Review Article

Quantifying the Stock of Soil Carbon Sequestration in Different Land Uses: An Overview

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A B S T R A C T

International efforts to mitigate human-caused changes in the Earth's climate are considering a system of incentives that would encourage specific changes in land use that can help to reduce the atmospheric concentration of carbon dioxide. The two primary land-based activities that would help to minimize atmospheric carbon dioxide are carbon storage in the terrestrial biosphere and the efficient substitution of biomass fuels and bio-based products for fossil fuels and energy-intensive products. These two activities have very different land requirements and different implications for the preservation of biodiversity and the maintenance of other ecosystem services. Carbon sequestration potential of soils in reduced clearing of primary ecosystems has attained substantial importance in modern agricultural farming systems apart from climate change adaptation. The adoption of diverse management strategies of carbon sequestration in croplands, grasslands etc., may provide potential estimation of carbon sequestration potential. Research needs to be done to identify both horizontal and vertical agricultural technologies that restore carbon pools and soil quality and create tools to measure, monitor and verify soil-carbon pools and fluxes of greenhouse gas emissions.

Introduction

World soils constitute the largest terrestrial carbon (C) pool, estimated at about 4000 Pg (Pg = 1015g = 1 billion or gigaton) to 3-m depth. The soil C pool has two components: soil organic C (SOC) and soil inorganic C (SIC) pools. The SOC pool is highly reactive and plays an important role in the global C cycle (GCC). It can be a source or sink of greenhouse gases (GHGs) depending on land use and management. Soils have been source of GHGs ever since the dawn of settled agriculture about 10 to 12 thousand years ago, because of conversion of natural to managed ecosystems through deforestation, biomass burning, land drainage, mechanical seedbed preparation and nutrient mining through extractive farming practices. Thus, soils of agroecosystems contain lower SOC pool than their counterparts under natural ecosystems. The magnitude of SOC loss in agroecosystems may be 20-40 Mg C/ha. The loss of SOC is generally more from tropical than temperate ecosystems, coarser than fine-textured soils, and those managed by extractive farming than science-based inputs. Accelerated erosion and other degradation processes aggravate the depletion of SOC pool. The projected climate change,

accelerated erosion, and the attendant increase in soil temperature may exacerbate the rate and magnitude of SOC depletion.

Soil carbon sequestration

Soil C sequestration implies transfer of atmospheric CO_2 into the soil C pol of long mean residence time either as humus or as secondary carbonates. The rate of C sequestration ranges from 0 to 1 Mg/ha/yr as humus and 2-5 Kg/ha/yr as secondary carbonates (Lal, 2004). The potential of SOC sequestration is limited in soils of the dry tropics (Lam *et al.,* 2013). The strategy of SOC sequestration as humus is to create a positive C (and N, P, S, and H2O) budget in soil through conversion to a restorative land use and adoption of recommended management practices (RMPs). Some examples of RMPs include conservation agriculture (CA) with retention of crop residue mulch and incorporation of cover crops in the rotation cycle along with the use of complex cropping systems and integrated nutrient management (*e.g.,* manuring), agroforestry, and other conservation-effective measures. The strategy is to adopt sustainable intensification (SI). The SI implies producing more from less through improvement of soil quality. In practice it means more agronomic production per unit of land area, per drop of water, per unit input of fertilizers and pesticides, per unit of energy, and per unit of CO_2-C emissions.

Carbon storage and sequestration

Globally there is a generally positive relationship between biodiversity and carbon stocks (Midgley *et al.,* 2010): tropical moist forests, unaffected by direct anthropogenic disturbances like logging and fire, are rich in both. Within tropical forests there is less correlation between spatial patterns of carbon stocks and biodiversity in undisturbed areas

and the patterns are complex (Talbot, 2010). At the macro-level, there is considerable variation from one tropical forest region to another in the number of species supported per unit area, but there is as of yet no compelling evidence that the most diverse tropical forests are also the most carbon-rich. In Amazonia there is little correlation between areas of highest species richness and areas of highest above ground biomass (Talbot, 2010).

