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Effect of Agricultural Land-use on Carbon Sequestration in Soils

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ABSTRACT: Carbon sequestration on agricultural lands is possible through a range of soil management strategies and could be substantial with widespread implementation. Sequestration of historic carbon emissions is now essential as mitigation alone is unlikely to stabilize our atmosphere. Land-use change, particularly the conversion of natural forest to agriculture to sustain the growing global population, has severe environmental impacts, including emission of greenhouse gases, diminished biodiversity, and altered soil functions. Contribution of GHGs to global warming is to an extent of 20% due to agricultural activities and 14% due to in land use changes and attendant deforestation. There are numerous management strategies for drawing carbon out of the atmosphere and holding it in the soil. These strategies vary in effectiveness across different climates, soil types, and geographies. There are still debates about the durability of sequestration in soil and about the precise conditions that maximize drawdown of carbon emissions. This paper explores how soil carbon is sequestered, the state of soil carbon research, and the debate on the extent of carbon sequestration by different land uses. It offers a set of recommendations for ongoing research and highlights the many co-benefits to increasing soil carbon.

Keywords: Carbon sequestration; Land use; soil organic carbon

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INTRODUCTION

An increase in the atmospheric concentration of carbon dioxide (CO_2) (from 280 parts per million (ppm) in the pre-industrial era to 390 ppm in 2010 and further 401.30 ppm in 2014) and other greenhouse gases (GHGs, such as nitrous oxide (N_2O) and methane (CH_4), may accentuate radiative forcing and alter the Earth's mean temperature and precipitation (NOAA, 2014). Because of this strong impact on radiative forcing, there is increasing emphasis on identifying strategies that will reduce the rate of enrichment of atmospheric CO_2 by offsetting anthropogenic emissions (Lal, 2012). The focus, therefore, is on sequestration of CO_2 from the atmosphere or point sources. Carbon sequestration can be defined as the capture and secure storage of carbon that would otherwise be emitted to or remain in the atmosphere (Gupta and Sharma, 2013).

Anthropogenic sources include the combustion of fossil fuel, cement manufacturing, deforestation and the burning of biomass, and land-use conversion including drainage of peatlands, soil tillage, animal husbandry, etc. Between 1750 and 2003, anthropogenic emissions were estimated at 292 Pg from the combustion of fossil fuels (Holdren, 2008), and at 136 ±30 Pg from land-use change, deforestation and soil cultivation (IPCC, 2001). Currently, approximately 8.3 Pg C yr^{-1} is emitted by fossil fuel combustion (IPCC, 2007) and 1.6 Pg C yr^{-1} by deforestation, land-use change and soil cultivation. The total for anthropogenic emissions is 9.9 Pg C yr^{-1}, of which 4.2 Pg C yr^{-1} is absorbed by the atmosphere and 2.3 Pg C yr^{-1} by the ocean. The remainder may be absorbed by unidentified terrestrial sinks.

Three strategies are available for lowering CO_2 emissions to mitigate climate change: (i) reducing global energy use; (ii) developing low or no-C fuel.

(iii) sequestering CO_2 from point sources or atmosphere using natural and engineering techniques (Schrag, 2007). The fact that carbon is stored for long periods of time in living biomass and soil is well documented extensively since 1992, although studies were carried out in this field since 1980. Several studies have established the fact that carbon sequestration by vegetation could provide relatively low cost net emission reductions.

The rate of future increase in atmospheric CO_2 concentration will depend on the anthropogenic activities, the interaction of biogeochemical and climate processes on the global C cycle and interaction among principal C pools. There are five global C pools, of which the largest oceanic pool is estimated at 38000 Pg and is increasing at the rate of 2.3 PgC yr^{-1}. The geological C pool, comprising fossil fuels, is estimated at 4130 Pg. The third largest pool is in the soil, pedologic and is estimated at 2500 Pg to 1 m depth. This pool has two distinct components: soil organic C (SOC) pool estimated at 1550 Pg and soil inorganic C (SIC) pool at 950 Pg (Batjes, 1996). The fourth largest pool is the atmospheric pool comprising ~800 Pg of CO_2-C, and is increasing at the rate of 4.2 Pg C yr^{-1}. The smallest among the global C pools is the biotic pool, which is estimated at 620 Pg, comprising 560 Pg of live biomass and 60 Pg of detritus material. The pedologic and biotic C pools together are called the terrestrial C pool estimated at approximately 3120 Pg. The terrestrial and atmospheric C pools strongly interact with one another through photosynthesis and respiration (Lal, 2012).

