carbon as NEP (10 Pg/yr) can persist in the terrestrial biosphere for decades to centuries to millennia [48]. However, NEP is further reduced by fire and other disturbances (Lc). Therefore, the remaining carbon as net biome productivity (NBP) is approximately 3 Pg/yr, with a range of 0.3–5 Pg/yr. Thus, management of NEP/NBP has the potential to offset some anthropogenic emissions [50]. Dyson opined that CO_2 generated by burning fossil fuels can theoretically be controlled by growing trees [51]. He observed that *"if we control what plants do with carbon and can restore the pool in the terrestrial biosphere, the fate of CO_2 in the atmosphere is in our hands"*. Therefore, the potential carbon storage capacity of the terrestrial biosphere using present and new techniques has been widely recognized [52,53]. It is in this context, therefore, that Hansen *et al.* proposed that while targeting atmospheric CO_2, humanity should aim at sequestering carbon in forestry and soils, which have a drawdown potential of 50 ppm by 2150 [54]. However, amplification of the hydrological cycle by global warming may impact ecosystem water balance and adversely affect NBP [55]. Drier summers can cancel out CO_2 uptake, as was the case during 2012 in the USA [56]. Temperature is a strong determinant of the growth of boreal forests [57], and of dynamics of soil organic carbon (SOC) [58].

Soil carbon & the GCC

World soils can be a source or sink of anthropogenic CO_2, which is an important GHG in the atmosphere with a strong radiative forcing [59]. The soil carbon pool, the largest reactive carbon in terrestrial ecosystems, may be as much as approximately 4000 Pg (10^{15} g) to 3-m depth (in view of the revised estimates of carbon in the permafrost) [60]. It comprises of two distinct components: SOC and soil inorganic carbon (SIC) pools. While the important role of the soil carbon pool in the GCC is widely acknowledged, there are numerous uncertainties that accentuate complexities and confound interpretation:

- Increased atmospheric CO_2, which may indirectly accentuate soil emissions of major GHGs (CO_2, CH_4, N_2O) [61];
- Alteration in the rate of carbon uptake by the soil and vegetation of tropical biomes by the current and projected climate change [62];
- Impact of chemical weathering of silicate rocks in altering terrestrial sinks and reducing radiative force [63];
- Unknown fate of carbon transported by soil erosion, which has been a major carbon sink over geologic time through the burial of carbon in the ocean and depressional sites [64], but may be a major source of carbon because of accelerated erosion on agroecosystems [65];
- A possible positive feedback from permafrost, which is a carbon sink at present and may become a source due to positive feedback [66];
- Decreasing efficiency of natural sinks (Figure 2) [38], probably due to soil and land degradation;
- The transient nature of carbon sequestered in soils and incomplete understanding of the mechanisms of stabilization of soil organic matter (SOM).

Some of the complexities and uncertainties, such as those caused by black carbon/soot [67] and accelerated erosion [64,65], must also be addressed.

Because of its large magnitude (4000 Pg to 3-m depth), changes in the soil carbon budget can have a large effect on the GCC. Therefore, understanding the properties and dynamics of SOC both under natural and managed ecosystems is critical to balancing the GCC. However, there are several unknowns and challenges that need to be addressed to fully realize the potential [68]. A major challenge lies in accurately measuring and modeling inputs and losses of carbon from soils, which necessitates a thorough understanding of the major processes involved and the interaction of these processes with soil characteristics. In theory, the rate of change in the SOC pool is simply computed as the difference between carbon input and loss from the soil. In practice, however, these computations are confounded by the fact that fluxes related to carbon input and losses are extremely large in comparison to the relative change in the SOC pool over a short period of 1–2 years. Thus, it is extremely difficult to separate the signal from the large background noise. However, on a global scale, agricultural land use and management can explain historic changes in the SOC pool [69]. With careful modeling and measurement, however, changes in the SOC pool related to the effects of elevated atmospheric CO_2 concentrations can be assessed [70], as can the effects of irrigation of desert soil on the SOC pool [71], as well as those of land use and soil/crop management.

Mechanisms of stabilization of SOC

Any gains in the SOC pool through adoption of restorative land use and recommended management practices (RMPs; see 'Fate of carbon transported by erosion'; 'Soil carbon sequestration in managed ecosystems'; 'Opportunities for enhancing soil carbon sinks'; and 'The challenge of measurement and monitoring of soil carbon pool' sections) must be protected against losses by heterotrophic respiration (Rh; **Equation 2**), accelerated soil erosion and leaching. Thus, understanding the mechanisms of stabilization of the SOC pool is crucial to increasing the mean residence time (MRT) and offseting anthropogenic emissions [72].

In addition to the effect on climate, the magnitude of the SOC pool also depends on soil texture, clay minerals, landscape position, and a range of other biotic and abiotic factors [73]. However, there are several determinants of stabilization of the SOC pool that affect its MRT (**Figure 3**). Principal mechanisms of SOC stabilization have been described by Six *et al.* [74]. Important among these are discussed below.

Physical protection

The SOC pool in the surface layer, the zone of frequent managerial manipulations and prone to erosional processes, is subject to drastic perturbations in croplands compared with shrublands, grasslands and forestlands. Thus, physical protection of the surface SOC pool is crucial to enhancing its MRT.

Deep placement

Jobággy and Jackson reported that, relative to the first 1 m, the percentage of carbon in the top 20-cm layer is 33% for shrublands, 42% for grasslands and 50% for

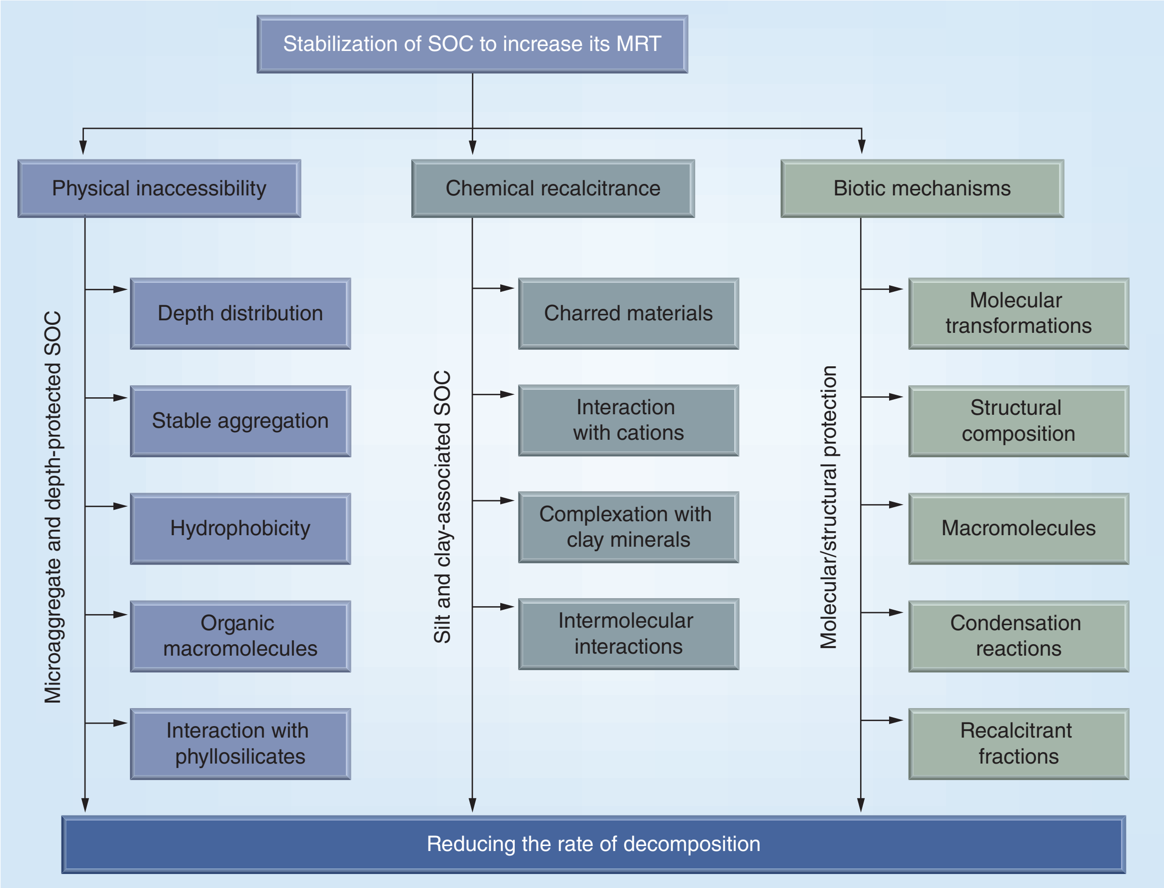

Figure 3. Mechanisms of stabilization of soil organic matter.
MRT: Mean residence time; SOC: Soil organic carbon.

