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SOILS IN THE NEXUS

A Crucial Resource for Water, Energy and Food Security

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World Soils and the Carbon Cycle in Relation to Climate Change and Food Security

Abstract

World soils constitute the largest terrestrial reserve of carbon (C). Estimated at 4,000 petagram (billion metric ton) to 3-meter depth, it plays a major role in the global C cycle and is closely linked with the atmospheric (790 petagram) and the biotic (620 petagram) pools. Two types of C are: soil organic C (SOC) and soil inorganic. The SOC pool and its composition are important parameters governing soil quality and provisions of numerous ecosystem services. The SOC pool of world soils, and especially those under agroecosystems, are vulnerable to degradation, and has been depleted by historic land use. The magnitude of historic depletion is estimated at 50 to 100 petagram. Agroecosystems with SOC pool below the critical level (1.5 percent to 2 percent) in the root zone have low use efficiency of inputs and below average productivity. Therefore, C sequestration in degraded/depleted soils can improve soil quality, enhance soil resilience to natural and anthropogenic perturbations, and adapt to and mitigate the abrupt climate change. The technical potential of C sequestration in world cropland soils is 0.4–1.2 petagram C/year for about 50 years. Despite its potential and numerous ancillary benefits (e.g., food security, water quality, biodiversity), there are several challenges that need to be addressed. Important among these are: finite sink capacity, transient nature, and the need for credible assessment of the flux over short period of one to two years. Nonetheless, it is a win-win option and an essential strategy to restoring degraded soils, advancing food security and improving the environment. It is a bridge to the future until alternates to fossil fuel take effect.

1 Introduction

The world is in transition (WBGU, 2011), and environmental issues are a serious concern (OECD, 2012). There is a strong interest in identifying natural sinks of atmospheric carbon dioxide (CO_2) and other greenhouse gases (GHGs) because a decisive action is needed to minimize the risks of abrupt climate change (ACC). Constraining the carbon

(C) cycle is also important to understanding the climatic processes at a range of spatial scales. Land use conversion and agricultural activities produce about 30 percent of total anthropogenic emissions both directly and indirectly (hidden carbon costs). Therefore, conversion to a restorative land use and adoption of best management practices (BMPs) must be integral to any strategy of mitigating ACC. The strategy is to minimize losses, and create a positive ecosystem C budget by enhancing the C pools in biomass and soil. Indeed, soil C sequestration is a feasible strategy with near-term (by 2100–2150) potential of sequestering 50–100 petagram (billion metric ton) C, with a significant drawdown of atmospheric CO_2 concentration (Hansen et al., 2008).

Rather than being a sink of GHGs, soils of agroecosystems and other biomes have been and can become even major sources if the ACC is not mitigated. Further, ACC can thaw the permafrost (Cryosols/Gelisols), and may create a major positive feedback releasing C and nitrogen (N). Thawing of permafrost could release up to 436 petagram C and 29 petagram N into the atmosphere, water and high latitude ecosystems by 2100 (Harden et al., 2012). Similarly, methane hydrate, stable at low temperatures and high pressures, may be destabilized by ocean warming at both human and geological time scales (Marshull et al., 2012). Oceanic uptake of atmospheric CO_2 may decrease with acidification of water. The average pH in surface water of 8.1 may decrease to 7.8 by 2100 (Malakoff 2012). Ocean acidity has increased by 30 percent since the Industrial Revolution circa 1750. Over and above the effects of increase in temperature, extreme events such as multi-year drought can adversely impact both soil and the biotic C pools. The terrestrial C pools in primary sectors of agriculture and forestry, especially in Europe, are vulnerable to the temperature increase by the enhanced greenhouse effect leading to drought and wildfires (Maracchi et al., 2005), such as the one experienced in the USA in 2012 (Lal et al., 2012a, b). Caesar and Lowe (2012) show that countries across the globe would experience hotter days and an increasing number of heat waves, even with aggressive mitigation strategies. Several regions of Sub-Saharan Africa (SSA) are projected to become increasingly prone to severe drought (Rojas et al., 2011). Droughts, as in Russia in 2010 (and USA in 2012), are linked to the ongoing long-term changes in the climatic settings (Loboda, 2012). Similar adverse effects of large reductions in agronomic productivity due to ACC are expected in the temperate agriculture of North America (Motha and Baier, 2005). The ACC in conjunction with extreme events can also exacerbate risks of accelerated soil erosion (Lal, 2003). Gonzalez-Hidalgo et al., (2012) observed that soil erosion is a time compressed process and its magnitude depends on the total number of daily erosive events rather than on the number of years. Nonetheless, processes making erosion a source or sink of atmospheric CO_2 need to be understood at the watershed scale to resolve controversial issues (Lal, 2003; Van Oost et al., 2007, 2012; Van Hemelryck et al., 2010).