Terrestrial carbon fluxes account for more than half of the carbon transferred between the atmosphere and the earth's surface (about 120 Gigatons/year), and current stores of carbon in terrestrial ecosystem are estimated at 2060 Gigatons. Increasing attention is being focused on the role of managing and sequestering carbon in the terrestrial biosphere as a means for addressing global climate change (U.S. Department of Energy, 1999). Terrestrial ecosystems are widely recognized as a major biological scrubber for atmospheric CO_2 and their ability to function as such can be increased significantly over the next 25 years through careful manipulation. The potential for terrestrial carbon gains has been the subject of much attention (DeLucia *et al.*, 1999). Globally, it is estimated that terrestrial vegetation sequesters some 100 picograms (Pg) of atmospheric carbon annually for the production of organic matter through photosynthesis (Attuaand Laing, 2005). Strategies that focus on soil carbon are likely to be effective because in addition to being a storage pool of carbon, soil carbon also improves site productivity through improving soil quality (e.g., water retention and nutrient availability).

Much effort is currently focused on ways of reducing carbon dioxide contributions to the atmosphere going from researching the science to understanding the fundamental biological and ecological processes in unmanaged and managed terrestrial ecosystems, to the development of protocols and new policies to address this global environmental dilemma. Technical potential of soil carbon sequestration using recommended management practices include: Afforestration, conversion of arable to forest or grasslands, revegetation of degraded land, sustainable forest management, reduction or elimination of mechanical tillage and adoption of no-till (NT) or minimum till; use of crop residues or synthetic materials as surface mulch in conjunction with incorporation of cover crops into the rotation cycle; adoption of conservation-effective measures to minimize soil and water losses by surface runoff and accelerated erosion bioengineering; enhancement of soil fertility through integrated nutrient management (INM) that combines practices for improving organic matter management (in situ), enhancing soil biological processes, and additions of organic wastes (biosolids, slurry) and synthetic fertilizers; and increasing use efficiency through application of drip irrigation/fertigation techniques; and better use of complex farming systems including mixed crop-livestock and agroforestry techniques that efficiently use resources, enhance biodiversity and mimic the natural ecosystems (Lal, 2012).

A. Carbon Sequestration

Climate change is one of the most important challenges facing the modern world. Temperature increases have now been unequivocally proven and are occurring with an unprecedented rate (IPCC, 2001, 2007). Carbon dioxide (CO_2), methane (CH_4) and nitrous oxides (NO_x) are important drivers of the anthropogenic greenhouse effect, which are released both through burning of fossil and biomass fuel as well as decomposition of above and belowground organic matter.

International efforts aim at reducing avoidable greenhouse gas emissions or off-setting unavoidable emissions through sequestration of C in the environment. ‘Sequester’ is defined as ‘to hold on to’ or ‘to keep separate’ and is sometimes used when illegal financial assets are seized or ‘sequestered’ by the state and are thus unavailable for other uses.

In this dictionary sense, any increase in the C content of soil resulting from a change in land management might be referred to as sequestration, in that additional C is held on to in the soil and is separated from other parts of the ecosystem (Powlson *et al.*, 2011). Different strategies were discussed in literature, mentioning wide-spread afforestation and reforestation in terrestrial ecosystems (IPCC, 2000). For terrestrial ecosystems it has been proposed that C sequestration can be increased by increasing soil C stocks (Batjes, 1996; Izaurralde *et al.*, 2001). Such a proposal is sensible given the fact that more than 80% of the terrestrial organic C stores are contained in soils (IPCC, 2000). However, recent analysis urge caution, highlighting that efforts aimed to achieve C sequestration in soil are often off-set by other greenhouse gas emissions (Schlesinger, 1999) and that soils generally show low potential to accumulate C; for example, in conjunction with forest growth (Schlesinger, 1990; Post and Kwon, 2000). The consensus appears to be that soil represents a finite C sink at best and will only provide a window of opportunity for reducing C emissions or exploring other opportunities for C sequestration (Freibauer*et al.*, 2004; Lal, 2004) and that these C sinks may have a low permanency and can be easily depleted upon land use change.