Key term

Soil quality: Inherent ability of the soil to perform functions relevant to pedological, biogeochemical and ecological processes.

forests [75]. The amount of SOC in the second and third meter relative to the first meter is 77% for shrublands, 56% for forests and 43% for grasslands. Sequestration of SOC in subsoil horizons, by growing plants with a deep root system, can provide physical protection. Lorenz and Lal observed that sub-soil below 1-m depth has a large carbon sink capacity [76]. Depth distribution or stratification of the SOC pool also influences water infiltration rates and structural properties [77]. Thus, there is a need for 3D mapping of the SOC pool by developing soil-specific depth functions [78].

Clay mineralogy

Both SOC storage and MRT depend on the interaction between SOC and the clay fraction in the formation of organo–mineral complexes or stable aggregates. In tropical soils, Bruun *et al.* observed that SOC lability may be significantly influenced by clay mineralogy but not by clay content [79]. Furthermore, the lability of SOC may be in the order of smectitic soils > kaolinitic soils > allophanis soils = chloritic soils. Bruun and colleagues suggested that the validity of predictive models of all SOC turnover in tropical soils would be improved by the inclusion of soil types and content of Fe and Al (hydro) oxides [79].

Landscape position

SOC has a low density and is easily transported by water and wind. Thus, landscape position strongly affects the SOC pool and its vulnerability to erosional processes. In soils of northern latitudes, the north-facing slopes may contain more SOC than south-facing slopes. In general, foot/toe slopes contain more SOC pool than summit or side slopes. In a landscape prone to wind erosion (e.g., the Loess Plateau in China), wind erosion of the shady slope can reduce the SOC pool relative to the sunny slope [80].

Humification & humic fractions

Some humic fractions are stable because of either their inherent chemical composition (e.g., polyphenols, seubrin) or attained by transformation during decomposition through complexation and condensation [81,82]. Soil management [83] and cropping systems [84] can impact humic fractions and the molecular structure of organic matter; however, there exists a growing skepticism toward the humification concept [85]. Thus, the importance of recalcitration to the stabilization of SOC is questionable [86]. Dungait *et al.* argued that the chemical composition of different pools (labile, intermediate, passive/recalcitrant) is not predictable and proposed that SOM turnover is governed by accessibility rather than recalcitrance [87].

Stable aggregates

Encapsulation of carbon within stable microaggregates protects SOC against microbial processes. Six *et al.* outlined four historical milestones that enhanced the understanding of physical protection of SOC within aggregates [74], including:

- A model proposed in 1959 depicting soil crumb formation from domains [88];
- The formation of organo–mineral complexes from interaction between SOC and polyvalent cations [89];
- The aggregate hierarchy concept proposed by Tisdall and Oades [90];
- The formation of microaggregates within macro-aggregates [91].

Arbuscular mycorrhizal fungi and glomalin also enhance and stabilize aggregates [92]. The fungal colonization of particulate organic matter is crucial to the formation of aggregate and SOC dynamics [93]. Notwithstanding complexities and uncertainties, a Carbon Management Index has been proposed based on the degree of oxidation of SOC fractions under diverse agroecosystems [94].

Fate of carbon transported by erosion

Because the global carbon budget cannot presently be balanced, it has been suggested that current estimates of agricultural sources and sinks may be erroneous and that erosion-induced transport of SOC may be unaccounted for [95]. Erosion-induced displacement of SOC can be large [65] and is estimated to be 1.6 + 0.1 PgC/yr between 1901 and 2100 [96]. Such a large magnitude of displacement can strongly affect the GCC [97].

Soil erosion is a four-stage process: detachment, dispersion, transportation and redistribution, and deposition. The physical process of erosion and distribution affect SOC distribution and its vulnerability to decomposition by several interactive mechanisms [65]. Tillage (plowing) plays an important role in aggravating erosional losses and altering SOC distribution [98]. Erosion risks in the USA and elsewhere may be aggravated by climate change [99]. Important among these are:

- Breakdown of aggregates and exposure of SOC to microbial processes;
- Change in soil moisture and temperature regimes, leading to increases in decomposition;
- Anaerobic decomposition under depositional conditions, causing emissions of CH_4 (and N_2O) with high global warming potential;
- Reduction in NPP on eroded sites because of degradation in **soil quality**.

Whereas some SOC transported by erosion may be buried in aquatic ecosystems [64], it is nonetheless highly prudent to minimize erosional losses from agroecosystems by the adoption of conservation-effective measures. Nonetheless, the relative magnitude of SOC loss from agroecosystems by erosion versus mineralization is not known for all site-specific situations [100]. Transport of SOC to lower landscape positions may also release some of it to streams and to the atmosphere [101]. Being a dominant factor in altering GCC, erosional impacts on the fate of carbon must be studied at a range of spatial scales, from aggregate to large watersheds.

Soil carbon sequestration in managed ecosystems

Soils in most agroecosystems are depleted of their SOC pool because of the negative budget caused by erosion, mineralization, leaching, residue removal and adoption of extractive farming practices [65]. Therefore, conversion to a restorative land use and adoption of RMPs on cropland, grazing lands and forestlands can restore the SOC pool while also adapting to and mitigating climate change.

Croplands

Soil quality is strongly influenced by SOM and its dynamics through influences on physical, chemical, biological, and agroecological properties and processes (Figure 4). However, cropland soils are strongly depleted of their SOC pool, and the extent and severity of soil degradation depend on the magnitude of SOC depletion. The magnitude of depletion is high in soils prone to accelerated erosion and those managed by extractive farming practices. Thus, degraded and depleted soils

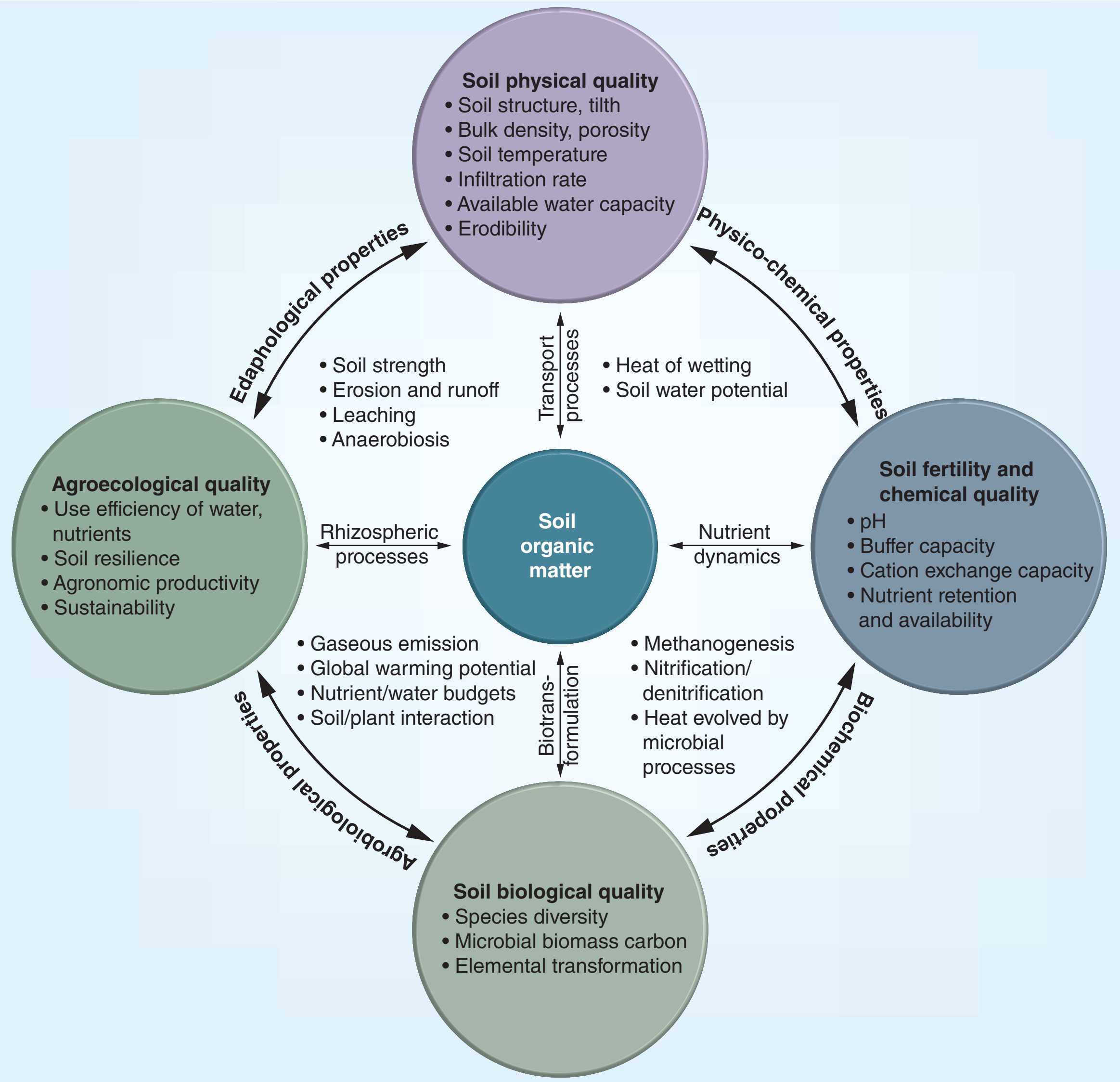

Figure 4. Effects of soil organic matter on soil quality.