The objective of this article is to describe the nexus between the world soils in relation to the global C cycle (GCC), ACC and food security.

2 World Soils and the Global Carbon Cycle

Soil is a four-dimensional body (length, width, depth, time) formed at the interface between the atmosphere and the lithosphere and is a crucial part of the earth's critical zone. Soils are formed by the chemical, physical and biological weathering of the lithosphere over millennial time scale. Progressive colonization of the weathered rock enhances soil organic carbon (SOC) concentration (Taylor et al., 2009), which improves quality of the soil and is the basis of microbial processes. The concentration of SOC increases over time and reaches the maximum capacity determined by the parent material, soil properties, climate, landscape position and slope aspect. The SOC concentration is higher in soils of cool and humid climates than those in warm and dry biomes (Table 1).

Biome	Area (10^6ha)	Mean Soil C Content (megagram/ha)
Tundra	880	218
Boreal desert	200	102
Cool desert	420	99
Warm desert	1400	14
Tropical desert bush	120	20
Cool temperate steppe	900	133
Temperate thonne steppe	390	76
Tropical woodland and savanna	2400	54
Boreal forest, moist	420	116
Boreal forest, wet	690	193
Temperate forest, cool	340	127
Temperate forest, warm	860	71
Temperate forest, very dry	360	61
Tropical forest, dry	240	99
Tropical forest, moist	530	114
Tropical forest, wet	410	191

Table 1: Estimate of the soil carbon pool in different biomes (Adapted from Amundson, 2001).

Cryosols/Gelisols and related peat soils have a high SOC pool because temperature and moisture regimes are the principal determinants of SOC dynamics (Batjes, 2011). World soils contain SOC pool estimated at ~1,500 petagram to 1-meter depth (Batjes, 1996) and 2,344 petagram to 2-meter depth (Jobbágy and Jackson, 2000). Soil inorganic carbon (SIC) pool is estimated at 720 petagram to 1-meter depth (Batjes, 1996) and 950 petagram to 2-meter depth. It is widely argued that the SOC pool is grossly underestimated, because of measurements to shallow depths and inaccurate assessment of C pool in peat soils (Jungkunst et al., 2012). Cryosols and peat soils may contain as much as 1,500 petagram C, which is equivalent to the present pool of world soils to 1-meter depth (Batjes, 1996). Thus, the total soil C pool may exceed 4,000 petagram to 3-meter depth. There is a strong need to improve estimates of the global soil C pool (Milne et al., 2010, Schmidt et al., 2011). In comparison, the biotic C pool comprises of 620 petagram, of which 60 petagram represents the detritus material, and the atmospheric C pool of about 790 petagram (WMO, 2011). The latter is increasing at the annual rate of about 2.3 parts per million by volume or 3.3 petagram C (WMO, 2011). Principal sources of atmospheric emission of CO_2-C are fossil fuel combustion (~10 petagram C/year) and land use conversion (~1.3 ± 0.4 petagram C/year) (LeQuéré et al., 2009) (Figure 1).