B. The Global Carbon Cycle

There are five global C pools, of which the largest oceanic pool is estimated at 38000 Pg and is increasing at the rate of 2.3 Pg C yr^{-1} (Fig. 1). The geological C pool, comprising fossil fuels, is estimated at 4130 Pg, of which 85 percent is coal, 5.5 percent is oil and 3.3 percent is gas. Proven reserves of fossil fuel include 678 Pg of coal (3.2 Pg yr^{-1} of production), 146 Pg of oil (3.6 Pg yr^{-1} of production) and 98 Pg of natural gas (1.5 pg yr^{-1} of production) (Schrag, 2007). Currently, coal and oil each account for approximately 40 percent of global CO_2 emissions (Schrag, 2007). Thus, the fossil fuel pool is depleting as a result of fossil fuel combustion, at the rate of 8.3 Pg C yr^{-1}.The third largest pool is in the soil, pedologic and is estimated at 2500 Pg to 1 m depth. This pool has two distinct components: soil organic C (SOC) pool estimated at 1550 Pg and soil inorganic C (SIC) pool at 950 Pg (Batjes, 1996). The SOC pool includes highly active humus and relatively inert charcoal C. It comprises a mixture of: (i) plant and animal residues at various stages of decomposition; (ii) substances synthesized microbiologically and/or chemically from the breakdown products; and (iii) the bodies of live micro-organisms and small animals and their decomposing products (Schnitzer, 1991). On the basis of the mean residence time (MRT) of decomposition, the SOC pool can be grouped into three categories: labile with an MRT of days to years, intermediate with MRT of years to decades and centuries and passive with MRT of centuries to millennia. The SIC pool includes elemental C and carbonate minerals such as calcite, and dolomite, and comprises primary and secondary carbonates. The primary carbonates are derived from the weathering of parent material. In contrast, the secondary carbonates are formed by dissolution of CO_2 in soil air into dilute carbonic acid and its interaction with calcium (Ca^{+2}) and magnesium (Mg^{+2}) brought in from outside the local ecosystem (e.g. calcareous dust, irrigation water, fertilizers, manures). The SIC is an important constituent of soils in arid and semi-arid regions.

The fourth largest pool is the atmospheric pool comprising ~800 Pg of CO_2-C, and is increasing at the rate of 4.2 Pg C yr^{-1} or 0.54 percent yr^{-1}. The smallest among the global C pools is the biotic pool, which is estimated at 620 Pg, comprising 560 Pg of live biomass and 60 Pg of detritus material.

The pedologic and biotic C pools together are called the terrestrial C pool estimated at approximately 3120 Pg. The terrestrial and atmospheric C pools strongly interact with one another through photosynthesis and respiration. The annual rate of photosynthesis is 120 Pg C, most of which is returned to the atmosphere by plant and soil respiration. Conversion from natural to managed ecosystems, extractive farming practices based on low external input and soil degrading land use tend to deplete terrestrial C pools. The pedologic pool loses 1.1 Pg C into the atmosphere as a result of soil erosion and another 0.3-0.8 Pg C yr-1 to the ocean through erosion-induced transportation to aquatic ecosystems. Yet, the terrestrial sink is currently increasing at a net rate of 1.4 ± 0.7 Pg C yr-1. Thus, the terrestrial sink absorbs approximately 2-4 Pg C yr^{-1} and its sink capacity may increase to approximately 5 Pg C yr^{-1} by 2050 (Scholes and Noble, 2001). Increase in the terrestrial sink capacity may be the result of the CO_2 fertilization effect and changes in land use and management. The biotic pool also contributes to an increase in atmospheric CO_2 concentration through deforestation and land-use conversion at the rate of ~1.6 Pg C/yr.

The strong interactions between the atmospheric, pedologic and the biotic C pools comprise important components of the global carbon cycle (GCC). Understanding and managing these interactions form the basis of any strategy to sequester atmospheric CO_2 in the biotic and pedologic pools. This report describes the underlying processes and outlines land use and management options that would transfer atmospheric CO_2into the pedologic pool on a long-term basis.

The atmospheric pool is connected to the oceanic pool, which absorbs 92.3 Pg yr^{-1} and releases 90 Pgyr^{-1} with a net positive balance of 2.3 Pg C yr^{-1}. The oceanic pool will absorb approximately 5 Pg C^{-1} yr^{-1} by2100. The total dissolved inorganic C in the oceans is approximately 59 times that of the atmospheric pool. On the scales of millennia, the oceans determine the atmospheric CO_2 concentration, not vice versa (Falkowski *et al.,* 2000).