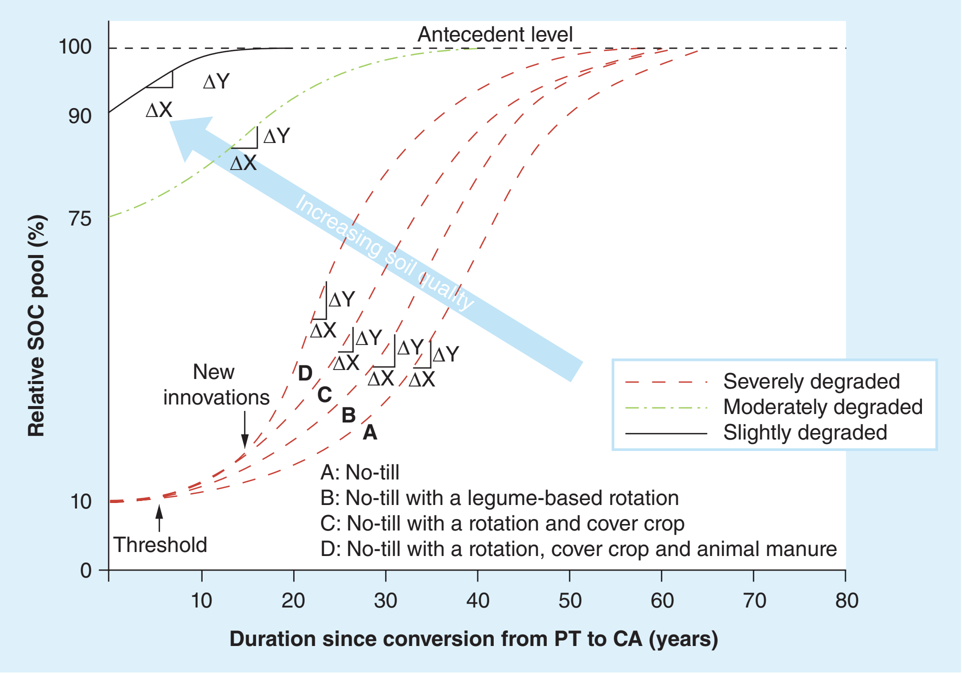

Figure 5. Sigmoidal response of soil organic carbon accretion upon conversion from plow tillage to no-till or conservation agriculture. The magnitude of historic depletion is 10% in slightly degraded, 25% in moderately degraded and 90% in severely degraded soil. The time to attain equilibrium depends on the severity of degradation, and in this schematic is 12–15 years, 30–35 years and 60–65 years for slight, moderate and severely degraded soils, respectively. Within severely degraded soil, the time to attain steady state decreases with adoption of complex rotation, cover cropping and manure application. The rate and time of the maximum soil organic carbon concentration (ΔY/ΔX) also depend on the severity of degradation and the management system. In severely degraded soils, there exists a threshold of 3–5 years before any measurable increase in soil organic carbon begins.
CA: Conservation agriculture; PT: Plow tillage; SOC: Soil organic carbon.

have a large unfilled SOC sink capacity. The SOC pool of soils of arable lands can be enhanced by the adoption of RMPs, which create a positive soil/ecosystem carbon budget including no-till (NT) farming or conservation agriculture (CA), cover cropping, complex crop rotations, agroforestry and integrated nutrient management. Applications of manure/compost and other biosolids can be useful to enhancing the SOC pool, but involve logistical problems of access and availability.

CA is a promising technology because of its effectiveness in conserving soil and water, reducing diesel consumption and improving soil biodiversity [102]. Beginning in the early 1960s, CA has now been adopted on approximately 125 million ha (Mha) or approximately 8.5% of global cropland area [103]. Of this 125 Mha, 45% is in South America, 32% in North America, 14% in Australia and New Zealand, 4% in Asia, 3% in Russia and the Ukraine, and only 1% each in Europe and Africa [103]. Thus far, CA has not been adopted by small landholders of Asia, Africa and elsewhere in developing countries.

Key term

Soil aggregation: Secondary particles formed through flocculation of primary clay and silt particles by polyvalent cations and cementation of floccules into stable structural units by humic substances, sesquioxides, fungal hyphae and microbial byproducts.

In general, conversion of plow tillage (PT) to CA enhances the SOC pool and improves the properties of the surface layer [104–111]. However, there have been questions regarding any substantial increase by CA in the SOC pool in the subsoil [112–114] and inconsistent increases in others [115]. In addition to differences in depth distribution of the SOC pool among tillage methods, the SOC pool is also affected by the duration of CA. Measurable changes in the SOC pool, even in the surface layer upon conversion from PT to CA, may take several years, with a peak rate of increase between 5 and 10 years and continuation of accretion for more than 25 years (Figure 5). In Saskatchewan (Canada), Campbell *et al.* reported that the conversion of PT to NT increased SOC and nitrogen concentrations to 15-cm depth, and that inputs of crop residues and other biomass were the main factors influencing the SOC change [113]. McCarty *et al.* reported changes in SOC and nitrogen pools after 3 years of conversion to CA [116]. Their data showed that transformation of the soil profile from that typical of PT to one characteristic of NT occurred rapidly within 3 years. During this period, stratification of SOC in the profile progressed along with substantial changes in SOC (38%), nitrogen (30%), biomass carbon (33%) and biomass nitrogen (87%) in the surface layer of CA, but decreases (7, 6, 15 and 35%, respectively) in the subsoil. Short-term (15 months) effects of cropping systems on potentially mineralizable carbon have been reported from a tropical soil in India [117]. In Indiana, Gál *et al.* assessed tillage-induced differences in the SOC pool to 1-m depth in six depth increments [118]. They observed that increases in the SOC pool with CA relative to PT were 23 Mg/ha to 30-cm depth but only 10 Mg/ha to 1-m depth. The depth distribution of SOC differed among two tillage systems, with relatively higher concentrations in the surface layer of CA and substantially more in the sub-soil of PT (Figure 6). The bulk density of the surface soil in CA is higher in the surface than in PT. Because of the plow pan, however, bulk density is generally higher just beneath the plow layer (Figure 6).

Whereas much research has been done in the USA and Brazil, relatively little research on SOC dynamics under CA has been done elsewhere, especially in dry-land farming systems [119]. In Perugia (Italy), Perucci *et al.* reported the positive effects of residue incorporation (vs removal) on soil quality and noted that SOC concentration was positively correlated with key soil practices [120]. In Sweden, Etana *et al.* reported that shallow tillage increased SOC concentrations in the surface layer but decreased it in deeper layers [121]. In the Mediterranean region of Spain, López-Garrido *et al.* reported on the depth distribution of SOC and other properties under two diverse tillage systems [122]. Their data showed more accumulation of SOC in the near surface under NT and reduced tillage compared with traditional tillage, and concluded that analysis of soils at depth could be very useful in long-term experiments to access the effects of CA. In South Africa, Preez *et al.* reported a decline in SOC as a result of agricultural land use and identified land use and management practices needed to restore the SOC pool for sustaining productivity [123,124].

West and Post synthesized a global database of 67 long-term agricultural experiments consisting of 276 paired treatments [125], and Post and Kwon described processes and potential by land use change [126]. The data indicated that conversion from PT to NT to CA can on average sequester 57 ± 14 gC/m^2/yr. Furthermore, SOC sequestration rates can be expected to peak in 5–10 years, with SOC reaching a new equilibrium in 15–20 rears. A schematic showing a generalized sigmoidal response is outlined in Figure 5.

Tillage systems also affect soil aggregation and aggregate stabilization. In general, CA systems exhibit increased aggregation [127]. Zibilske and Bradford investigated the effects of 13 years of diverse tillage systems and observed that aggregation in 0–5-cm depth was significantly greater under NT than PT systems, and aggregate carbon and nitrogen concentrations were 60 and 100% greater under NT than PT [128]. Simpson *et al.* observed that microbial-derived SOC is stabilized in NT soils, primarily due to a greater fungal-mediated improvement of soil structural stability and concurrent deposition of fungal-derived carbon in microaggregates contained within macroaggregates [129]. In Romania, Moraru and Rusu observed that adoption of CA (minimum tillage) increased the SOC concentration from 0.8 to 2.2% and water-stable aggregation from 1.3 to 13.6% at 0–30-cm depths [130]. In Switzerland, Weisskopf *et al.* observed clear quantitative and qualitative differences in structural regeneration among management practices [131]. Thus, soil quality indices have been developed to characterize tillage-induced differences in soil parameters [132].