Being the largest terrestrial pool, world soils play an important role in the GCC. Indeed the terrestrial biosphere has been a major source of emission of CO_2 and other GHGs since the pre-historic times (Ruddiman, 2003). Over and above the historic loss of 320 petagram C, additional loss since 1750 is estimated at about 156 petagram (Figure 1). Conversion of natural to agroecosystems leads to depletion of the SOC pool because of a multitude of interacting factors including lower input of biomass C, higher rate of decomposition caused by alterations in soil moisture and temperature regimes, and vulnerability of soils under agroecosystems to accelerated erosion and other degradation processes. Vulnerability to decomposition and depletion of SOC is affected by complex factors that are not clearly understood (Tuomi et al., 2008; Conant et al., 2011; Falloon et al., 2011). Drainage and cultivation of peatland is a major global source of anthropogenic emissions (Joosten, 2009). Therefore, soils of agroecosystems are presently sources of major GHGs (Janzen, 2005; Powlson et al., 2011). The magnitude of emission from soils may increase with expansion of agriculture into ecologically sensitive ecoregions such as tropical savannas (Noellemeyer et al., 2008), rainforests (Cerri et al., 2007), and peatlands (Jungkunst et al., 2012; Couwenberg, 2011) and especially tropical peatlands (Jauhiainen et al., 2011). Thus, soils under agroecosystems have a C sink capacity with reference to the baseline of SOC pool under natural ecosystems. The latter, equivalent to the historic SOC depletion by 25 to 75 percent (Lal, 2004b), may be as much as 30 to 50 megagram C/hectare or 50 to 100 petagram C globally. The magnitude of historic loss, and thus the SOC sink capacity, is relatively high for soils of degraded and desertified ecosystems and those that have been used over a longtime for extractive farming practices. Therefore, recarbonization of the soils and the biosphere (Lal et al., 2012a, b) is an important strategy to mitigate the ACC.

The gross primary productivity (GPP) is estimated at 123 petagram/year, of which 60 petagram is respired by plants and leaving net primary productivity (NPP) of 63 petagram/year. Accounting for the heterotrophic metabolism, the net ecosystem productivity (NEP) is about 10 petagram C/year. A large proportion of NEP is lost because of landuse, fire and other perturbations. The net biome productivity (NBP) is estimated at 0.3 to 5.0 petagram with an average value of about 3 petagram/year (Jansson et al., 2010).

