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Carbon sequestration in soil

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Soil carbon (C) sequestration implies transferring of atmospheric CO_2 into soil of a land unit through its plants. Co-benefits of soil C sequestration include: advancing food and nutritional security, increasing renewability and quality of water, improving biodiversity, and strengthening elemental recycling. Threshold level of soil organic C (SOC) in the root zone is 1.5–2.0%. SOC is influenced by land use, soil management and farming systems. To 1-m depth, more than 50% total C pool is contained between 0.3 and 1 m depth. Soils of agroecosystems are strongly depleted of their SOC stock and are degraded. Restoring soil quality necessitates increasing SOC concentration by adopting best management practices (i.e., conservation agriculture) which create a positive C budget. French Government is proposing to COP-21 of UNFCCC in December 2015 that SOC concentration be increased globally at 4 per 1000 per year to mitigate climate change and advance food security.

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Introduction

Generically, carbon (C) sequestration in soil refers to capture and secure by storage of atmospheric CO_2 with pedosphere in a manner that also increases its mean residence time (MRT) and minimizes sinks of re-emission [1••]. Among numerous objectives of soil C sequestration are: (i) off-setting anthropogenic emissions by fossil fuel combustion, cement production and deforestation, (ii) reducing net increase in atmospheric concentration of CO_2 (which reached 400 ppmv in 2013) and pool (~800 PgC), (iii) improving soil organic C (SOC) concentration (and pool) to above the threshold level of 1.5–2.0%, (iv) restoring soil quality and its ecosystem functions and services, (v) improving water and nutrient retention capacity, (vi) enhancing use efficiency of inputs in soils of managed ecosystems, (vii) reducing risks of accelerated erosion and non-point source pollution (NPSP), (viii) creating climate-smart soils and agroecosystems, (ix) improving use efficiency of inputs, and strengthening soil's disease-suppressive characteristics, and (x) increasing and sustaining agronomic productivity, and advancing food and nutritional security. Because of numerous co-benefits, there is a strong interest in the definition, concepts, experimental approaches, procedures of laboratory analyses, and methods of determining SOC sequestration rates. In this context, SOC sequestration is defined as, 'process of transferring CO_2 from the atmosphere into the soil of a land unit through units plants, plant residues and other organic solids, which are stored and retained in the unit as part of the soil organic matter (humus)'. Retention time of sequestered carbon in soil (terrestrial pool) can range from short-term (immediately released back to the atmosphere) to long-term (millennia) storage. The sequestered SOC processes should increase the new SOC storage during and at the end of a study to above the previous pre-treatment baseline [2]. Minister of Agriculture of France, Mr Stephane Le Foll, is proposing to UNFCCC-COP21 in Paris in December 2015 SOC sequestration at the rate of '4 per 1000' to offset anthropogenic emissions.

Some concerns have been expressed about the concepts [3,4], and the magnitude of SOC sink capacity [5] or the merits of pool vs. depth distribution of SOC in relation to management [6,7], the short-term vs. long-term effects of soil management on SOC [8], and the fate of erosion-induced transport of SOC as a source or sink of atmospheric CO_2 [9••,10]. Therefore, the objective of this article is to address potential and challenges of SOC sequestration to mitigate climate change, improve soil quality and advance food security and nutritional security.

Soil carbon pool and characteristics

Soil inorganic carbon pool

The soil inorganic carbon (SIC) pool comprises about 950 Pg C in the top 1 m [11]. The predominant SIC forms are carbonate minerals either derived from the soil parent material (primary, lithogenic) or synthesized during soil formation (secondary, pedogenic). Secondary carbonates are formed through the reaction of dilute carbonic acid with Ca^{2+} or Mg^{2+} brought in by dust, runoff, manure, ocean drift and sediment from outside [1••]. This process is a principal mechanism for SIC sequestration in arid and semiarid climates, but the role of SIC in mitigating atmospheric CO_2 and sequestration mechanisms has not been studied widely.

Soil organic carbon pool

The SOC pool contains more than three-times the amount of C of atmospheric CO_2, that is, 1325 Pg C in the upper 1 m and 3000 Pg C when estimates for deeper soil layers are included [12]. SOC pools can be arbitrarily separated into different fractions based on recalcitrance. Chemical, physical and biological methods are used to study the functional relevance of different SOC pools. The SOC sequestration capacity is governed by complex interactions of SOC pools with microbial community structures over time along with biotic and abiotic factors and degree of SOC association with inorganic components [13•].

Depth distribution

Soils hold C not only close to the soil surface but also to the full soil profile depth [14]. For example, more than 50% of the SIC and SOC stocks to 1-m depth are recorded in subsoil horizons below 0.3-m depth [15••]. Increasing C sequestration within soil profiles may be possible by adapting adequate soil management techniques [16]. While SOC concentrations in surface soils are generally higher than those at deeper depth, subsoil may be very far from being saturated with SOC [17]. Where deep soil coincides with deep rooting, the biological deposition of C from roots and their associated biota at depth is inevitable [14]. Breeding crops with desirable below-ground C sequestration traits, and exploiting attendant agronomic practices optimized for individual species in their relevant environments, are therefore important goals for SOC sequestration at deeper depth [17].