Because of the differences in soil quality, and in the amount of recalcitrance of SOC and its fractions, gaseous emissions from soils also differ among tillage systems. Soil temperature is the driving factor on gaseous emission from soil [133]. While CH_4 may be oxidized under NT/CA, because of favorable structure, N_2O emissions may be more from CA than PT systems

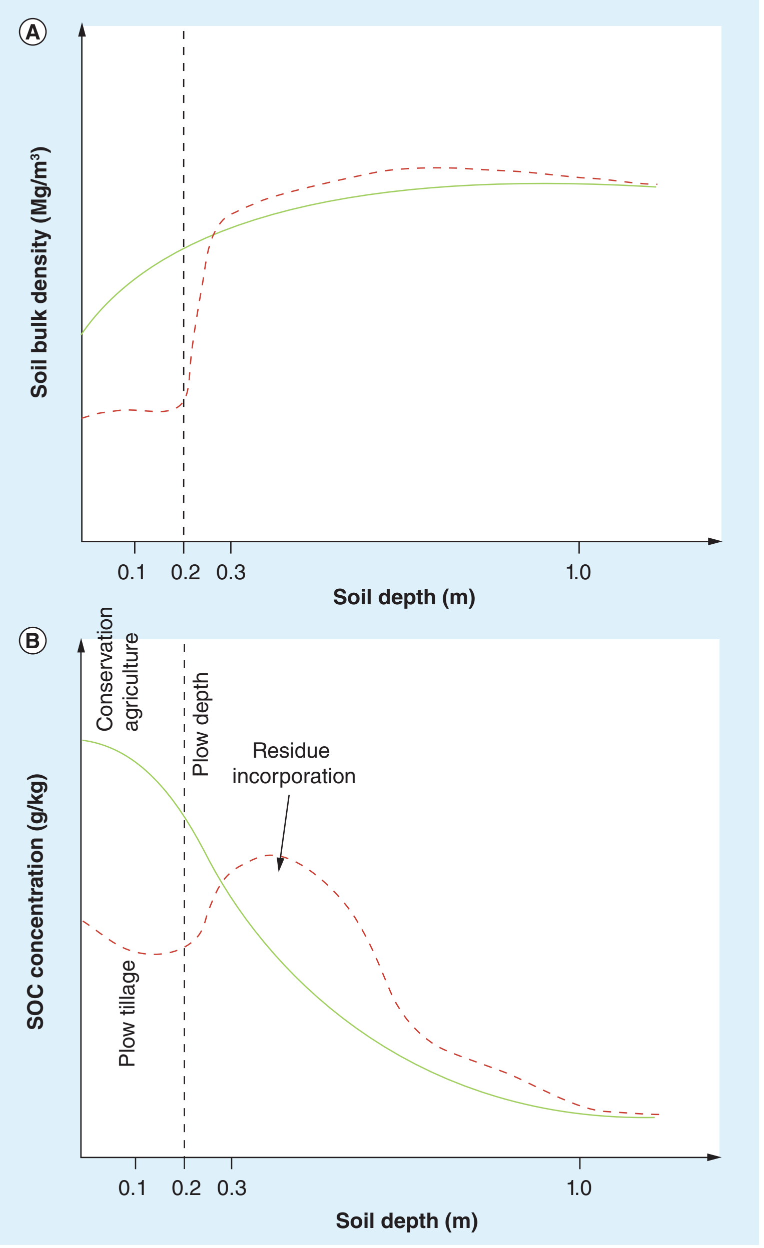

Figure 6. Generic trends. (A) Bulk density of soil profile and **(B)** soil organic carbon concentration profile under the conservation agriculture and plow tillage system.
SOC: Soil organic carbon.

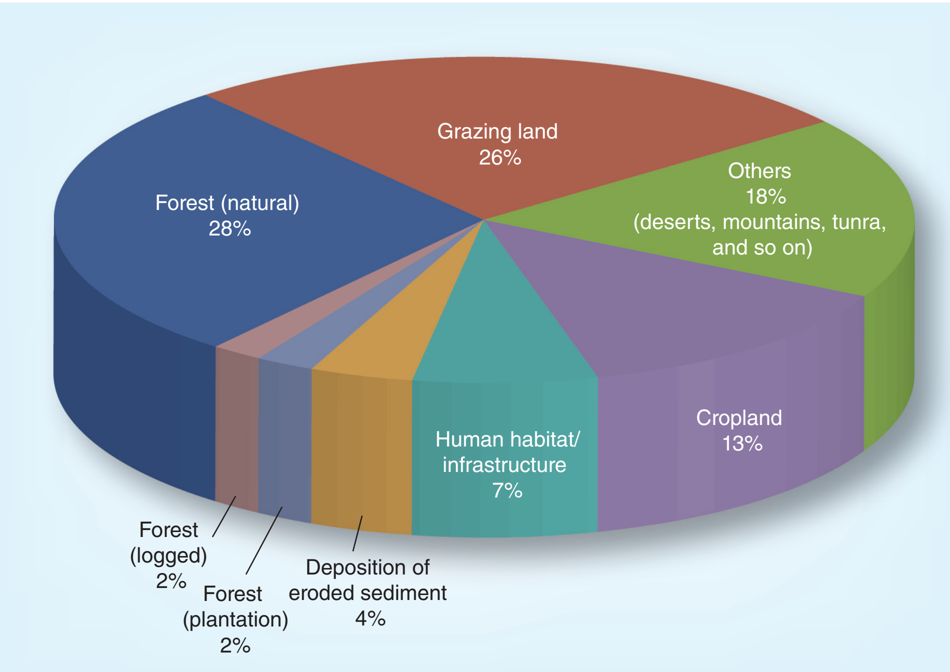

Figure 7. Global land use in 2007. Total land of ice-free Earth surface = 13.01 billion ha. Adapted from [137].

because of surficial characteristics. In addition, soil nitrites can also influence gaseous emissions and affect atmospheric chemistry [134]. The rate of SOC sequestration in cropland soils has been estimated at 120–270 Tg/yr for the USA [135] and 9–120 Tg/yr for Europe [136].

The available literature can be summarized as follows:

- Conversion of PT to CA can enhance the SOC pool in the surface layer;
- Increase in the SOC pool under CA to 1-m depth is variable and may be more under PT in some situations;
- Conversion to CA improves aggregation and reduces losses by soil erosion;
- Soils under CA can oxidize CH_4, but may enhance N_2O emissions;
- There are savings in fuel use under the CA system, thereby favorably affecting the net ecosystem carbon budget;
- Conversion to CA may also increase adaptation to extreme climate events (e.g., drought) by conserving water in the root zone.

Key term

Secondary carbonates: Precipitation of dissolved CO_2 in the soil air as a weak carbonic acid as carbonates of Ca^{2+}, Mg^{2+} and other cations added from external sources (e.g., amendments, aeolian deposition, water run on).

Grazing lands/grasslands

Of the ice-free global land surface, grazing lands occupy 25.3% of the land area compared with 12.8% under cropland (**Figure 7**) [137]. The world's grazing lands with a total area of approximately 3.5 billion ha (Bha) constitute a large reservoir of soil carbon and play an important role in the GCC because grasslands contain 20% of the global SOC stocks [138]. Change in land use and management can be a strategic undertaking to enhance SOC sequestration in rangelands [139–141]. Preez *et al.* indicated that overgrazing of rangeland has resulted in significant losses of SOC, and approximately 58% of soils studied contain <0.5% SOC and barely 4% contain >2% [123,124]. The use of fire in rangeland management decreases the SOC because litter is destroyed by burning. Thus, controlled grazing and restricting burning may restore degraded rangelands and enhance the SOC pool.