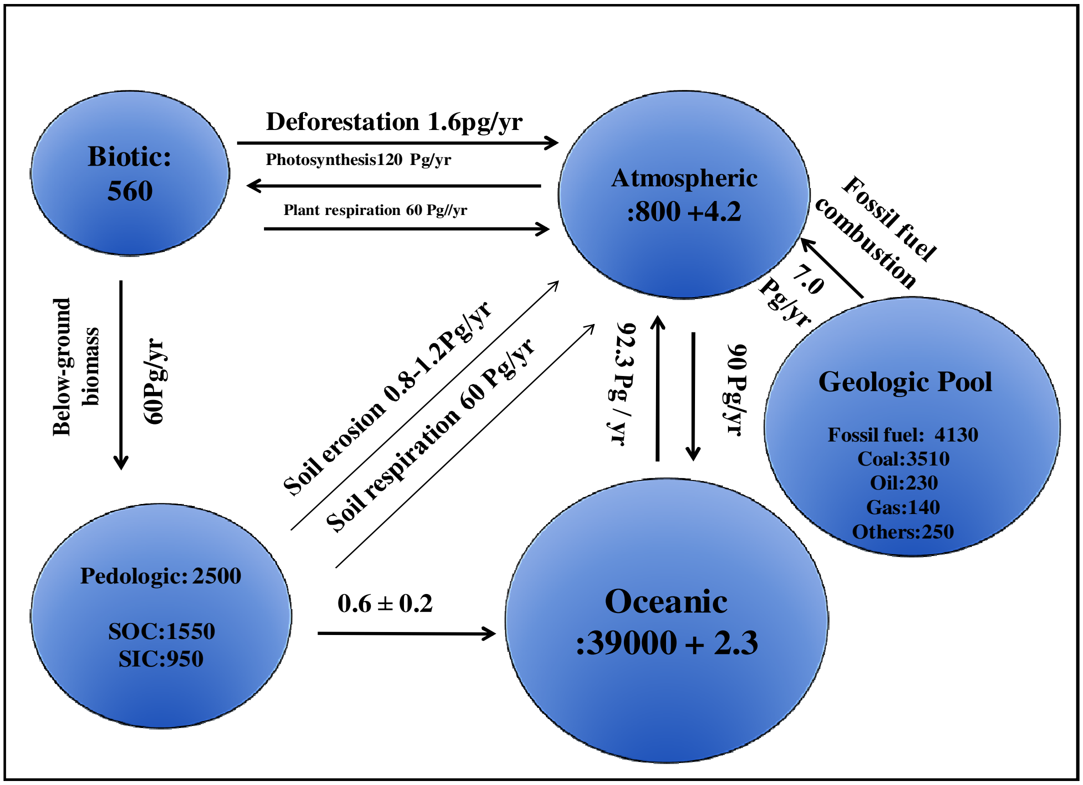

Fig. 1. Principal global C pools and fluxes between them.

C. Soil carbon pool

It is a major component of the global carbon cycle. It significantly impacts:

(i) The atmospheric composition of radiatively active gases (e.g., CO_2, CH_4, N_2O),

(ii) Elemental cycling,

(iii) Purification of water by denaturing and filtering pollutants,

(iv) Soil quality and net primary productivity, and

(v) Activity and species diversity of soil flora and fauna.

Among the numerous ecosystem services that it provides, its influence on the atmospheric chemistry with the attendant effect on radiative forcing has received considerable attention from soil scientists, ecologists, climatologists, economists and policy makers. Historically, the soil C pool has been a major source of atmospheric abundance of CO_2, contributing as much as 78 ± 12 Pg of C, and likely more. Such a transfer of soil C to the atmospheric pool has created a C deficit in world soils, the so-called "C sink." Consequently, world soils now contain a lower C pool than their potential capacity under specific climatic, terrain, and landscape characteristics. This C sink capacity can be filled by conversion to a restorative land use (e.g., reforestation, perennial vegetation cover) and adoption of recommended management practices that create positive C and nutrient budgets and favorable soil temperate and moisture regimes. The process of transfer of atmospheric CO_2 into the soil C pool, either through humification of photosynthetic biomass or formation of secondary carbonates, is termed soil C sequestration.

Soil carbon pool consists of soil organic pool and soil inorganic pool. Soil organic carbon (SOC) is a great component of the global carbon budget and is important to agricultural productivity (Lal, 2004). It is estimated that around 2500 Pg carbon (C) is stored in soils globally, which means that the soil C pool is about 3 times the size of the atmospheric C pool and 4 times the biotic C pool (Batjes, 1996; Lal, 2004).