About one third of the global soil C to 1-m depth is held as inorganic C [15••]. However, estimates for SIC stock below this depth are scanty. Because of its long turnover time, formation of secondary carbonates can be an important C sequestration mechanism. However, the contribution of SIC depth distribution to sequestration of atmospheric CO_2 are unknown.

Soil carbon dynamics

In general, SOC is extremely dynamic, because its highly reactive, a source of energy for all microorganisms and other biota in the soil, and is preferentially removed by erosional processes because it has low density and is located in vicinity of the soil surface. Therefore, SOC pool is in a dynamic equilibrium with its environment. Its magnitude and the rate of change depend on the balance between gains of biomass-C or input (Eq. (1)) and losses of biomass-C or output (Eq. (2)):

$$I = A + R + D + M \quad (1)$$

where I is input, A is aboveground input, R is root-C input including root exudates, D is deposition by water run-on or wind-blown sediments, and M is the management-related input of biomass-C including compost, cover crops, crop/animal residues, among others.

$$L = O + E + L \quad (2)$$

where L is loss or output of C, O is oxidation/mineralization, E is erosion, and L is leaching. The magnitude of change in SOC pool, by natural or anthropogenic factors, depends on the balance between I and L (Eqs. (3) and (4)).

$$\text{Accretion or Sequestration} : I > L \quad (3)$$

$$\text{Depletion or Degradation} : I < L \quad (4)$$

The SOC pool attains a new equilibrium with change in land use and management only if erosion-induced loss is effectively controlled and leaching losses (dissolved organic C) are negligible. Therefore, the objective of management is to maintain a positive SOC budget by strategically increasing I and decreasing L. Site-specific technologies to create a positive SOC budget include conservation agriculture or no-till farming in conjunction with mulching and cover cropping, integrated nutrient management including a judicious use of organic amendments and chemical fertilizers, agroforestry, among others. All of these recommended management practices (RMPs) have trade-offs (hidden costs), which must be critically and objectively assessed under site-specific conditions.

Stabilization mechanisms

Physical protection

Soil aggregate formation is among the mechanisms for SOC stabilization. Understanding physical mechanisms of SOC sequestration and stabilization in soils have received much research interests for decades [8,18•,19•,20,21•,22]. Tillage disintegrates soil aggregates fractions and can substantially transfer protected SOC pools with mean residence times of decades to active pools with mean residence times of only weeks [23–25].

Like tillage practices, subsequent drying–rewetting cycles may also increase SOC decomposition rates by exposing physically protected SOC in aggregate fractions. The protection of SOC depends also on soil texture where clay soils protect more C than sandy soils under similar environment.

Chemical protection

The SOC is thermodynamically unstable but persists in soil sometimes for thousands of years [26••]. However, the persistence of SOC is primarily not a molecular property but an ecosystem property controlled by environmental factors such as the presence of reactive mineral surfaces, climate, water availability, soil acidity, soil redox state and soil microbial community [26••]. Specifically, the 'recalcitrance' of humic substances may only be marginally important for SOC cycling [27]. Also, the molecular structure of plant inputs and OM has only a secondary role in determining C residence times over decades to millennia [26••]. However, it is unclear whether the joint physical–chemical mechanism of SOC stabilization can be enhanced by the addition of OM relatively richer in compounds with molecular structures and/or assemblies more resistant to decomposition such as black carbon and aliphatic C [28].

Among the predominant stable forms of C are also bicarbonate and carbonate ionic forms, as well as carbonated salts in the solid phase under the environmental conditions of most soils [29•]. Thus, binding of C through the formation of soil carbonates is an effective stabilization mechanism.

Biological protection

The mean residence time (MRT) varies from a few seconds to millennia. It is only the SOC with a long MRT of decades to millennia that can influence atmospheric concentration of CO_2 and CH_4. The decomposition rate is moderated by the environmental and biological controls, rather than the molecular structural properties. Among biological controls, decomposition of SOC is mainly microbially-mediated. Merely 10–15% of the SOC-energy is utilized by soil animals, and abiotic chemical oxidation hardly accounts for 5% of SOM decomposition. The latter include formation of organo-mineral complexes involving Fe and Al oxides and hydroxides.

Thus, biotic mechanisms of occlusion of SOC by formation of stable micro-aggregates and non-hydrolyzable compounds are important to stabilization of SOC [30•]. Micro-aggregates are formed by the cementing effects of microbial cells, root exudates and faunal mucus. Micro-aggregates are combined into macro-aggregates (>250 μm) through enmeshment of larger fragments of particulate organic matter (POM), fungal hyphae and fine roots. Rather than indigenous or primary recalcitrance, the biological protection leads to secondary recalcitrance through formation of microbial products, and humic polymers, among others. Indeed, the spatial (physical) inaccessibility is enhanced by occlusion of SOC by aggregation and its encapsulation within the micro-aggregates, hydrophobicity (obtuse contact angle) imparted by SOC, and intercalation within phyllosilicates in soils of acidic reaction [19•].