A great deal of uncertainty still surrounds biomass distributions and their causes, and different research groups and different approaches (including remote-sensing and ground-based measurements) have found different results.

Overall, few studies yet exist that address whether the variation in biodiversity coincides empirically with large variation in biomass and soil carbon stocks. Whether and to what degree biodiversity influences carbon stocks in tropical forests is still uncertain, although experimental work in other ecosystems has shown that biodiversity often promotes stability and primary productivity, and therefore carbon stocks (Miles *et al.,* 2010a).

Principal mechanisms that determine SOC and SIC sequestration in soils

These mechanisms are generally addressed as physical and chemical processes. In contrast, this review takes a soil ecological approach to describe the four mechanisms listed below and provides a unifying conceptual framework that combines all mechanisms into a single and provocative model. i) Soil aggregation and carbon sequestration ii) interaction of carbon with clay fractions iii) transport of dissolved organic carbon into subsoil horizons iv) formation of secondary (pedogenic) carbonates.

Soil aggregation and carbon sequestration

Soil aggregation implies the formation of secondary particles or aggregates through flocculation of clay colloids and the cementation of floccules by organic and inorganic materials. Gijsman and Thomas (1995) and Gijsman (1996) observed a strong non-linear relationship between aggregate stability and hot-water extractable carbohydrates of microbial or plant-derived origin in a tropical Latin American Oxisol. An increase of microbially-derived carbohydrates in the clay and silt-sized fractions has been observed by Feller *et al.,* (1991) and Guggenberger *et al.,* (1995). Microbial-derived carbohydrates can be separated from those sugars of plant origin.

In the former group, galactose (G) and mannose (M) accumulate preferentially in the fine fractions, whereas plant-derived sugars arabinose (A) and xylose (X) are dominant in coarse fractions. The G+M/A+X ratio is higher in clay-size separates. On the death of roots and hyphae the stability of macro-aggregates declines at about the same rate at which plant material decomposes in soils. The degradation of macro-aggregates creates micro-aggregates that are considerably more stable than macro-aggregates. For aggregates <20 μm Ø there appears to be a random mixture of clay microstructures, biopolymers and microorganisms. The general structure of an aggregate is outlined in figure 1.

Interaction of carbon with clay fractions

The relationship between clay type and content and SOM accumulation and stabilization is complex. Clay content is usually correlated with factors that result in SOM production, like plant nutrients and water regime, and also to the formation of aggregates. Residence times of SOC in clay minerals can exceed a hundred years (Laird, 2001), compared to several months for partially mineralized SOC. The SOM associated to silt- and clay-size fractions has a strong link to mineral particles, so that an OM-mineral complex is formed. The majority of the research on SOM linkages with particle-size fractions is from 2:1 clay temperate soils. In these studies, 10-30% of total SOC pool is associated with the sand-size fraction (> 50 μm), 20-40% with the silt-size fraction (20-50 μm) and 35- 70% with the clay-size fraction (0-20 μm) (Feller and Beare, 1997). The fine-clay fraction contains less stable SOM than the coarser fine silt and coarse clay fractions. In contrast, some studies have shown that the stability of OM increase with decrease in the particle-size fraction (Christensen, 1992). The interaction between clay and SOC concentration is determined by the molecular structure of clay and requires a review of the different clay minerals that are normally found in tropical soils. A classification scheme for phyllosilicates related to clay materials..

Transport of dissolved organic carbon into subsoil horizons

The dissolved organic carbon (DOC) is defined as all carbon of plant, animal, fungi and/or bacteria origin that is dissolved in a given volume of water at a particular temperature and pressure. These dissolved organic carbon compounds are comprised of soluble carbohydrates, amino acids to more complex high-molecular weight molecules. The chemical structure of Dissolved organic carbon molecules can be recognizable and easily defined, such as fats, carbohydrates, and proteins. However, most have non-identifiable structure and are lumped under the term humic or tannin substances. Recent studies indicate that the oceanic DOC reservoir may be comparable in size to the terrestrial C reservoir.