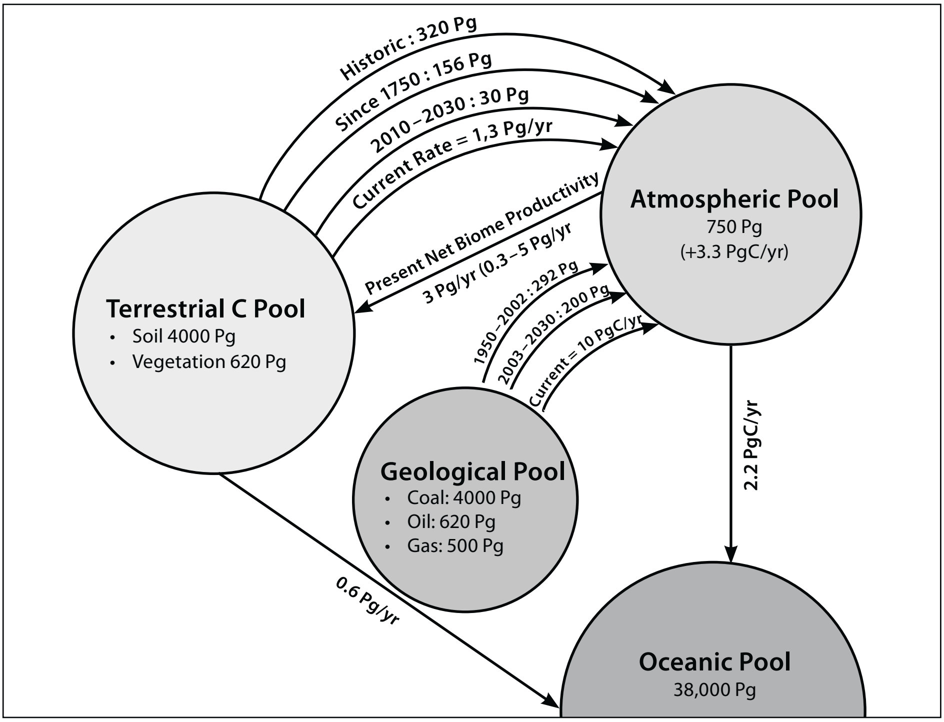

Figure 1: Principal components of the global carbon cycle (Data cited in this diagram are from Ruddiman, 2003; Holdren, 2008; Jansson et al., 2010; Lal, 2004b; WMO 2011; LeQuéré et al., 2009).

Therefore, managing the biosphere and enhancing the NBP could be an important option to offset anthropogenic emissions. It is argued that if we control what plants do with C and can restore the pool in the terrestrial biosphere, the fate of CO_2 in the atmosphere is in our hands (Dyson, 2008).

3 Climate Change and Global Food Security

Settled or the intentional agriculture ten to twelve millennia ago was the defining moment in human history. Domestication of plants and animals began independently at numerous sites. Two among other factors responsible for origin of agriculture were (1) increase in global temperature, and (2) increase in atmospheric concentration of CO_2 from 180 to 280 parts per million by volume. Along with the increase in mean global temperature by as much as 5°Celsius, the increase in atmospheric CO_2 concentration enhanced biomass production of C_3 plants (wheat, barley) dramatically and that of C_4 plants (corn) moderately. Another impact was the increase in biological nitrogen fixation (BNF) by legumes, which enhanced soil fertility. With progressive developments in agriculture, both the human population and the ones under agricultural land use (cropland and grazing land) increased. For example, the agricultural land area in 1 AD corresponding with a human population of 188 million was 240 million hectare. The agricultural area increased to 930 million hectare for population of about one billion in 1800, and to 4,738 million hectare for population of seven billion in 2010.

Challenges to achieving food security for projected population of 9.2 billion by 2050 include land degradation already estimated at 3,500 million hectare (23.5 percent of Earth's land area) (Bai et al., 2008) and affecting an additional 5 to 10 million hectare/year, urbanization needing 3 million hectare/year of agricultural land, land area needed for establishing biofuel plantations, and mitigating the climate change. While food grain production must be increased 70 percent by 2050, it is also widely believed that 1°Celsius increase in mean temperature can reduce global grain yield by 10 to 17 percent. Thus, additional land area would be needed to meet the food demands of increasing affluent population with growing preference towards animal-based diets. The latter may also contribute to an increase in GHG emissions.

Changing and uncertain climate affects food security in numerous ways: direct and indirect; and positive and negative. However, in some site-specific cases ACC may also enhance agronomic/food production. Over and above the positive effects of prolonging the growing season in higher latitudes, some geoengineering techniques that reflect sunlight may enhance crop performance through the CO_2 fertilization effects (Pongratz et al., 2012). For example, despite the adverse impact of climate change, rice productivity in SSA increased by 9.5 percent/year between 2007 and 2011 (Seck et al., 2012), compared to merely 1.6 percent/year in Asia. Thus, filling the yield gap, as has been done with rice in SSA, is a high priority to increasing global food production. Air quality, concentration of trace gases and dust/particulate materials, affect productivity through their effects on plant growth and also by changing precipitation, temperature and the growing season. Air pollutants (e. g., heavy metals and trace gases) affect plant growth directly and through their impact on abiotic and biotic stresses (Bender and Weigel, 2011). Climate-induced alterations in available water resources, alternate drought and floods as extreme events, and insufficient supply of water for crop growth are among major threats to advancing the global food security (Rockström et al., 2012; O'Neill and Dobrowolski, 2011), especially in the developing countries (Wheeler and Kay, 2010). Rapid melting of glaciers in the Arctic is decreasing seasonal rates of precipitation, increasing evapotranspiration, and drying lakes and rivers existing in the permafrost region (Evengard et al., 2011). Widespread fear of food insecurity has accelerated the problem of land grab in SSA, but also in Latin America and the Caribbean (Borras et al., 2012).