Managing soil carbon pool

Croplands

Globally, croplands occupy about 1500 million hectares (Mha). Conversion of natural ecosystems into agro-ecosystems depletes the SOC pool because of: (i) lower return of biomass-C, (ii) higher losses of SOC by erosion, mineralization and leaching, and (iii) stronger variations in soil temperature and moisture regimes. Depletion of SOC pool from croplands is also exacerbated by degradation processes (e.g., erosion, salinization, nutrient depletion, decline in soil structure and aggregation). Thus, agricultural soils contain 25–75% less SOC than their counterparts in undisturbed or natural ecosystems [31•]. Thus, depleted soils of arable lands have a large potential to sequester C and offset anthropogenic emissions [32]. Thus, re-carbonization of soil (and the terrestrial biosphere) is an important strategy for climate change adaptation and mitigation [33]. It is widely recognized that a field of corn (*Zea mays*) can capture about 400 times as much C as the annual increase by anthropogenic emission of CO_2 in the entire column of air above the field from ground to the upper reaches of the atmosphere. Thus, identification and adoption of site-specific soil and crop management systems can lead to sequestration of atmospheric CO_2 [34].

Thus, adoption of recommended management practices (RMPs) is important to restoration of SOC pool, improving the environment, and sustaining agronomic productivity. Some RMPs, useful to reducing emissions of GHGs by enhancing the use efficiency of inputs, include conservation agriculture (CA), precision farming, integrated nutrient management (INM), micro-irrigation, among others. The strategy is to create a positive C budget (Eqs. (1)–(4)). The CA is already adopted on some 155 Mha of cropland [35].

Technical potential of C sequestration is a cropland soil is 0.4–1.2 PgC [31•,32]. Despite some concerns of the significance of SOC sequestration to mitigating the climate change [3,4] and on agronomic yield [36], there are some positive and encouraging reports indicating that SOC-induced improvements in soil quality can sequester C, mitigate climate change and improve agronomic yield [37,38••]. Indeed, SOC sequestration along with improvements in agronomic productivity is a win–win scenario.

Grasslands

Grasslands cover an estimated 52.5 million square kilometers or 40.5% of the terrestrial area excluding Greenland and Antarctica [39]. The SOC sequestration potential of grasslands is greater than that of croplands. Land use changes, biomass removal, soil amendments, soil texture, plant species composition and climate conditions are among the factors that affect SOC sequestration potential of grasslands. Increasing rate of fertilizer application and frequent cutting also reported to increase SOC sequestration potential of grasslands [40]. Although converting cultivated croplands to permanent grasslands can increase SOC pools [41], the current situation, particularly, in developing countries do not allow conversion of croplands to grasslands unless cropland is abandoned from cultivation because of low productivity. Any management practice that increase forage production can also increase SOC sequestration. These management practices comprise fertilization, improved grazing management and conversion from cultivation to grassland, sowing of legumes and grasses, and irrigation [42]. Frequency and intensity of animal grazing can affect the potential of grasslands for SOC sequestration. However, there are contrasting findings on effects of grazing on SOC stocks. Thus, developing appropriate stocking rate and rotational grazing not only alleviate grassland degradation but also enhances SOC sequestration in grassland. Management strategies should integrate rotation of grazing animals, limiting the timing and number of grazing animals on degraded pastures, and restoration of severely degraded land by replanting with perennial grasses and ensuring appropriate management over the long-term [43].

Forest lands

Natural forests store about 25 Mg SOC ha^{-1} more to 1-m depth than forest plantations [44]. However, the SOC pool of forest plantations may be enhanced by decreased regeneration delay, increased rotation length, harvesting, pruning/thinning, fertilization, drainage, tree species selection, and control of natural disturbances such as fires and pests [45•]. Forest management can directly influence the C flow into soil, and aim should be to secure a high productivity and, in particular, to avoid soil disturbances for enhancing the SOC pool by formation of stable organo-mineral complexes [46]. However, little is known about the effects of specific management activities on the full profile SOC pool [47]. The importance of tree species selection for forest land SOC stocks was emphasized by a recent meta-analysis [48]. Based on studies with minimal influence of site-related confounding factors (e.g., common garden experiments), Vesterdal *et al.* [49•] suggested that SOC stocks of boreal and temperate forest can be increased by tree species change. Some species may be better engineers for sequestration of C in stable form in the mineral soil, but it is unclear whether the key mechanism is root litter input or macro-faunal activity. Specifically, belowground litter inputs in forest lands should be managed as mineral soils store more than half of the forest SOC stock [47]. Harvesting reduces SOC in temperate forests by 8% mainly by causing C losses from the forest floor [50]. Tree species can also affect SOC losses by wildfire in temperate forests [51•]. Proactive management, such as the prudent use of prescribed fire or other management tools, is recommended as a preferable management alternative to losing larger quantities of SOC especially from the forest floor in wildfire [51•]. Addition of nitrogen (N) to forest ecosystems may not result in C pool changes in both organic horizons and mineral soil [52].

Governance and policy

Developing countries

Land governance involves the rules, processes, and structures through which decisions are made about access to land and its use, the manner in which the decisions are implemented and enforced, and the way that competing interests in land are managed [53]. Developing countries are facing complex problems regarding insecurity of food, feed, water, and energy which are aggravated by soil degradation, climate changes, and lack of land tenure security. Soil degradation exacerbates challenge of livelihood of billions of people by negatively affecting economic and environmental benefits obtained from land resources. Lack of clear land right and supporting policy contribute to soil degradation. Currently, more than 70% of the total populations of developing countries practice unsustainable agriculture that contributes to soil degradation. Continuing unsustainable agriculture not only challenges livelihood of small scale farmers but also aggravate degradation of natural resources base: the soils.