Formation of secondary carbonates

Despite the dominant role that calcium carbonate plays in modifying the physical, chemical and biological properties and behaviour of plant nutrients in the soil, its role in C sequestration in calcareous soils is not widely documented (Lal, 2002). The role of SIC is important for sequestering C, but the mechanisms involved are not well understood.

The rate of SIC sequestration as secondary carbonates is low (2 to 5 kg C ha^{-1} yr^{-1}) and is accentuated by biogenic processes and leaching of carbonates into the groundwater (Nordt *et al.,* 2001), especially in soils irrigated with water containing low carbonates.

The soil inorganic carbon occurs in carbonate minerals in two forms, i.e. calcium carbonate ($CaCO_3$) and dolomite ($MgCO_3$). In tropical highly weathered acid-soils the amount of soil inorganic carbon is not considerable because most of the carbonates present in the parent material have been dissolved. Fractions of soil organic carbon are given in table which is shown as under in table 1.

Total soil organic and inorganic carbon pools in world

Estimates of soil organic and inorganic carbon pools in world soils given by Eswaran *et al.,* 1993 and studied that the inorganic carbon was found more in aridisols which is approximately 1044 tons per hactere, aridisols are soils which are found in arid and semi arid regions. While as organic carbon was found more in Histosols. Histosols are soils which contain organic carbon percentage more as compared to other soil orders. Table 2 below shows the content of organic carbon and inorganic carbon content in world soil given in tons per hector.

Carbon sequestration and storage, and the resilience of carbon stocks

Important climate-related functions of forest ecosystems are carbon sequestration and carbon storage, which create carbon stocks. The persistence and resilience of these carbon stocks as well as the continued ability of forests to absorb carbon dioxide from the atmosphere are significant factors in the role that forests can play in climate change mitigation (Díaz *et al.,* 2009), particularly in a world characterised by rapid change. This section is built on a critical review of five existing reviews and syntheses on biodiversity and, carbon stocks and their resilience (Brodie *et al.,* 2012; Midgley *et al.,* 2010; Miles *et al.,* 2010a; Parotta *et al.,* 2012; Thompson *et al.,* 2012), as well as additional related literature found through supplementary searches. As such, this section has not applied the same search and appraisal methodology as other sections of the review; however, the findings are presented in a similar way, using the same levels of confidence as applied throughout the review.

Carbon sequestration and insect mass outbreaks

In such cases, not only has tree species composition changed but also the character of the entire landscape, resulting in an increased deterioration of forests and their associated fauna and flora. This phenomenon is known to occur in managed forest systems as well as in their unmanaged counterparts. At the biogeochemical scale, forest insects also have the potential to greatly affect nutrient cycles in terms of quantity and quality, with substantial consequences for C and N storage capabilities in above and below-ground systems. During mass outbreaks (defoliation), insect-mediated organic matter fluxes from canopy to soil foster soil decomposition activity of microorganisms and subsequently

elevates CO_2 and N_2O production significantly. In forest ecosystems, insect mass outbreaks following severe or repeated periods of drought might therefore serve as a trigger for converting carbon sinks turn into carbon sources due to limited C sequestration in woody material and enhanced soil-induced respiration. Due to an insect induced limited above and below ground C sequestration ability and an enhanced production of CO_2 and N_2O forest stands with an enhanced susceptibility to mass outbreaks are likely to occur with an increased global warming potential (GWP).

Carbon credits and debits from land management

The Kyoto Protocol currently provides incentives for two different types of land management activities that could reduce atmospheric CO_2 concentrations, one explicitly and the other implicit in the details of the Protocol. Removal of CO_2 from the atmosphere by sinks (carbon sequestration) is explicitly discussed in the Protocol. Implicitly, substitution of biomass energy for fossil-fuel energy or of biomass based materials for alternate, more energy-intensive materials can reduce a country's emissions of CO_2. Whereas all combustion of fossil-fuels results in emissions of CO_2 that would need to be counted under the Kyoto Protocol, the combustion of recently grown plant material is counted only if it results in a change in the standing stock of plant biomass. These two types of activities raises interesting, but different, challenges for conservation of biodiversity because the harvest of biomass fuels or biomass products has different land-use implications than does carbon sequestration.