Of the soil C pool, over 60% is SOC that is sensitive to both macroscale environmental conditions and microscale soil conditions, and 40% is soil inorganic carbon, which can be relatively resistant to environmental changes. SOC, in this sense, is a key component in determining the carbon budget. Also, SOC is an important indicator for soil fertility and soil quality, acting as an active sink and source reservoir for plant nutrients, improving soil microenvironments through physical, chemical, and biological processes, and thus determining ecosystem productivity (Six *et al.*, 2002; Bronick and Lal, 2005).

Global soils could have a C sequestration potential of 0.4–0.8 Pg C yr^{-1} (Lal, 2004). It has long been assumed that SOC level is positively related with C input level in a linear relationship, and most SOC models employ first-order kinetics to model decomposition processes; however, recent studies found little or no SOC change observed in response to varying C input in a number of long-term agroecosystem experiments, and, to the contrary, a ceiling on the capacity of SOC content was observed, which limits increases in SOC, even with additional C inputs (Stewart *et al.*, 2007: Gulde *et al.*, 2008). After tens or even hundreds of years of field experiments (Fig. 2), studies in Africa (Kamoni *et al.*, 2007), Asia (Manna *et al.*, 2007; Yang *et al.*, 2007), Australia (Coleman *et al.*, 1997; Smith *et al.*, 1997), Europe (Schmidt *et al.*, 2000), North America (Izaurralde *et al.*, 2001), and South America (Bayer *et al.*, 2006) show that soil can accumulate a significant amount of C when the preexisting SOC is still at a low level, and therefore, SOC at steady state increases with C inputs; however, after SOC content reaches a certain level, it shows little or no significant change, even with more C inputs. It is believed that soil at the final SOC stable state reaches its “carbon saturation” state, and the SOC achieves the SOC saturation level (Six *et al.*, 2002; Stewart *et al.*, 2007). Based on long-term field experiment observations, Stewart *et al* (2007) proposed nonlinear carbon saturation models against the linear model to test the SOC-C input relationship. Results suggest that the saturation of soil C does occur, and the highest efficiency of C fixation is in soils further from C saturation (Stewart *et al.*, 2007).

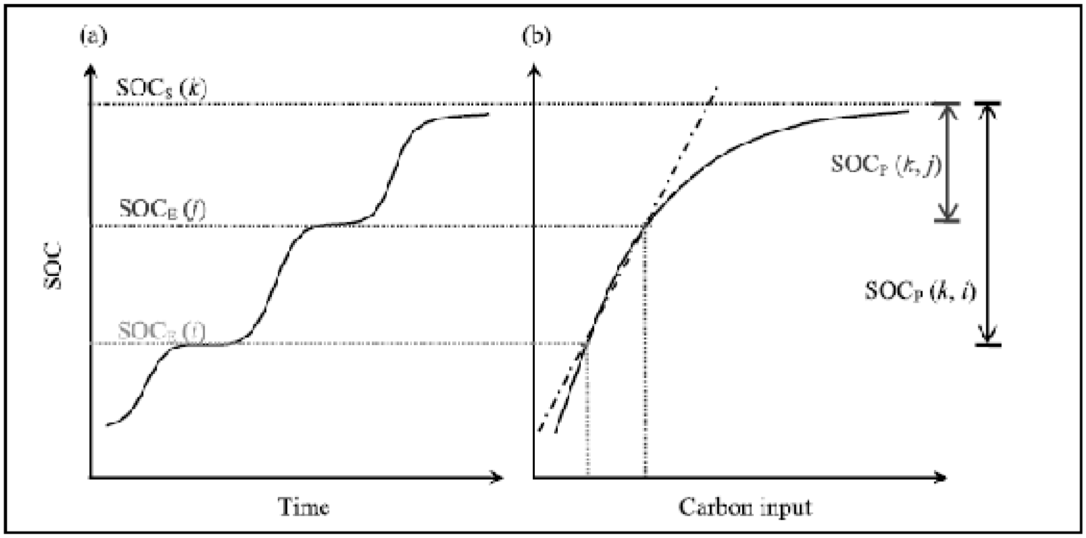

Fig. 2. SOC dynamics following (a) time and (b) carbon input. SOC density at the steady state varies with carbon input level. SOC sequestration potential (SOCP) is the difference between existing SOC at the steady state [e.g., SOCE (i) or SOCE (j)] and saturated SOC [e.g., SOCS (k)].