Large scale agriculture is currently expanding in most developing countries. This has great potential to absorb small scale farmers who practice low input agriculture on highly degraded soils. Profit-oriented large scale farmers also may not be interested in investing in sustainable land management as there is no clear agreement between the governments and investors on this aspect. Many scientists have voiced their concern on 'land grabbing' in developing countries (e.g. [54,55]).

In general, good land governance and tenure security should be part of the sustainable development goal framework to support the protection of a range of tenure, promote poverty reduction, strengthen food security, empower women, reduce resource conflicts, encourage responsible use and management of natural resources to alleviate the impacts of increasing commercial pressures on land [56]. Lack of secure land tenures and supporting policy discourages small scale farmers to invest on land resources management because environmental benefits like SOC sequestration does not have an immediate solution to food security problems. Of course, any techniques that enhance SOC sequestration also improve soil fertility and agricultural productivity; however, the benefits of soil rehabilitation are not short term. Thus, small scale farmers need commodities that can sustain their life and livelihood while implementing soil rehabilitation techniques. The presence of carbon markets [57•,58] and payments for ecosystem services [59] may be an additional income and important incentive for the resource-poor farmers to invest in soil rehabilitation and adoption of recommended management systems. For instance, a considerable part of depleted SOC pool can be restored through conversion of marginal lands into restorative land uses, adoption of conservation tillage with cover crops and crop residue mulch, nutrient cycling including the use of compost and manure, and other systems of sustainable management of soil and water resources [31•,60].

Europe

Issues involving SOC must achieve a higher policy profile in Europe and other regions [61]. Policy-maker and decision-maker do not often recognize the potential importance of soil C in the global C cycle nor for climate change mitigation. However, European SOC data are of relevance since 'soils' are among the mandatory C pools to be reported on under the Land Use, Land-Use Change and Forestry (LULUCF) activities listed in articles 3.3 and 3.4 of the Kyoto Protocol [62]. Further, the amount of SOC in Europe is an important factor in the preparation of climate change and agricultural policies [63]. Soil management and land use are affected by many different policies and some of them may affect SOC sequestration in Europe. The legislative proposal for a Soil Framework Directive would have obliged EU Member States to tackle the loss of SOC [63], but never went into effect and was withdrawn. One of the goals of the European Commission's Roadmap for a resource-efficient Europe is to maintain and improve SOC levels [64]. Among the milestones is the increase of SOC. For evaluating the soil status in Europe, SOC content and topsoil SOC stocks are specifically defined as priority indicators.

SOC in Europe as in other global regions is often privately managed but has global impacts on atmospheric C [61]. This planetary dimension requires a collective management approach for SOC with governance arrangements that are targeted for different stakeholders at different levels. Governance structures must embed SOC in all levels of decision-making and action. The principal actors involved are land users as the immediate users and managers of SOC, local professionals, local government and NGOs. Good governance by nation states has a pivotal role both in filtering down to the local level and aggregating up to the global and international levels [61].

Table 1

An estimate of the societal value of soil organic carbon [38••]

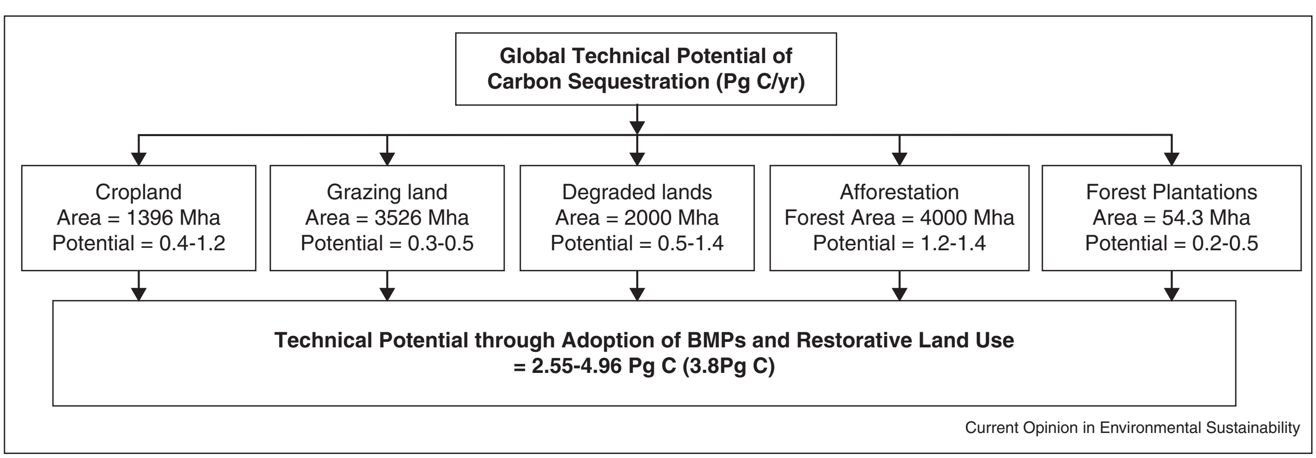
Parameter	Societal value (US $/Mg)
Soil organic C	132.70
CO_2 equivalent	36.20
Soil organic matter (58% C)	75.00