There is a growing interest in the effect of climate change on NPP and the SOC pool in grasslands. Van Dasselaar and Lantinga developed a simulation model of the carbon cycle of grasslands (CCGRASS) in Holland to assess the long-term effects of different management strategies on SOC sequestration [142]. They observed that the rate of increase in the amount of SOC is the highest at low-to-moderate rates of application of nitrogen, because of the stimulated growth of unharvested plant parts (roots and stubble), and higher under grazing than under mowing as a result of a greater amount of carbon added to the soil. Van Dassalaar and Lantinga also observed that increase in atmospheric CO_2 concentration may induce an increases in the decomposition rate of the SOC because of a simultaneous increase in temperature [142]. Thus, there may be 2% less SOC sequestration by grasslands at the end of 100 years because of a predicted 3°C increase in temperature. A simulation study on grassland responses to global environmental changes in California by Shaw *et al.* indicated that elevated CO_2 may increase NPP, but may also suppress root allocation, thereby decreasing the positive effects of increased temperature, precipitation and nitrogen deposition on NPP [143]. Luo *et al.* studied the effects of artificial warming by 2°C on soil respiration in a tall grass prairie ecosystem in the US Great Plains [144]. Their data show that the temperature sensitivity of soil respiration decreases or acclimatizes under warming, and that acclimatization is greater at high temperatures. Luo and colleagues concluded that this acclimatization of soil respiration to warming may weaken the positive feedback. Thus, there are several uncertainties regarding the possible effects of predicted climate change on the carbon cycle of grasslands. Therefore, long-term field experiments are needed to assess the impact of land use and management on the SOC pool and its dynamics in grassland ecosystems.

A 4-year study conducted in northeast Thailand by Noble *et al.* indicated that the application of nitrogen fertilizer on light-textured soils, characterized by acidic conditions on the sub-soil, increased the SOC pool and caused strong carbon sequestration [145]. However, strong acidification can also occur. There is a significant impact of root-carbon inputs on the SOC pool in grassland ecosystems, which can be as much as 50% of NPP. The input of root-derived organic carbon many range from 0.1 to 2.8 Mg C/ha/season [136]. While quantifying the magnitude of inputs from different processes is difficult, separating heterotrophic from root respiration is also a major challenge. Several studies show that soil respiration may vary from 4 to 26 Mg C/ha/yr depending on soil type, tillage methods, drainage, grazing and manure management [136]. There are also compositional relationships between the SOC pool and soil drainage [146].

Whereas the carbon footprint of dairy production systems can be large [147], there is indeed a vast SOC sequestration potential of grassland ecosystems [139,148,149]. Follett *et al.* estimated the total potential of US grazing land for carbon sequestration and fossil fuel offset at 29.5–110.1 Tg C/yr (mean: 69.8 Tg C/yr) [150]. Conant estimated that many management techniques intended to increase livestock forage production have the potential to increase SOC pools by 54.5–218.2 Tg C/yr [138]. Methods of improved management to achieve these rates include fertilization, irrigation, intensive grazing management, and sowing of more favorable grasses and legumes. Nonetheless, the hidden carbon cost of most inputs must be considered while assessing the net sequestration rate. Emissions of CH_4 and N_2O may be enhanced by intensive grazing management.

Similar to croplands, soils of grazing lands also have a large potential to sequester CO_2 both as SOC and SIC. However, management options are limited and primarily involve controlled grazing, managing or reducing fire, and improving forage species. Because of the large land area (3.5 Bha), grazing lands have a large carbon sink capacity. The research information is sparse, especially with regards to the dynamics of **secondary carbonates**.

▪ Forest lands

The evolution of forests have played a major role in the GCC. The increase in the area under forest cover, following the glacial retreat 15–20 millennia ago, enhanced the terrestrial carbon pool and reduced the atmospheric concentration of CO_2 [151]. It is also argued that early Paleozoic GHGs may have been reduced by the evolution of rhizospheres in forest soils [152]. Forests ecosystems cover 4.13 Bha or 31.7% of the Earth's ice-free surface. Of this, 0.24 Bha is logged forest and 0.27 Bha is forest plantation **(Figure 7)**. Together, forest vegetation and forest soils contain approximately 1500–1800 PgC [153]. Of this pool, 37% is in low-latitude forests, 14% is in the mid-latitudes and 49% is in high-latitude forests. A large proportion of the global SOC pool is contained in forest soils and associated peat deposits [153]. The proportion of carbon stored in soils is increased in the order of tropical, temperate and Boreal [154]. Temperate forests cover a total land area of 0.77 Bha [151]. Soils under temperate forests may contain approximately 100 Mg C/ha in the entire profile and often more [153]. Under the protective effect of vegetation cover, along with that of the detritus material and leaf litter, the SOC pool in soil under forest is protected against erosion and other perturbations. Harrison *et al.* estimated that soils of the UK contain 22 PgC compared with 115 Tg, which is contained in all vegetation [154]. However, 96% of all soil carbon in the UK is contained in peat (see the following section).

The carbon pool in the above-ground biomass is also recalcitrant because tannins make up a significant portion of forest carbon pools, and foliage and bark may contain up to 40% of tannins [155]. Being recalcitrant, tannins can affect nutrient cycling by hindering decomposition rates, complexing proteins and inhibiting enzyme activities. The presence of tannins can reduce nutrient losses in soils of low inherent fertility, such as those of the tropical rainforest (TRF) [155]. In TRF ecosystems, the below-ground allocation of carbon in deep-rooting forests is large (~19 Mg C/ha/yr) compared with that in the detritus material (4.6 Mg C/ha/yr). Thus, the presence of live roots influences the carbon cycle to below 1-m depth. Trumbore and colleagues [156] estimated that up to 15% of the carbon in deep soil has turnover times of decades [156]. Furthermore, the magnitude of fast-cycling SOC between 1 and 8-m depths (20–30 Mg C/ha out of 170–180 Mg C/ha) is large in comparison to the SOC pool in the top 1-m of the soil profile (30–40 Mg C/ha out of 100–110 Mg C/ha) **(Figure 8)**. Thus, the SOC pool in sub-soil carbon below 1-m depth must be considered in assessing the soil/ecosystem carbon budget.

Whereas deforestation and conversion of forests to agro ecosystems depletes the SOC pool and releases approximately 2 Pg C/yr, reforestation of arable lands can enhance the SOC/terrestrial carbon pool. In a study in South Carolina (USA), Richter *et al.* observed

Key term

Degraded soils: Soils with a reduced ability to perform ecosystem functions and services because of accelerated erosion, nutrient/elemental depletion and imbalance, salt accumulation in the root zone, adverse reactions, and so on.

that of the total carbon absorbed in reforested lands, trees accounted for 80%, the forest floor 20% and mineral soil <1% of the carbon accretion [157]. Sequestration of carbon in mineral soils is limited by rapid decomposition, especially in coarse-textured soils containing low-activity clay minerals. Nonetheless, conversion of lowland (and some upland) croplands to forests can result in carbon accretion in soils [154]. In this context, plantation forest management can also enhance the carbon pool in the soil and biomass [151,158].

Soils under forest ecosystems, because of their large area and low disturbance, are important to SOC sequestration. In addition to afforestation and reforestation, avoiding deforestation of TRF is also an important strategy. Species with deep root system can transfer carbon into the subsoil and increase its MRT.

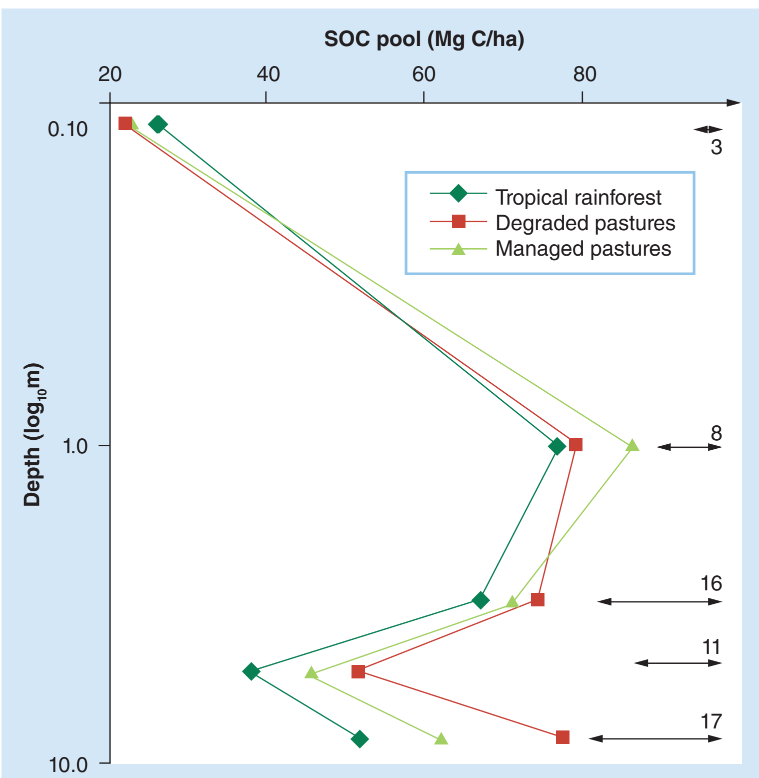

Figure 8. Depth distribution of the soil organic carbon pool in soils of a tropical ecosystem show that a large fraction of the total soil organic carbon pool in the forest soil exists below 1-m depth. The deep-root system of trees is one of the factors affecting the SOC pool in the sub-soil. A favorable depth distribution enhances mean residence time and protects the SOC pool against biotic and abiotic perturbations.
SOC: Soil organic carbon.
Redrawn from [156].