Soil carbon sequestration and tillage

Both positive and negative effects of tillage on SOC stocks have been reported in the literature as reviewed in several recent studies summarized by Kätterer *et al.,* (2013a). In several reviews, the importance of crop production response to tillage operations has been emphasized. According to a recent meta analysis, annual C inputs to soil were the only factor that could significantly explain differences in soil C stocks between tillage systems (Virto *et al.,* 2012). Increases in SOC under no-till are likely to occur as long as C inputs are at least equal or greater than 85% of those in tilled systems (Ogle *et al.,* 2012), in a review of European data, it was shown that yields under no-till were, on average, 8.5% lower than those under conventional tillage, albeit results varied between countries and soil types (Van de Putte *et al.,* 2010). Under Scandinavian conditions, tillage effects on crop yields are small (Rasmussen, 1999).

Soil carbon sequestration in conservation agriculture

Conservation agricultural systems sequester carbon from the atmosphere into long-lived soil organic matter pools – while promoting a healthy environment and enhancing economically sustainable production conditions for farmers throughout the world. Soil organic carbon is fundamental to the development of soil quality and sustainable food production systems. Soil, soil organic carbon, and soil quality are the foundations of human inhabitation of our Earth. We must enhance the ability of soil to sustain our lives by improving soil organic carbon. Conservation agriculture systems have three guiding principles that can be globally applied: • Minimizing soil disturbance, consistent with sustainable production
• Maximizing soil surface cover by managing crops, pastures and crop residues
• Stimulating biological activity through crop rotations, cover crops and integrated nutrient and pest management. These three principles help to assure the positive balance between carbon inputs and carbon outputs.
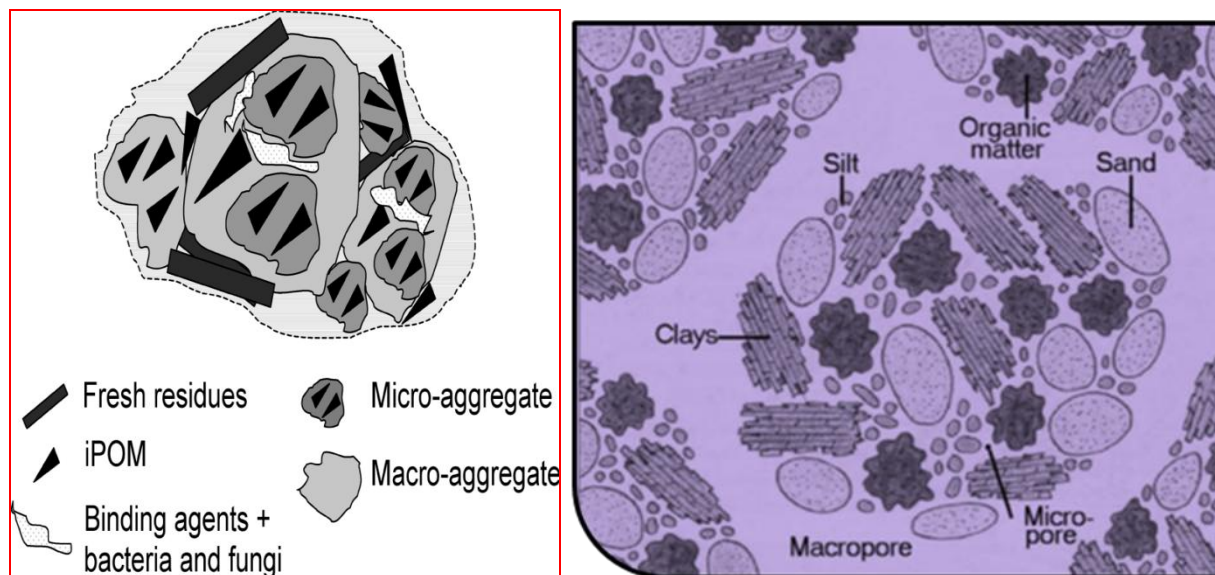
Table.1 Fractions of soil organic carbon