Legislation

Sequestration of atmospheric CO_2 in soil and the terrestrial biosphere is a win–win option. It leads to: (i) climate change adaptation and mitigation along with improvements in the environment, (ii) improvements in soil quality, increase in use efficiency of input, and advancements of global food and nutritional security, and (iii) provides an opportunity to create another income stream for farmers and land managers. The numerous co-benefits of soil C sequestration, especially the food security and water quality/renewability, warrant a strong policy intervention to incentivize farmers and land managers for adoption of RMPs. Specifically, farmers must be rewarded by payments for ecosystem services provisioned through sequestration of C in soil and the vegetation. Payment must be made at fair market value or just price that reflects the societal value of soil C, and by transparent and credible methods. The societal value of SOC can be assessed on the basis of the cost of crop residues (biomass-C) and nutrients (N, P, S) required to transform biomass into SOC. An assessment of the societal value of SOC shown in Table 1 indicates the market value of US $ 0.13/kg of SOC [38••]. Essential resources (e.g., SOC, water, atmosphere) must be under-valued to avoid 'tragedy of the commons' [65].

Not only is the innovation hindered by underlying precious resources (e.g., SOC), but it also leads to abuse and exploitation.

Figure 1



Technical potential of carbon sequestration in principal land use.
Source: Redrawn from Lal [66••].

In this context, the initiatives undertaken by President Obama are pertinent. On June 2, 2014, US-EPA proposed to cut C pollution from power plants by 2030 by 30% from 2005 levels. Further, U.S. and China signed an agreement in November 2014 to reduce emissions and adopt strategies of low-C economies to achieve the goal of limiting global warming to less than 2 °C. Thus, U.S. intends to reduce its emissions by 26–28% below its 2005 level in 2025. Similarly, China plans to achieve the peaking of CO_2 emissions around 2030 and to use non-fossil energy of 20% by 2030. The most encouraging initiative thus far is that by the French government entitled '4 per 1000' targeting terrestrial SOC sequestration. With SOC pool of 706 Pg to 30-cm depth [15••], implementation of 4 per 1000 program would have technical potential of 2.8 PgC/yr in soils of the world. Technical potential of the terrestrial biosphere (soil and biota) has been estimated at about 3.8 PgC/yr (Figure 1 [66••]). Thus, agriculture, soils and the terrestrial biosphere are important solutions to the problems of global warming, environmental degradation, and food insecurity. Indeed, this is a win–win–win option.

Agriculture, accounting for 30% of the global emissions (direct and indirect) must be integral to any agenda of climate change adaptation and mitigation. Thus, legislative provisions of compensating farmers for SOC sequestration are important to achieving these goals.

Conclusions

Soil organic carbon is the essence of all terrestrial life, and is critical to human well-being and nature conservancy. Through its impact on soil quality and several key pedospheric processes, it is the source of numerous ecosystem goods and services. Being the largest terrestrial reservoir of C to 3-m depth (~4000 Pg), total soil C pool (both organic and inorganic) can be a source or sink of atmospheric CO_2 depending on land use and management. World soils have been the source of CO_2 and other GHGs ever since the dawn of settled agriculture, and total emissions from soil and land use change exceeded those from fossil fuel combustion until about 1940s. During 2010s, as much as 30% of total global emissions (both direct and indirect) are contributed by agriculture.

Soils of agroecosystems, especially those severely degraded by accelerated erosion and other processes (e.g., salinization, nutrient depletion) and managed by extractive farming practices, are severely depleted of their SOC pool. Some soils have lost as much as 30–35 MgC/ha and their SOC concentration is below the threshold/critical level of 1.5–2.0% in the root zone. Some severely depleted soils under arable land use have SOC concentration of <0.1%. The latter have low productivity and do not respond to input such as improved varieties, chemical fertilizers, and soil/water conservation measures.

Thus, soils of agroecosystems (croplands, grazing lands, drastically disturbed and degraded lands) have a large C sink capacity. The strategy is to choose a restorative land use and animal management through a holistic approach, and create a positive C budget. The latter can be achieved by increasing the input of biomass-C (above and below-ground biomass, compost, manure) to excess the output/losses by erosion, mineralization and leaching. Some technological options, which can create a positive soil C budget, include conservation agriculture adopted in conjunction with crop residue mulch and complex rotations along with INM, agroforestry systems, water harvesting and recycling through micro-irrigation, among others. Restoration of degraded soils (eroded, salinized, low fertility) and desertified ecosystems through afforestation is an important option to create a large C sink capacity. The rate of soil C sequestration ranges from 100 to 1000 kg C/ha/yr for SOC and 2–5 kg C/ha/yr for secondary carbonates. The rate of SOC sequestration is high in soils of cool and humid than warm and dry climates, heavy or clayey than light or sandy texture, containing 2:1 expanding lattice than those with 1:1 fixed lattice minerals, and those with deep than shallow soil solum.