Peatlands

Peatlands or hydromorphic soils cover a land area of 1.74 Bha or approximately 13% of the Earth's land surface. Of these, Histosols cover 0.25 Bha or approximately 1.9% of the Earth's land surface. Peatlands have a high carbon density [159,160], and may contain 1230–2640 Mg C/ha to 2-m depth [161]. Miller *et al.* reported a SOC pool in the frigid southern Appalachian mountain soils of 112 Mg C/ha [162]. Cryosols are also a major carbon reservoir and may contain 1400–1700 Pg [163]. Northern peatlands cover 0.3 Bha or 2.3% of the Earth's surface area and constitute a significant carbon sink and major CH_4 source [164]. Estimates of the total carbon reservoirs in the world's peatlands vary widely. The mean value of the SOC pool is estimated at 1501 Pg carbon, with a range of 963–2057 Pg [66]. It is on this basis that the total carbon pool in the world's soils to 3-m depth is estimated at approximately 4000 Pg (see 'Soil carbon and the global carbon cycle' section).

Drainage, deforestation and tillage lead to rapid depletion of the SOC pool of peatlands. The average rate of loss of peatlands by cultivation (drainage, tillage) in temperate climates can be 1–2 cm/yr [165,166]. Drainage, deforestation and cultivation of tropical peatlands can lead to a large carbon debt [156]. Undrained and natural peatlands are a small sink for atmospheric CO_2.

Projected climate change may also thaw cryosols, create a positive feedback and drastically impact the GCC [167]. Global warming, predicted to be the most severe at high latitudes, may impact the SOC pool in cryosols of Tundra and Boreal ecosystems. Mack *et al.* conducted long-term fertilization experiments in the Alaskan Tundra and observed that increased nutrient availability caused a net ecosystems loss of almost 20 MgC/ha over 20-year period [168]. Therefore, restoration of drained peatlands is considered to be an important strategy to mitigate climate change. The goal of peatland restoration is to regenerate a self-sustaining and naturally functioning wetland ecosystem that is a carbon sink. Rewetting and raising the water table to encourage establishment of wetland vegetation is essential to restoring drained peatlands.

Similar to protecting and restoring TRF ecosystems, preservation and restoration of peatlands is also important for enhancing terrestrial carbon sinks. Drainage and deforestation of peatlands must be prohibited. Restoration of wetlands can be promoted through payments to land managers for provisioning of ecosystem services.

Shrublands/savannas

The world's savannas cover 20% of the Earth's land area and occupy 20×10^6 km^2 in the tropics and 9×10^6 km^2

in the temperate regions [169]. These ecoregions play a major role in the GCC [170]. The soil carbon pool of the savannas and grasslands may be 326–480 Pg C to 1-m depth, and contain a large amount of black carbon or charcoal. Native savannas are a sink of atmospheric CO_2. A large portion of the world's savannas are being converted into agroecosystems (e.g., Cerrados in Brazil and Llanos in Colombia). Adoption of NT farming (CA systems) on croplands and improved grazing systems on pastures can enhance the soil carbon pool. The rate of soil carbon sequestration in the Brazilian Cerrados is estimated at 0.3–1.15 Mg C/ha/yr through conversion to NT farming [171]. Savanna ecosystems, grasslands and rangelands have a high technical SOC sink capacity [169]. Re-establishments of shrubs on **degraded soils** of croplands and pasturelands can restore some of the depleted SOC pool. As a major determinant of soil quality, improving the SOC pool is essential for better crops and sustainable soil management [172].

▪ Urban ecosystems

Approximately 50% of the world's population already lives in urban centers, and the urban population is expected to increase to 60% of the total by 2030 and 70% by 2050 [173]. Urban ecosystems now cover approximately 3% of the terrestrial land area. Thus, urban ecosystems affect energy use and have a strong impact on the GCC, along with that on nitrogen, phosphorous, and water resources and cycling. Soils of residential areas have a high SOC density of 15.5 ± 1.2 kg/m^2 [174]. There are numerous options of SOC sequestration in urban soils through input of biomass carbon, an efficient use of water and nutrients, and recycling of biosolids [175–178]. Urban agriculture is also gaining prominence, with the goal of producing food locally and restoring abandoned lands [179]. Thus, a judicious management of urban ecosystems is important to choosing numerous options of adaption to and mitigating anthropogenic climate change.

Opportunities for enhancing soil carbon sinks

Managing terrestrial carbon sinks in general, and soil carbon sinks in particular, provides an opportunity to meet the challenge of limiting global warming below 2°C [180]. There exists a vast potential for enhancing terrestrial and pedologic soil carbon sinks to mitigate anthropogenic climate change [181,182], and to strengthen ecosystem services through recarbonization of the biosphere [183]. Pedospheric carbon sinks can be enhanced by restoration of degraded soils and desertified ecosystems. Despite some uncertainties [112], NT farming and CA with cover crops and residue mulch is an important option to enhance soil carbon sinks in croplands [181,184–186]. Management of crop residues is of crucial importance in SOC sequestration [187,188], especially during the seasons adversely affected by drought (e.g., the 2012 growing season in the US Corn Belt). Soil application of zeolite can improve soil water storage and soil nitrogen availability, and thus impacts SOC dynamics [189]. There are also opportunities for mitigating N_2O emissions from croplands through management of fertilizers [190,191] and forest/rangeland [192]. Some options for reducing N_2O emissions include modification of the rate, source, placement and timing of nitrogen fertilizer application. There are also opportunities for reducing CH_4 emissions from livestock [193] and biogenic fluxes from other agroecosystems [194]. Intermittent drainage of rice paddies, and growing aerobic rice using alternative water regimes [195] and varieties [196], are among some other options [197]. However, these strategies must be objectively considered in view of the elevated CO_2 concentration in the atmosphere and projected increase in global temperatures [198]. A critical examination is needed to identify the true and the false [199], as well as options for soil management in relation to sustainability and ecosystem services [200]. Improving the database on the potential soil carbon sinks [201] and promoting RMPs are essential to realizing their potential. In this context, promoting the sustainable intensification of soils of the tropics is strategically important for advancing food security and adapting/mitigating to climate change.

Mitigating anthropogenic enrichment of atmospheric CO_2 is a complex issue. There is neither a panacea nor a silver bullet. There is a menu of options for reducing emissions and sequestering emissions. Soil carbon sequestration is only one of those options, and has a small carbon sink capacity. Nonetheless, it is an important option with numerous co-benefits, and improving agronomic productivity and advancing food security is the most important. Enhancing the SOC pool to a level above the critical threshold is needed to improve soil quality and meet the food demands of a growing and increasingly affluent population. In addition, it also offsets some of the anthropogenic emissions.

The challenge of measurement & monitoring of the soil carbon pool

Whereas the global potential of soil carbon sinks is large, credible assessments of the sinks and the rate of change under diverse land uses and soil/crop/animal management systems remains a major challenge. The input of carbon into an ecosystem is through NPP, but the loss of carbon occurs through decomposition, erosion, leaching and fire. Despite the progress in developing protocols and standardizing methodology [202], it is the lack of credible quantification of these sources and sinks that is the basis of uncertainties [203]. Insufficient information about soil bulk density [204], lack of data on depth distributions of soil carbon and its measurement in the subsoil, unstandardized techniques of measuring the pool and flux, problems with scaling up of laboratory/greenhouse studies, insufficient knowledge about the effects of carbon input on reducing SOC concentration [205–207], discrepancies in computations of the SOC pool based on equal depth or mass basis [208], debate on the impact of soil erosion on emissions [65] or sequestration [64], questions about the permanence of the SOC pool and saturation of SOC sinks [81], and the doubts regarding the predictive power of the SOC pool change data from agricultural field experiments [209]. There are a lack of credible statistics on land area under different managed and natural ecosystems, the magnitude and dynamics of SOC/SIC pools (Figure 9A), the area and SOC/SIC pools under different soil orders (Figure 9A), and on the effect