SOC material	Composition	Pool category
Surface plant residue	Plant material residing on the surface of the soil, including leaf litter and crop/ pasture material	Fast (or labile) pool Decomposition occurs at a timescale of days to years
Buried plant residue	Plant material greater than 2 mm in size residing within the soil	Fast (or labile) pool Decomposition occurs at a timescale of days to years
Particulate organic matter (POC)	Semi-decomposed organic material smaller than 2 mm and greater than 50 μm in size	Fast (or labile) pool Decomposition occurs at a timescale of days to year
'Humus'	Well decomposed organic material smaller than 50 μm in size that is associated with soil particles	Slow (or stable) pool Decomposition occurs at a timescale of years to decades
Resistant organic carbon (ROC)	Charcoal or charred materials that results from the burning of organic matter (resistant to biological decomposition)	Passive (or recalcitrant) pool Decomposition occurs at a timescale of decades to thousands of years

Table.2 Content of organic carbon and inorganic carbon content in world soil

Soils	Carbon pool to 1-m depth	
	Organic (tons/hac)	Inorganic (tons/hac)
Ultisols	101	0
Andisols	69	1
Aridisols	110	1044
Oxisols	150	0
Inceptisols	267	258
Alfisols	136	127
Mollisols	72	139
Vertisols	38	25
Spodosols	98	0
Entisols	106	117
Histosols	390	0
Miscellaneous	18	0
Total	1555	1738

Fig.1 General structure of soil aggregation

Carbon sequestration in forest

Land use change and forest management effects on biomass carbon stocks are relatively well known, but effects on soil C stocks are more scarcely reported and appear less consistent. Recent changes in agricultural policies and targeted afforestation programs have led to natural or planned afforestation of former grassland and cropland throughout Europe (Fuchs *et al.,* 2013). Several recent field-scale and meta-analysis studies have highlighted that rates of SOC sequestration following afforestation depends on previous land use, e.g. rates of SOC sequestration are higher in afforested cropland than in afforested grassland (Poeplau *et al.,* 2011). However, uncertainties are large, and little is known about temporal dynamics, the key processes and stability of sequestered SOC. A few recent studies have synthesized evidence regarding forest management effects on SOC (Lal, 2005; Jandl *et al.,* 2007), but generalizable quantitative information is limited for specific management issues. Some of these are e.g. change in tree species and species diversity, rotation length, management intensity, continuous cover

forestry, harvesting intensity and soil drainage. Current trends in forest management may support (reduced drainage) as well as compromise (*e.g.* whole-tree harvesting) SOC sequestration.

Carbon sequestration in cropland

The historic expansion of agricultural land has led to large soil organic carbon losses (Lal and Follett, 2009). The present net loss of C from tropical vegetation and soils caused by land use change is according to recent estimates 1.3 ± 0.7 Pg C yr^{-1}, which corresponds to approximately 17 % of the CO_2 emissions caused by fossil fuels and cement production (Pan *et al.,* 2011). As soil SOC stocks are generally higher in grassland and forest ecosystems, land use conversion into cropland results in most cases in a net increase of CO_2 emissions from soils (Poeplau *et al.,* 2011). Cropland management has been proposed as a cost-effective option for soil carbon sequestration (Freibauer *et al.,* 2004). Previous estimates of the sequestration potential in European soils (Freibauer *et al.,* 2004) were very optimistic. However, biological C sequestration is limited and its

finite and reversible effects with respect to climate mitigation have been documented (Paustian *et al.,* 1998; Andrén and Kätterer, 2001). Moreover, options where local and short-term accumulation of soil C rather than long-term C sequestration have been accounted are the major reason for too optimistic estimates. We emphasize that the term 'carbon sequestration' should only be used for options leading to additional retention of C in soils (Powlson *et al.,* 2008; Kätterer *et al.,* 2013a) by a net removal of C from the atmosphere through photosynthesis resulting in soil organic matter pools with long turnover times. However, changes in management practices that reduce CO_2 emissions from soils compared to the status quo will also contribute to mitigation even if this will not lead to a net C sequestration in soil.