In addition to off-setting anthropogenic emissions, SOC sequestration has numerous co-benefits. Important among these are advancing food security, improving the environment, enhancing water quality and renewability, increasing biodiversity etc. Thus, it is important that farmers/land managers are compensated through payments for ecosystem services. The societal value of SOC estimated at ~$0.13 kg/C, must be assessed and paid through fair, just and transparent system. Undervaluing the SOC can lead to tragedy of the commons.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Lal R: **Carbon sequestration**. *Philos Trans Roy Soc* 2007,
•• **363**:815-830.
Biotic and abiotic techniques of soil carbon sequestration, merits and limitation of each strategy, and policy implications.

2. Olson KR, Al-Kaisi M, Lal R, Lowery B: **Experimental considerations, treatments and methods in determining soil organic carbon sequestration rates**. *Soil Sci Soc Am J* 2014, **78**:348-360.

3. Janzen H: **Beyond carbon sequestration: soil as conduit of solar energy**. *Euro J Soil Sci* 2014 http://dx.doi.org/10.1111/ejss.12194.

4. Powlsen DS, Stirling CM, Jat ML, Gerard BG, Palm CA, Sanchez PA, Cassman KG: **Limited potential of no-till agriculture for climate change mitigation**. *Nat Climate Change* 2014, **4**:678-683.

5. Schlesinger WH: **Carbon sequestration in soils**. *Science* 1999, **314**:1217-1223.

6. Baker JM, Ochsner TE, Venterea RT, Griffis TJ: **Tillage and soil carbon sequestration—what do we really know?** *Agric Ecosyst Environ* 2007, **118**:1-5.

7. Blanco-Canqui H, Lal R: **No-tillage and soil-profile carbon sequestration: an on farm assessment**. *Soil Sci Soc Am J* 2008, **72**:693-701.

8. Six J, Ogle SM, Breidt FJ, Conant RT, Mosier AR, Paustian K: **The potential to mitigate global warming with not-tillage management is only realized when practiced in the long term**. *Glob Change Biol* 2004, **10**:155-160.

9. •• Lal R: **Soil erosion and global carbon budget**. *Environ Int* 2003, **29**:437-450.
The fate of erosion-induced transport, redistribution and deposition of soil carbon and attendant emission of greenhouse gases.

10. Van Oost K, Verstraeten G, Doetterl S, Noteaert B, Wiaux F, Broothaerts N, Six J: **Legacy of human-induced C erosion and burial on soil-atmosphere C exchange**. *PNAS* 2012, **109**:19492-19497.

11. Eswaran H, Reich PF, Kimble JM, Beinroth FH, Padmanabhan E, Moncharoen P: **Global carbon stocks**. In *Global Climate Change and Pedogenic Carbonates.* Edited by Lal R, Kimble JM, Eswaran H, Stewart BA. Taylor and Francis Publishing; 2000:15-25.

12. Köchy M, Hiederer R, Freibauer A: **Global distribution of soil organic carbon—Part 1: masses and frequency distributions of SOC stocks for the tropics, permafrost regions, wet-lands, and the world**. *SOIL* 2015, **1**:351-365.

13. • Schnitzer M, Monreal CM: **Quo VADIS soil organic matter research? A biological link to the chemistry of humification**. *Adv Agron* 2011, **113** 143-127.
Definition of soil organic matter, constituents of soil organic matter and their genesis through biogeochemical transformations.

14. Harper RJ, Tibbett M: **The hidden organic carbon in deep mineral soils**. *Plant Soil* 2013, **368**:641-648.

15. •• Batjes NH: **Total carbon and nitrogen in the soils of the world**. *Eur J Soil Sci* 1996, **47**:151-163.
Global reserves of soil organic carbon and soil inorganic carbon pools, their depth distribution, and comparison with other estimates.

16. Rumpel C: **Opportunities and threats of deep soil organic matter storage**. *Carbon Manage* 2014, **5**:115-177.

17. Kell DB: **Large-scale sequestration of atmospheric carbon via plant roots in natural and agricultural ecosystems: why and how**. *Philos Trans R Soc B* 2012, **367**:1589-1597.

18. • Tisdall JM, Oades JM: **Organic matter and water-stable aggregates in soils**. *J Soil Sci* 1982, **33**:141-163.
Mechanism of formation of stable aggregates and the role of soil organic matter, impact of aggregation on physical protection of soil carbon encapsulated within the micro-aggregates.

19. • Lützow MV, Kögel-Knabnera I, Ekschmitt K, Matzner E, Guggenberger G, Marschnerf B, Flessa H: **Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions a review**. *Euro J Soil Sci* 2006, **57**:426-445.
Scientific basis of the stabilization of soil organic matter in soil, and the mechanisms (chemical, physical, biological) which moderate the mean residence time.

20. Lützow MV, Kögel-Knabner I, Ekschmitt K, Flessa H, Guggenberger G, Matzner E, Marschnerf B: **SOM fractionation methods: relevance to functional pools and to stabilization mechanisms**. *Soil Biol Biochem* 2007, **39**:2183-2207.

21. • Jastrow JD, Amonette JE, Bailey VL: **Mechanisms controlling soil carbon turnover and their potential application for enhancing carbon sequestration**. *Climatic Change* 2007, **80**:5-23.
Mechanisms affecting soil carbon sequestration in relation to the turnover time.