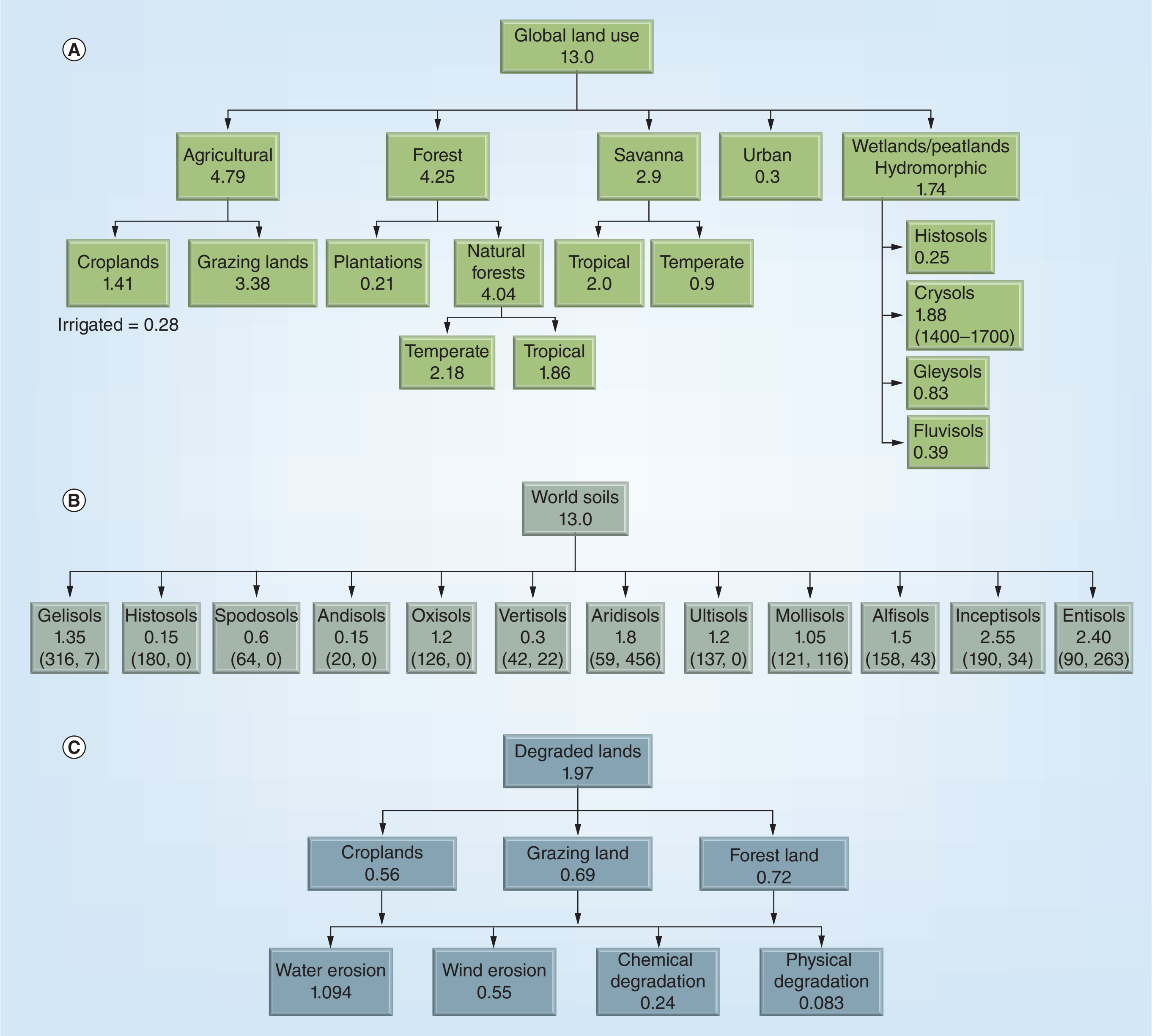

Figure 9. Global estimates of land use, soil resources and the state of their degradation by different processes. (A) Estimates of land area are 109 ha under different ecosystems. Data on land area taken from [60,169,173,306]. **(B)** Estimates of area in 109 ha under different world soil orders (data on area are from [244]) and of the magnitude of carbon pool to 1-m depth in Pg shown in parenthesis (soil organic carbon, soil inorganic carbon) are from [245]. Data on soil organic carbon pool in Cryosols taken from [60]. **(C)** Estimates of areas affected by soil degradation under different land uses and by different processes are from [246]. The sum of the individual land use area may exceed the total because of overlaps and duplications.

of soil degradation on global SOC/SIC pools (Figure 9C). These challenges have exacerbated controversies and the debate. Despite significant advances in methods of measuring the SOC pool, even bigger challenges await in estimating the turnover time of active SOC pool, understanding the steady-state carbon input rate and the turnover time of SOC, studying the seasonal and annual dynamics of the soil carbon cycle and identifying the cause of recalcitrance are among the major challenge. Monitoring SOC change over large areas remains to be among one of the major challenges [210]. Models are an important tool in understanding SOC dynamics [211]. These are useful to identifying the knowledge gaps and providing information about alternative scenarios. However, models are not a substitute for credible data from long-term experiments. A large proportion of the data on rates of SOC depletion and sequestration in relation to soil management (tillage, rotation, manuring, fertilizer) comes from long-term experiments not specifically established to assess the rate of change in the SOC pool. Thus, the data from paired plot studies often lack baseline information and are, at best, an assessment of the comparative values for two management scenarios at a specific point in time. However, there exists a strong need for establishing long-term field experiments specifically designed to assess the SOC dynamics and rate of change over time under the conditions of changing climate, yet there is an urgency to completely decarbonize the global energy system by 2025 or 2030. Despite the challenges listed above, using the SOC pool as a significant sink is not an impossible task. On the contrary, it is an essential strategy with numerous ancillary benefits (see 'Opportunities for enhancing soil carbon sinks' section). Furthermore, carbon sequestration in soils and the terrestrial biosphere is a bridge to the future until no-carbon fuel sources take effect.

Well-designed experiments are also needed to assess SOC sequestration/depletion under different climate-change scenarios [212,213]. In this context, the SOC-based soil quality index is widely considered as a tool to assess the impact on biophysical properties [214,215], but must be validated under soil/site-specific conditions.

Trading of soil carbon credits

The SOC pool critically influences the soil's life support systems, ecosystems services and human wellbeing [216]. Thus, protection and enrichment of the SOC pool is as vital to human survival as are air, water and solar radiation. Increasing soil water retention by improving the SOC pool is important to alleviating the adverse effects of agronomic/peodologic droughts [217]. Thus, trading SOC credits in a global marketplace offers an opportunity to preserve and enhance critical ecosystems functions. With a relatively long MRT in soil vis-à-vis the atmosphere, increasing the soil carbon sink capacity also provides a partial, medium-term strategy to offset the anthropogenic emissions of CO_2 [218]. It is a cost-effective method of securing CO_2 to prevent its release into the atmosphere [219], and has numerous co-benefits. In comparison to the geologic sequestration, albeit with a larger technical potential [219], soil-based carbon sequestration of even low technical potential is essential to numerous co-effects. Therefore, including co-effects and associated social costs and benefits can significantly change the outcome of cost–benefit effects [220]. Indeed, new research (science) is needed that considers the full ensemble of processes and feedbacks for a range of biophysical and social systems to better manage the ecosystems on which humans rely [221]. Lohmann outlined ten processes of ignorance creation facilitated by the new carbon markets, and queried what the quest for climate justice becomes in the context of carbon market framework [222]. There are also trade-offs between the SOC pool and crop yield. West *et al.* computed the SOC pool versus crop yield on agricultural lands under different biomes [223]. West and colleagues estimated that for each unit of land cleared, tropical biomes lose almost twice as much carbon (120 vs 63 Mg C/ha) and produce less than 50% the annual crop yield compared with temperate regions (1.7 vs 3.8 Mg/ha/yr). Thus, assessment of the soil/ecosystem carbon pool with all its co-effects must be objectively considered in developing national, regional and global policies.

Researchable priorities

Until the 1990s, most of the published literature on the SOC pool and its impact was focused on soil fertility and agronomic production. However, interaction of SOC with the GCC and its impact on climate change has enhanced the need for understanding processes, properties and biotic/abiotic factors that determine the SOC pool and its dynamics. Indeed, there has never been a greater need for understanding the importance of land use and management on the SOC pool, and its dynamics in relation to climate change, water quality, soil degradation, desertification, biodiversity and species extinction, and numerous other processes of interest to humans and relevant to nature. Canadell *et al.* prioritized a research agenda in the context of the carbon–climate–human system [224]. They identified the following researchable issues: understanding the variability and trends in underlying drivers; assessing the magnitude of the carbon–climate feedback; and exploring pathways to climate stabilization and their uncertainties, with specific reference to the role of SOC. There are also critical issues on emissions of CH_4 and N_2O from soils, and of the biogeochemistry of trace gases in general [225].

Key terms

Soil carbon sink capacity: The amount of additional carbon that can be stored in the soil profile without its release into the atmosphere.

Soil carbon farming: Enhancing the soil carbon pool with the objective to trade (buy and sell) it as a farm commodity.

The importance of SOC in enhancing resilience of agroecosystems and their adaptation to climate change merits basic and site-specific research [303]. Despite a long and vigorous debate on the existence of a large carbon sink in the northern forests, the magnitude, mechanisms and temporal variations remain elusive [226]. The relative contribution of the soil carbon pool to a large terrestrial carbon sink is not yet known.