Carbon sequestration in wetlands

Wetlands cover about 3% of the global land area, but contain 20–30% of the terrestrial stocks of soil organic carbon. It is highly important to protect these vulnerable stocks which are seriously threatened by drainage and climate change. In wetlands decomposition can be aerobic inside soils or at the sediment/water interface, but is anaerobic in deeper waterlogged zones or in the centre of particles under anaerobic condition electron acceptor other than O_2 are used for decomposition of organic compounds. Anaerobic oxidation is energetically less efficient than aerobic oxidation in the sense that more substrate is needed to provide the same amount of energy. However, because the C/N ratio of aerobic and anaerobic decomposers is similar, more N is mineralized under anaerobic than under aerobic conditions. Usually anaerobic conditions are associated with incomplete decomposition as in evidenced by poorly decomposed plant remains in peat. However,

Neue and Scharpenseel (1987) showed that decomposition of 14 c labeled straw in the tropics was as rapid in flooded, anaerobic, soils as in aerobic soils. Peat may play an important role in the net C exchange between the terrestrial biosphere and the atmosphere since the amount of C stored on an areal basis may be up to ten times larger than in other terrestrial ecosystems (Schlesinger, 1991). In addition peat often plays a major role in the C.

Carbon sequestration in grasslands

Different management practices on grassland/rangeland, involving internal nutrient cycling on farms, have been shown to result in fast increases in soil carbon and lower energy use of non-renewable sources. Climate change can pose a threat to carbon stocks in grassland/rangeland as higher temperatures lead to acceleration of decomposition of organic carbon in litter and soil and decreased soil moisture, resulting in loss of carbon and ecosystem degradation. Grasslands and savannas cover 20% of the earth's land surface (Lieth, 1975) and store 30% of global soil organic carbon Field *et al*, 1998. Grassland ecosystems managed for livestock production represent the largest land-use footprint globally, covering more than one-quarter of the world's land surface (Asner *et al*., 2004). Global estimates of the relative amounts of carbon in different vegetation types suggest that grasslands probably contribute >10% of the total biosphere store (Nosberger *et al.,* 2000). Plant diversity greatly influences carbon accumulation rates in grasslands. The presence of species with differing functional traits increases soil carbon and nitrogen accumulation (Fornara and Tilman, 2008). Carbon from plants enters the SOC pool in the form of either aboveground litter or root material. Greater carbon accumulation is associated with greater root biomass (*i.e.,*

greater carbon and nitrogen inputs in the soil) resulting from positive interactions among legumes and C4 grasses and the greater soil depths through which their roots are located at higher diversity (Fornara and Tilman, 2008) turnover in aquatic ecosystems.

Key research issues need to resolve

Developing low cost methods of accounting for soil carbon;

Quantifying net carbon sequestration under different management practices for different soil types, climates and agricultural systems;

Supporting existing long term cropping rotation trial sites and the establishment of new ones where appropriate; and

Soil carbon models need to be updated to account for locally relevant agricultural management practices.

In conclusion soil carbon sequestration and preservation of present stocks reduces net global greenhouse gas emission and can contribute significantly to both Nordic and international goals of limiting serious climate change. In order to achieve this, sustainable use of soil resources, better soil and water management practices, and restoration of degraded soils is needed. Protection and restoration of soil organic carbon are also key solutions to many of the most pressing global challenges facing mankind today. Highlighting the importance of the soil and the multiple benefits of soil organic carbon sequestration has never been more needed than now.

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