22. Moyano FE, Manzoni S, Chenu C: **Responses of soil heterotrophic respiration to moisture availability: an exploration of processes and models**. *Soil Biol Biochem* 2013, **59**:72-85.

23. Grandy AS, Robertson GP: **Initial cultivation of a temperate-region soil immediately accelerates aggregate turnover and CO_2 and N_2O fluxes**. *Global Change Biol* 2006, **12**:1507-1520.

24. Grandy AS, Robertson GP: **Aggregation and organic matter protection following tillage of a previously uncultivated soil**. *Soil Sci Soc Am J* 2006, **70**:1398-1406.

25. Grandy AS, Robertson GP: **Land-use intensity effects on soil organic carbon accumulation rates and mechanisms**. *Ecosystems* 2007, **10**:58-73.

26. •• Schmidt MWI, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Kleber M, Kogel-Knabner I, Lehmann J, Manning DAC *et al.*: **Persistence of soil organic matter as an ecosystem property**. *Nature* 1478, **201**:49-56.
Rather than the molecular structure and chemical composition, it is the environmental/ecological factors which affect the mean residence time, turnover rate, and stabilization of soil organic carbon.

27. Kleber M, Johnson MG: **Advances in understanding the molecular structure of soil organic matter: implications for interactions in the environment**. *Adv Agron* 2010, **106**:77-142.

28. Courtier-Murias D, Simpson AJ, Marzadori C, Baldoni G, Ciavatta C, Fernández JM, López-de-Sác EG, Plazac C: **Unraveling the long-term stabilization mechanisms of organic materials in soils by physical fractionation and NMR spectroscopy**. *Agric Ecosyst Environ* 2013, **171**:9-18.

29. • Macías F, Arbestain MC: **Soil carbon sequestration in a changing global environment**. *Mitig Adapt Strateg Glob Change* 2010, **15**:511-529.
Impact of global change on soil carbon sequestration, impact of change in environmental variables on soil carbon dynamics.

30. • Six J, Bossuyt H, Degryze S, Denef K: **A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics**. *Soil Tillage Res* 2004, **79**:7-31.
Historical evolution of different theories of aggregate formation, and the impact of soil organic carbon on aggregation.

31. • Lal R: **Soil carbon sequestration to mitigate climate change**. *Geoderma* 2004, **123**:1-22.
Potential of soil carbon sequestration to mitigate climate change, along with principles and practices for enhancing soil carbon pool and increasing its mean residence time (MRT).

32. Lal R: **World soils and the carbon cycle in relation to climate change and food Security**. In *Soils In The Nexus: A Crucial Resource for Water Energy and Food Security.* Edited by Weigelt J, Mueller , Beckh , Toepfer . IASS; 2014:32-66.

33. Lal R, Lorenz K, Huttle R, Schnieder BU, von Braun J (Eds): *Recarbonization of the Biosphere*. Springer Verlaag; 2012:545.

34. Gan Y, Liang C, Chai Q, Lemke RL, Campbell CA, Zentnerm RP: **Improving farming practices reduces the carbon footprint of spring wheat production**. *Nat Commun* 2014, **5**:5012.

35. Kassam A, Friedrich T, Derpsch R, Kienzle J: **Worldwide adoption of conservation agriculture**. *6th World Congress of Conservation Agriculture, 22–27 June, Winnipeg, Canada*. 2014.

36. Pittelkow CA, Liang X, Linquist BA, Groenigen KJV, Lee J, Lundy ME, Gestel NV, Six J, Venterea RT, Van Kessel C: **Productivity limits and potentials of the principles of conservation agriculture**. *Nature* 2014, **517**:365-368.

37. Fan M, Cao J, Wei W, Zhang F, Su Y: **Managing soil organic carbon for advancing food security and strengthening ecosystem services in China**. In *Ecosystem Services and Carbon Sequestration in the Biosphere.* Edited by Lal R. Springer; 2012:420-428.

38. •• Lal R: **Societal value of soil carbon**. *J Soil Water Conserv* 2014, **69** 186A–192A.
Societal versus economic/market value of soil organic carbon based on the inputs required to produce it, and the use of this information for payments of ecosystem services.

39. FAO: *Grasslands of the World*. Food and Agricultural Organization of the United Nations; 2005:. p. 514.

40. Ammann C, Flechard CR, Leifeld J, Neftel Fuhrer J: **The carbon budget of newly established temperate grassland depends on management intensity**. *Agric Ecosyst Environ* 2007, **121**:5-20.

41. McLauchlan KK, Hobbie SE, Post WM: **Conversion from agriculture to grassland builds soil organic matter on decadal timescales**. *Ecol App* 2006, **16**:143-153.

42. Conant RT, Paustian K, Elliott ET: **Grassland management and conversion into grassland: effects on soil carbon**. *Ecol App* 2001, **11**:343-355.

43. FAO: *Sustainable Grassland Management*. Food and Agricultural Organization of the United Nations; 2014:. p. 79.

44. Liao C, Luo Y, Fang C, Li B: **Ecosystem carbon stock influenced by plantation practice: implications for planting forests as a measure of climate change mitigation**. *PLoS ONE* 2010, **5**:e10867 http://dx.doi.org/10.1371/journal.pone.0010867.