The present and projected climate change is affecting food security globally, but especially in regions with scarce resources and large population (Table 2). Important among

Country/Region	Crop	Climatic Factor	Time Period	Reference
China	Winter wheat	Drought in winter wheat	Near future (10–30 years)	Song and Zhao (2012)
Russia/Ukraine/ Kazakhstan	Wheat	Climate variability	Next decades	Lioubimtseva and Henebry (2012)
Africa	Rice	Coping with climate change	By 2035	Seck et al. (2012)
South Asia	Dryland crops	Managing water and SNRM	Next decades	Venkateswarlu and Shanker (2012)
Mexico	Maize	Drying and warming trends (Highlands)	Near future	Shiferaw et al. (2011)
South Asia	Lentil	Drought stress	2010–2050	Erskine et al. (2011)
West Africa	Rainfed crops	Drought, warming	Near future effects: – Sudano-Sahelian = –18 % – Guinean Zone = –13 % – Overall = –11 %	Roudier et al. (2011)
Sub-Saharan Africa	Food crops	Drought and temperature	Near future effects: – Maize = –22 % – Sorghum = –17 % – Millet = –17 % – Groundnut = –18 % – Cassave = –8 %	Schlenker and Lobell (2010)

Table 2: Examples of regions and crops prone to food insecurity aggravated by the changing climate.

these are biomes/ecoregions with predominantly small landholders and resource-poor farmers (Altieri et al., 2012). The overall effect of climate change in West Africa shows a yield decline of –11 percent to –15 percent, with –18 percent in northern West Africa, –13 percent in southern West Africa, and –15 percent in regions with intense warming (Roudier et al., 2011). Globally, major food crops vulnerable to climate change include wheat (Asseng et al., 2011; Song and Zhao, 2012; Lioubimtseva and Henebry, 2012), rice (Seck et al., 2012), maize (Shiferaw et al., 2011; Bellon et al., 2011), lentils and others (Table 2). It is estimated that an additional 116 million megagram of rice will be needed by 2035 to feed the growing population (Seck et al., 2012). In SSA, on the contrary, 30 million megagram more rice will be needed by 2035 – an increase of 130 percent, and about one-third of this extra need is for Nigeria. Globally, rice production will have to be increased by 1.2 percent to 1.5 percent or an average yield increase of 0.6 megagram/ hectare. In SSA, yield of food crops are projected to decline from 8 percent to 22 percent depending on crop type (Schlenker and Lobell, 2010).

The dryland (rainfed) agroecosystems, especially in South Asia (SA) and SSA, are prone to vagaries of changing climate (Venkateswarlu and Shankar, 2012). Maize, which supplies 30 percent of the food calories to less than 4.5 billion people in 94 developing countries (Bellon et al., 2011), may be adversely affected by the climate change. Among legumes, lentils are also an important source of protein in SA. The annual rate of increase in grain yield of lentil has been hardly 8.6 kilogram/hectare/year between 1961 and 2008 (Erskine et al., 2011), and adaptation to ACC would boost production by filling the yield gap.

Yet, there exists a yield gap between attainable and actual national yield. Lobell et al., (2009) estimated the yield gap of 4.5 megagram/hectare for wheat and 3.8 megagram/hectare for rice in India, and that of 3.8 megagram/hectare for corn in SSA. The yield gap can be abridged by adopting BMP's of improving soil quality by enhancing the SOC pool. The strategy of sustainable soil management is to replace what is removed, respond wisely to what is changed, and predict changes in soil quality by natural and anthropogenic perturbations so that adaptive systems can be implemented.