In the case that SOC level will reach its ceiling or saturation level, whether in the short or long term, soil carbon sequestration potential could be used to assess the carbon holding capacity in soil. Soil carbon sequestration potential measures the difference between the theoretical SOC saturation level and the existing SOC level and corresponds to the soil saturation deficit (Stewart *et al.*, 2007). Soil carbon sequestration potential may represent the potential for an additional transfer of C from the atmosphere (Powlson *et al.*, 2011).

The rate of soil C sequestration ranges from about 100 to 1000 kg ha^{-1} yr^{-1} for soil organic C and 5 to 15 kg ha^{-1} yr^{-1} for soil inorganic C, depending on land use, soil properties, landscape position, climate, and cropping/farming systems. Total global C sink capacity, approximately equal to the historic C loss of 78 ± 12 Pg, can be filled at the potential maximum rate of about 1 Pg C yr^{-1}. The attainable and actual cumulative global rate of soil C sequestration may be lower because of managerial, economic, and policy constraints.

D. Soil carbon in different ecosystems

Globally, soils contain 3258 Pg of organic carbon, with wetland soils holding 513 Pg (16%) of that total (Fig. 1) (Pg = petagram = 1015 g = a million billion grams). The relatively high contribution of wetlands to the total soil organic carbon pool is remarkable since wetlands cover only ~4% of Earth's land surface (Fig. 3). Forests and grasslands hold the largest store of soil carbon (1104 Pg and 641pg, respectively). The patterns of soil organic carbon storage and global area are reflected in the carbon density of each ecosystem type (that is, how much carbon is stored in a defined area). Wetlands have the greatest carbon density of any ecosystem type at 860 Mg ha^{-1} (Fig. 3) (Mg = megagram = 106 g = a million grams; ha = hectare = 10,000 m^2). Forests and grass/ shrub lands contain the most soil carbon on a global basis, but the carbon density in wetlands is ~three times greater than that in forests (265 Mg ha^{-1}) and ~six times greater than that in grasslands/shrub lands (141 Mg ha^{-1}) (Neubauer, 2013).

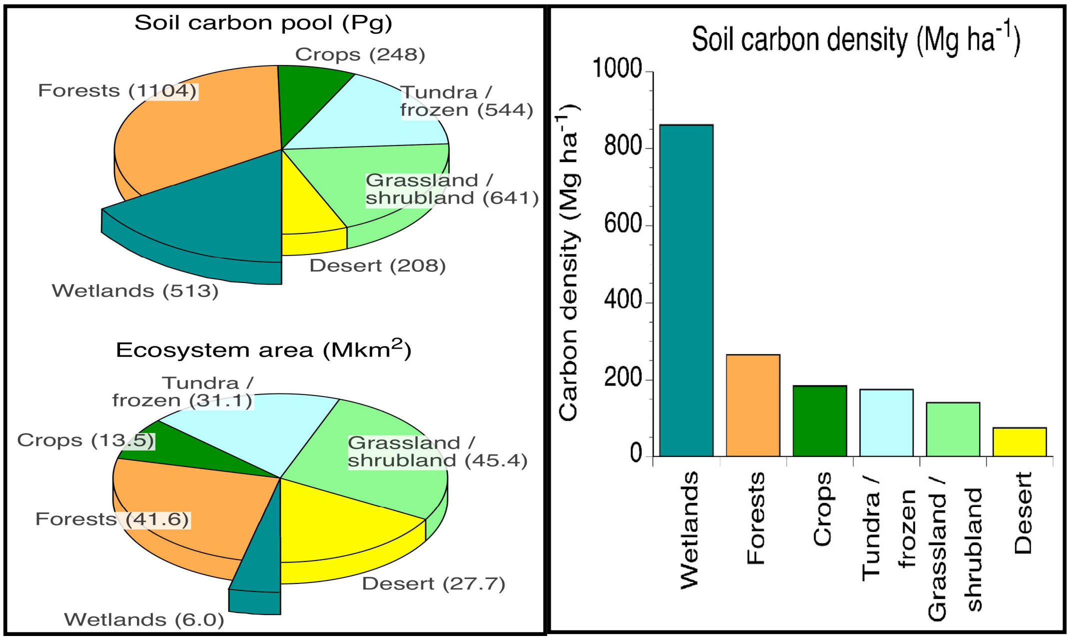

Fig. 3. Carbon storage, global area and soil carbon density under different ecosystems.