The SOC pool of the terrestrial ecosystems is a major force to fight climate change [227]. However, the impact of the past (and importantly future) terrestrial changes on climate change and *vice versa* [228,229] are not understood. Soil is a source or sink of a range of GHGs (CO_2, CH_4 and N_2O) depending on land use and management [230]. Therefore, holistic GHG management is needed to identify judicious managerial interventions [304].

There are serious issues regarding changes in the SOC pool and composition with regards to organic farming [231], drainage of peatlands [232] and the total SOC pool in organic soils [60], impact of soil degradation such as salinization [233], biofuel feedstock production [234], biochar amendment [235], biomass burning [236], and black carbon in soils and soot in the atmosphere [67].

With reference to sustainability, there is also a need to understand the human dimensions such as land ownership and drivers of land-management decisions. Decision-making is driven by a variety of economic, social and policy factors [237]. However, there is also a strong need for in-depth science in support of decision-making [238].

Desertification is a global issue [239]. Desertification control and restoration of dryland can be a large carbon sink [240], including that through the formation of secondary carbonates. However, restoration of drylands can alter albedo and the energy budget with a positive feedback. Soils managed by resource-poor farmers in the developing world are strongly depleted of their SOC pool. These soils have a large carbon sink capacity. However, an effective strategy must be developed on how to include terrestrial soil carbon in developing nations in the overall climate change solution [305] while feeding the growing and increasingly affluent world population.

There is also a question of gross versus net soil carbon sequestration. Assessment of net carbon sequestration involves a complete accounting for the hidden carbon cost of farm operations and other inputs [241]. Therefore, a complete life cycle analysis is needed to assess the net gains in the soil carbon pool. Performing life cycle analysis is an important tool to evaluate the net amount of carbon that can offset anthropogenic emissions.

An accurate prediction of future climate change also necessitates a thorough understanding of the dynamics of the soil carbon pool and its component fluxes on the basis of an integrated methodology including measurement and modeling over a range of spatial scales [242]. Standardization of soil sampling (1–2 m) and monitoring methods are essential.

Estimating **soil carbon sink capacity** depends on obtaining credible statistics on land area under different ecosystems **(Figure 9A)**, soil orders **(Figure 9B)**, degraded soils under different land uses and processes **(Figure 9C)**, and on the magnitude of the SOC/SIC pool to different depths (up to 3 m in peat soils), as well as on the effects of degradation on SOC/SIC pools. Most of the available statistics are obsolete and obtained by unstandardized methodology. There is an urgent need to improve the data presented in **Figure 9**.

Conclusion

Management and sequestration of the SOC pool is integral to any strategy of limiting global warming below 2°C, advancing global food security and improving the environment. In comparison with geoengineering and CCD in geological and oceanic strata, soil carbon sequestration and management is cost effective and natural, and has numerous co-effects [302]. Nonetheless, additional research is needed to minimize numerous uncertainties and understand principal drivers, quantify co-effects and ecosystem services, develop protocol for trading soil carbon credits, improve techniques of measuring changes in the SOC pool over large spatial scales in 1–2 years' time, and develop protocols to facilitate payments to land managers for ecosystem services based on the real economic worth of the SOC pool [243]. Long-term experiments are needed to understand feedbacks and processes of soil carbon stabilization, assess soil carbon dynamics under different climates and land uses/management scenarios, and identify policy interventions to promote the adoption of proven technologies. Specific attention needs to be paid to the protection and restoration of peatlands, stabilization of cryosols and permafrost, the preservation and expansion of forest (tropical forests) lands, and reclamation of degraded/desertified lands. Watershed-level experiments are needed to understand the fate of carbon transported by erosional processes and the impact of landscape position on gaseous fluxes. Understanding the impact of enhancing carbon pools in degraded soils on the use efficiency of input in agroecosystems and agromic productivity needs soil-specific studies on coupled cycling of carbon, nitrogen, phosphorous and water. Land use (e.g., cropland, biofuel plantations) and soil-management practices must be characterized for their carbon footprint through detailed life cycle analysis.

Future perspective

Soil carbon management will be an increasingly important strategy during the coming decades because of its numerous co-benefits as a natural fix to climate change. In addition to being a cost-effective option of reducing the net anthropogenic emission of CO_2, restoring the soil carbon pool is also essential to achieving global food security, improving renewable freshwater supply and quality, and enhancing biodiversity. Food insecurity, affecting approximately 1 billion people globally, can be realized through enhancing soil quality by restoring the soil carbon pool to above the critical level of 1.2–1.5% in the root zone. **Soil carbon farming** (trading carbon credits) will be an important income stream for farmers, and a major incentive for adoption of RMPs. Advances in the measurement and monitoring of changes in the soil carbon pool to 1-m depth over watershed and landscape scales (Mg C/ha/yr) are needed to facilitate trading of soil carbon. With increasing funding support available from industry and the private sector, Earth scientists will enthusiastically pursue research on emerging issues relevant to:

- Preserving the vulnerable soil carbon pools (e.g., permafrost, soils of the tropics, peatlands);

Executive summary

The global context

- The world's soils are the largest reservoir of terrestrial carbon, including soil organic carbon (SOC) and inorganic carbon (SIC).
- Soils are a source or sink of GHGs depending on land use and management.

Soil carbon pool & climate change

- The soils of agroecosystems have been a source of GHGs for 10–12 millennia.
- Most soils of agroecosystems are depleted of their SOC pool and the magnitudes of depletion and carbon sink capacity depend on the severity of degradation.

Soil quality & ecosystem services

- The SOC pool is a principal control of soil quality and numerous ecosystem services and functions: net primary production, water quality, elemental cycling and biodiversity.
- The threshold level of the SOC pool at a 0–20-cm layer is 1.2–1.5%, and some severely degraded soils of developing regions have a <0.5% SOC pool.

Soil carbon sequestration

- Soil carbon sequestration involves the transfer of atmospheric CO_2 into SOC as humus and SIC pool as secondary carbonates with a long mean residence time.
- Strategies of soil carbon sequestration involve sustainable intensification, restoration of degraded soils and adoption of recommended management practices, such as conservation agriculture, cover cropping, complex rotations, integrated nutrient management, use of organics (e.g., compost, biochar) and agroforestry for croplands, and controlled grazing, fire management and appropriate forage species for grazing lands.

Rate of soil carbon sequestration

- Rates (kg/ha/yr) of SOC sequestration for 25–50 years range from 500 to 1000 in croplands, 50 to 500 in grazing lands, 500 to 1000 in forestlands, 1000 to 3000 in restored wetlands/peat soils, and 500 to 1500 in urban and recreational lands.
- Rates of SIC sequestration are 5–10 kg/ha/yr.

Magnitude of soil carbon sink capacity

- World soils may have lost 50–80 Pg carbon (Pg = petagram = 1015 g = 1 billion metric tons) because of historic land use, soil depletion and degradation.
- Whereas SOC in soils with inherent constraints can be enhanced beyond the level under natural ecosystems, SOC in most soils can be refilled up to approximately two-thirds (66%) of the historic loss.

Constraints/uncertainties in soil carbon sequestration

- Constraints to SOC sequestration include: the slow adoption of recommended practices, a finite carbon sink capacity, and risks of re-emissions.
- Major uncertainties include: climate change and an increase in decomposition of the SOC pool, positive feedback by thawing of permafrost soils, factors governing the CO_2 fertilization effect, and monitoring changes in the SOC pool over a landscape, watershed or region for a short period of 1–2 years.

Merits of soil carbon sequestration

- Enhancing the SOC pool has numerous co-benefits (e.g., advancing global food security, improving water quality, enhancing biodiversity, increasing biodiversity).
- Being a natural and the most cost-effective fix, it is a win–win strategy and a bridge to the future until low-carbon or no-carbon fuel sources take effect.
- Farming carbon and making payments to land managers for provisioning of ecosystem services can create another income stream for farmers, alleviate poverty, reduce hunger, empower women and advance Millennium Development Goals.

- Restoring degraded and desertified soils;
- Establishing a link between agronomic productivity and the soil carbon pool in the root zone;
- Understanding mechanisms/processes of preserving the soil carbon pool and enhancing carbon sink capacity;
- Conducting research on secondary carbonates;
- Developing a protocol for the trade of carbon credits as well as assessing the societal value of soil carbon;
- Determining the fate of carbon transported by erosional processes.

Trans-disciplinary and inter-institutional research teams will conduct basic and applied research to explore the ecological, economic and social benefits of this emerging discipline of Earth sciences.

Financial & competing interests disclosure

The author has no relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript. This includes employment, consultancies, honoraria, stock ownership or options, expert testimony, grants or patents received or pending, or royalties.

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