The world population is projected to grow from about seven billion in 2011 to 9.3 billion by 2050, with almost all the increase to occur in developing countries. Merely a handful of developing nations (e.g., India, China, Nigeria, Bangladesh, Indonesia and Pakistan) account for half of the world population but have finite natural resources (low per capita arable land and renewable freshwater). The so-called ›hidden hunger‹ is caused by the deficiency of micronutrients which include iron, iodine, zinc etc. (Swaminathan, 2012) and is exacerbated by soil degradation (Lal, 2009). Furthermore, there is a strong competition for land among principal uses such as agriculture, biofuel plantations, urbanization, nature conservancy, and cultural and aesthetical uses.

In view of the immediate future (three to four decades or up to 2050), important issues are: (1) how to adapt agriculture to an uncertain climate; (2) how to synchronize responses to local vulnerabilities with global disparities; and (3) how to prioritize the adaptation strategies (Iglesias et al., 2011). It is in this context that the importance of improving soil quality and enhancing SOC concentration/pool cannot be over emphasized.

4 Soil Organic Carbon and Soil Quality

The SOC concentration is a key determinant of soil quality (Figure 2). It strongly impacts soil physical/mechanical quality by favorable changes in surface area, formation and stabilization of aggregates, total porosity and pore size distribution, aggregate strength, erodibility and susceptibility to crusting and compaction. Soil tilth, physical condition of the seedbed, is also improved by an optimal SOC level. Principal impacts of SOC concentration on soil hydrologic properties include increase in plant available water capacity (AWC) because of alteration in soil moisture characteristic curves (pF) which favor retention of water at low potential (−0.01 to 0.03 megapascal range). Notable among other impacts of SOC on hydrological properties include increase in water infiltration rate (infiltrability), and decrease in surface runoff (rate and amount). Improvements in these soil hydrological properties are important to reducing susceptibility of agroecosystems to pedological/agronomic droughts, such as the one experienced in the USA during 2012 (Lal et al., 2012a). Key parameters of soil chemical quality improved by increase in SOC pool and its quality include charge properties affecting both anion exchange capacity (AEC) and cation exchange capacity (CEC), thereby enhancing the nutrient retention by reducing loses through leaching and volatilization. Increase in charge characteristics also improves soils buffering capacity against sudden changes in reaction (pH), and elemental transformations. Attributes of soil biological quality enhanced by improvements in SOC concentration include activity and species diversity of soil organisms including earthworms, which accentuate bioturbation and enhance soil structure, microbial biomass (MBC) which affects C turnover and rhizospheric processes including nitrification/denitrification. The overall improvement in soil quality also enhances ecological pro-