E. Terrestrial carbon sequestration

Carbon is an essential part of life on Earth. It plays an important role in the structure, biochemistry, and nutrition of all living cells. All living tissues have carbon atoms in their composition and the cycle of this element is basically the cycle of life in our planet. The carbon cycle involves the soil and all vegetation and animal life on earth. Plants absorb carbon dioxide from the atmosphere and through photosynthesis, capture the carbon molecules for energy and build up of structural components. Part of this carbon returns to the atmosphere soon after being processed through respiration. Other parts stay as standing biomass for some time, returning to the cycle as organisms die and decompose. Some of the standing biomass will eventually be eaten by animals, with half of it exhaled immediately, the other returned as bodily wastes to the soil later in time. Once in the soil, microorganisms metabolized them, gradually returning them to the atmosphere, or leaching out as carbonates through the soil.

The Intergovernmental Panel on Climate Change (2000) is consistent with this prescription, defining carbon sequestration as an increase in carbon stocks anywhere but not in the atmosphere. Terrestrial carbon sequestration involves the photosynthetic fixation of atmospheric CO_2 by plants (e.g., trees, food crops, grasses, etc.) and the long-term accumulation and storage of both standing and below-ground biomass (Fig. 4). Rates of terrestrial carbon sequestration can be increased by reforestation and afforestation and by changing soil management practices (i.e., reduced or no till agriculture) to promote the formation and retention of soil organic matter (Paustian *et al.*, 1998). The terrestrial biosphere currently stores approximately 2000 Gt of carbon (600 Gt in plant biomass and 1400 Gt in soil humus) which compares to an estimated 4000 Gt of carbon deposited in fossil fuel reservoirs (Gruebler *et al.*, 1993).

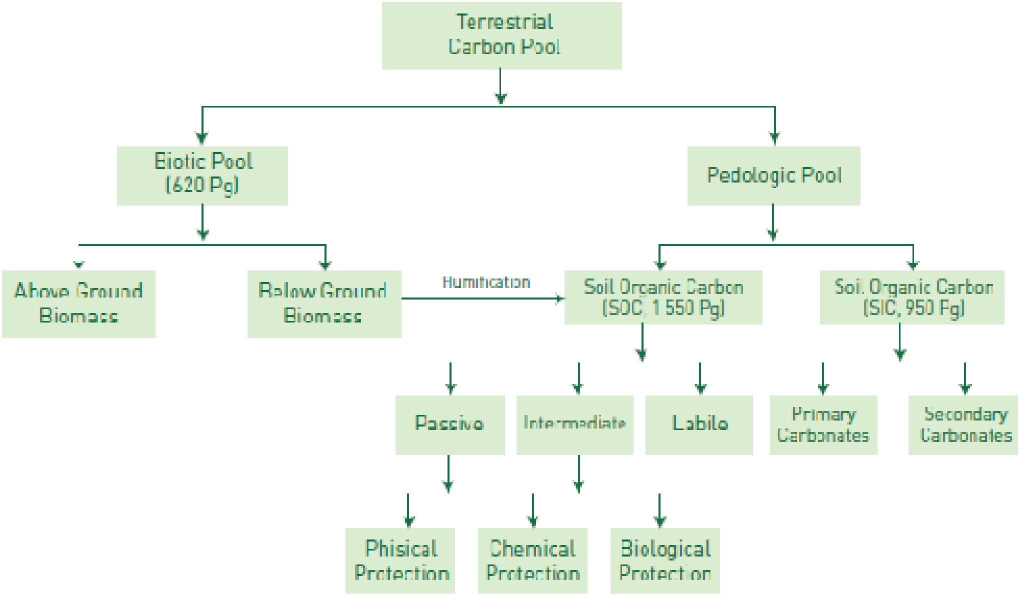

Fig. 4. Terrestrial carbon sequestration.