45. Lorenz K, Lal R: *Carbon Sequestration in Forest Ecosystems*.
• Springer; 2010.
Importance of forest ecosystems to the global carbon cycle, depth distribution of soil C, and the importance of deep carbon to the global soil C pool.

46. Jandl R, Lindner M, Vesterdal L, Bauwens B, Baritz R, Hagedorn F, Johnson DW, Minkkinen K, Byrne KA: **How strongly can forest management influence soil carbon sequestration?** *Geoderma* 2007, **137**:253-268.

47. Buchholz T, Friedland AJ, Hornig CE, Keeton WS, Zanchi G, Nunery J: **Mineral soil carbon fluxes in forests and implications for carbon balance assessments**. *GCB Bioenerg* 2014, **6**:305-311.

48. Boča A, Van Miegrot H, Gruselle MC: **Forest overstory effect on soil organic carbon storage: a meta-analysis**. *Soil Sci Soc Am J* 2014, **78**:S35-S47.

49. Vesterdal L, Clarke N, Sigurdsson BD, Gundersen P: **Do tree**
• **species influence soil carbon stocks in temperate and boreal forests?** *Forest Ecol Manage* 2013, **309**:4-18.
Soil C pool in forest ecosystems and the impact of species in terms of litter input, root biomass, and chemical composition.

50. Nave LE, Vance ED, Swanston CW, Curtis PS: **Harvest impacts on soil carbon storage in temperate forests**. *Forest Ecol Manage* 2010, **259**:857-866.

51. Nave LE, Vance ED, Swanston CW, Curtis PS: **Fire effects**
• **on temperate forest soil C and N storage**. *Ecol Appl* 2011, **21**:1189-1201.
Impacts of fire on soil C pool and dynamics, change in soil color and albedo, and other effects of fire.

52. Lu M, Zhou X, Luo Y, Yang Y, Fang C, Chen J, Li B: **Minor stimulation of soil carbon storage by nitrogen addition: a meta-analysis**. *Agric Ecosyst Environ* 2011, **140**:234-244.

53. FAO UNHSP: **Towards Improved Land Governance**. *Land Tenure Working Paper 11*; *Food and Agriculture Organization of the United Nations, and United Nations Human Settlements Programme: 2009:55*.

54. Cotula L, Vermeulen S, Leonard R, Keeley J: *Land Grab or Development Opportunity? Agricultural Investment and International Land Deals in Africa*. IIED/FAO/IFAD; 2009:. p .119.

55. von Braun J, Meinzen-Dick R: *''Land Grabbing'' by Foreign Investors in Developing Countries: Risks and Opportunities. IFPRI Policy Brief 13*. 2009:. April.

56. Sustainable Development Solutions Network (SDSN): *An Action Agenda for Sustainable Development*. Report for the UN Secretary General; 2013.

57. Lal R: **Challenges and opportunities in soil organic matter**
• **research**. *Eur J Soil Sci* 2009, **60**:1-12.
Despite the potential of soil carbon sequestration to mitigating climate change and provisioning of numerous ecosystem services, there are numerous challenges and unknowns which are researchable priorities.

58. Lal R: **Agriculture and Climate Change: An Agenda for Negotiation in Copenhagen. The Potential for Soil Carbon Sequestration. 2020 Vision for Food**. *Agriculture, and the Environment. Focus 20 Brief 5 May*. 2009.

59. Lal R, Lorenz K, Huttle RR, Schneider BU, von Braun J (Eds): *Ecosystem Services and Carbon Sequestration in the Biosphere*. Springer; 2013:464.

60. Lal R, Griffin M, Apt J, Lave L, Morgan MG: **Managing soil carbon**. *Science* 2004, **304**:393.

61. Banwart S, Black H, Cai Z, Gicheru P, Joosten H, Victoria R, Milne E, Noellemeyer E, Pascual U, Nziguheba G *et al.*: **Benefits of soil carbon: report on the outcomes of an international scientific committee on problems of the environment rapid assessment workshop**. *Carbon Manage* 2014, **5**:185-192.

62. Panagos P, Hiederer R, Van Liedekerke M, Bampa F: **Estimating soil organic carbon in Europe based on data collected through an European network**. *Ecol Ind* 2013, **24**:439-450.

63. Schils RLM, Kuikman P, Liski J, van Oijen M, Smith P, Webb J, Alm J, Somogyi Z, van den Akker J, Billett M *et al.*: *Service Contract: Review of Existing Information on the Interrelations Between Soil and Climate Change (CLIMSOIL). Final Report*. European Commission; 2008:. (http://ec.europa.eu/environment/soil/pdf/climsoil report dec 2008.pdf).

64. EC: *Roadmap to a Resource Efficient Europe. Communication COM (2011) 571 final*. European Commission; 2011.

65. Hardin G: **The tragedy of the commons**. *Science* 1968, **162**:1243-1248.

66. Lal R: **Managing soils and ecosystems for mitigating**
•• **anthropogenic carbon emissions and advancing global food security**. *Bioscience* 2010. 60-708-721.
Rational for bio sequestration of carbon in terrestrial ecosystems, the technical potential of soil and ecosystem C sequestration in principal biomes, and the role of restoration of degraded soils on soil carbon sequestration. Policy implication and the relevance of payments for ecosystem services,and the implications to food and nutritional security.