Thus, to store all additional carbon (4000 Gt) that is expected to be released from the burning of the remaining fossil fuel resources in green plants would require a tripling of terrestrial biomass from the current 2000 Gt to 6000 Gt–a proposition which is almost certainly technically impossible. A more realistic possibility is to reverse the long-term trend of terrestrial carbon loss by reforestation and improved farming practices with the goal of restoring the terrestrial carbon pool to its pre-1750 size. Approximately 200 Gt carbons have been lost during the last 250 years as a result of land use changes, primarily through conversion of forests to farmland (Scholes and Noble, 2001). This is the maximum amount of carbon that can be realistically expected to be sequestered in the terrestrial biosphere via massive restoration efforts (*Note*: This is only 5% of all fossil carbon deposited in reservoirs or ca. 10–20% of predicted cumulative carbon emissions by 2100). Even if all this previously lost carbon could be returned to terrestrial eco-systems during the next 100 years, it would reduce atmospheric CO_2 concentrations by only 40–70 ppm (IPCC, 2001; Scholes and Noble, 2001), indicating that even under the best conditions, terrestrial carbon sequestration would only be able to make a minor contribution to the mitigation of climate change. Indeed, it will be a major challenge to even partially “refill” the depleted terrestrial carbon sinks via reforestation and better agricultural soil management practices. Consider, for example, that approximately 1162 million ha of forests have been cleared worldwide in the last 200 years (Gruebler *et al*., 1993), an area larger than the United States (i.e., 962 million ha). Thus, a massive reforestation effort would have to be initiated to restore forest biomass to its pre-1800 levels – a proposition which is particularly challenging given that deforestation has not halted but is currently proceeding globally at a rate of 9 million ha per year (Topfer, 2001; Williams, 2003).

Consequently, terrestrial carbon sequestration can at best be seen as a way to slow the rise of CO_2 emissions (i.e., by ca. 2 Gt per year) for a limited time (50–100 years) until all carbon sinks are filled, thereby “buying” time to develop other sequestration technologies or make the transition to a zero carbon economy. The global potential of soil C sequestration is 0.6 to 1.2 Pg C/yr which can off-set about 15% of the fossil fuel emissions (Lal, 2007).

Terrestrial carbon sequestration is not only of interest in those countries which have an obligation to reduce greenhouse gas emission under the Kyoto Protocol. Contemporary rational for its policy making includes that it

(i) Offers cost effective solutions for limiting Greenhouse Gases (GHG) concentration in the atmosphere for countries while enhancing their natural capital;
(ii) Enhances cooperation for knowledge and technology transfer amongst states;
(iii) Provides opportunities in developing countries (over US$30 billion/year); and
(iv) Has potential for rural poverty reduction.

F. Global SOC sequestration potential

Worldwide, clearing and subsequent management practices on agricultural land have resulted in significant loss of soil carbon. Globally this has been estimated to be 78±12 Gt C (this is equivalent to 29 % of total CO_2-C emission due to fossil fuel combustion of 270± 30 Gt (Lal, 2007). All the evidence points to substantial potential of SOC sequestration to mitigate climate change. Overall this potential contribution is equivalent to 5-14% of total annual GHG emissions and is expected to last for the next 50-100 years.

Furthermore, according to the latest IPCC estimates, soil carbon sequestration globally can contribute to 89% of the total technical mitigation potential for agriculture whereas mitigation of soil CH_4 and N_2O emissions account for only 9% and 2% respectively (Smith *et al.,* 2007). This further indicates significant role that SOC sequestration can play in mitigating climate change. Globally around 90% of the technical GHG mitigation potential from agriculture will arise from improved management of crop lands, grazing lands, organic soils and degraded soils. Further small contributions can be made from (in order of significance) improved management of rice, livestock, bioenergy crops, irrigation water, land use change, agroforestry and manure management (Smith *et al.,* 2008). Approximately 50% of the technical GHG mitigation potential from agriculture occurs in Asia and South America.

CONCLUSION

Since the industrial revolution, CO_2 concentrations in the atmosphere have increased from 290 parts per million (ppm) by volume to greater than 400 ppm and continue to rise and may exceed 500 ppm by 2050 (IPCC, 2001). Currently, human activity is directly or indirectly responsible for the release of six to seven billion metric tons of carbon annually. Adoption of proper and planned measures can help in its mitigation. With proper land-use and management practices, agricultural soils can sequester a good amount of CO_2 as SOC. Important land uses and practices with the potential to sequester SOC include conversion of cropland to pastoral and forest lands, conventional tillage to conservation and no tillage, no manure use to regular addition of manure, and to soil specific fertilization rate. Addition of fertilizers on a regular basis for many years often leads to increase in SOC content. Addition of N fertilizer increased the SOC level by increasing net primary productivity and residue input. Inclusion of rotation and growing cover crops increased the SOC in crop rotation either through change from monoculture to rotation or by increasing the number of crops in rotation and it was associated with increase in C concentration. Intensive cultivation is a viable strategy for biotic C sequestration in agricultural soils. Choosing species with deep root system is desirable for increasing C inputs. Agro-forestry, growing of multi-purpose trees along with agricultural crops, is one of the best option to increase carbon sequestration. Land-use change has great potential to sequester carbon. Change from cropland to forest or grassland has been estimated to have a high global sequestration rate.

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