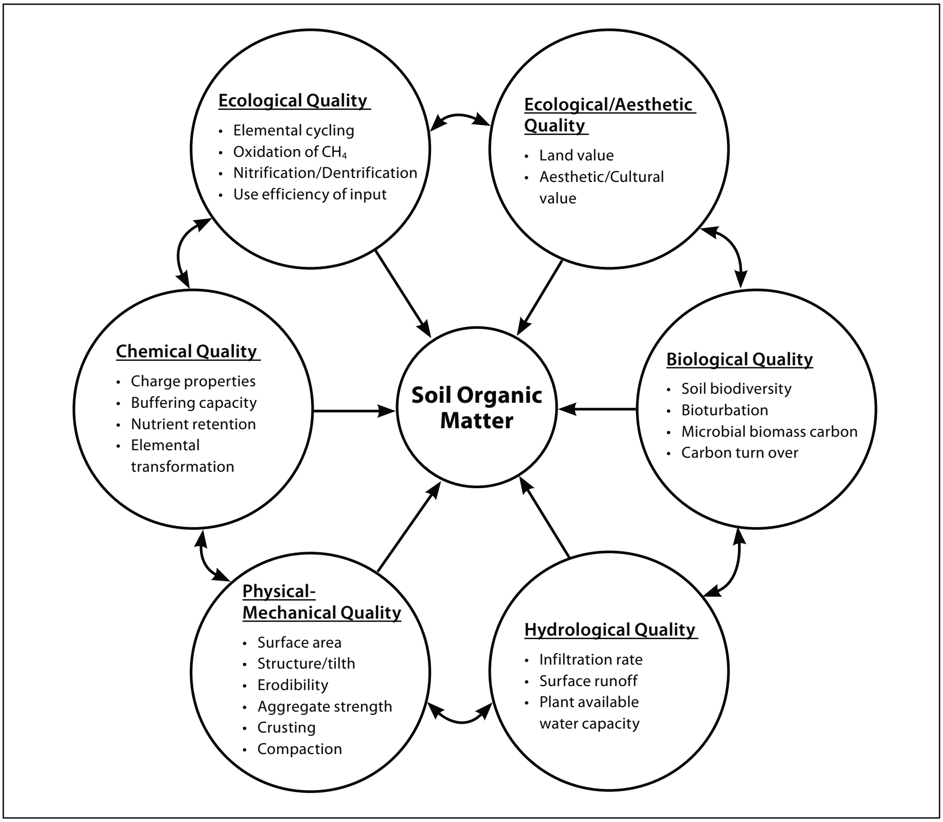

Figure 2: Effects of soil organic matter content on soil quality.

Soil/Ecological Processes	Ecosystem Services
1. Hydrological cycle: Runoff, evaporation, seepage, soil water storage.	1. Filtering and recycling of water: Infiltration, soil water storage etc.
2. Energy balance: Albedo, soil temperature, heat transfer, latent heat.	2. Energy balance: Soil temperature regime and its diurnal/annual cycles.
3. Nutrient cycling: Nutrient input (macro, mirco) through residues.	3. Nutrient retention: Elemental cycling.
4. Food and habitat biota: crop and animal residues provide habitat and source of energy for macro, meso and micro-organisms.	4. Biodiversity: Food and habitat for above and below ground biota.
5. Soil conservation: crop residues, mulch residues raindrop impact and shearing force and carrying capacity of runoff.	5. Soil formation: biotic interactions enhance rate of soil formation, and conservation of soil.
6. Water quality: mulch cover reduces non-point source pollution, sedimentation, and risks of anoxia in aquatic ecosystems.	6. Adaptation to climate change: Buffering against extreme events.
7. Eco efficiency: Increase in use efficiency of inputs.	7. Mitigating of climate change: Increasing soil C sink capacity and offsetting anthropogenic emissions.
8. Land saving: Increase in productivity of existing land.	8. Pest & Disease: Suppressive soils through alterations in rhizospheric processes.
9. Sustainability: Enhanced sustainability of soil use and management.	9. Primary Production: Improvement in soil quality enhances NPP.
10. Resilience: Soils are adaptable and resilient to climate change and other perturbations.	10. Nature conservancy: Enhancing goods and services by preserving natural ecosystems through savings of land resources.

Table 3: Beneficial impacts of crop/animal residue retention for improving SOC concentration on soil processes and provisioning of ecosystem services.

cesses such as elemental cycling, oxidation/uptake of CH_4, and use efficiency of input (fertilizers, water, decline in sedimentation, non-point source pollution). There is an improvement in land value, and also enhancement in aesthetic/cultural attributes (Figure 2). Strategies of enhancement of SOC pool in agroecosystems include those that create a positive C budget. In this regard, the importance of retention of crop/animal residues by surface application of by-product (e. g., mulch, manure) cannot be over emphasized. There are numerous advantages of crops residue retention (Table 3), which impact SOC dynamics and enhance provisioning of important ecosystem services. The significance of cultivating perennial grain crops is also being considered (Glover et al., 2010, 2012)

There is a wide rage of soil quality indices (Lal, 1994, Erkossa et al., 2007; Bastida et al., 2008, Schloter et al., 2003). Most indices, which involve SOC concentration/pool as an important determinant, are based on critical limits of SOC and other parameters (Aune and Lal, 1998; Arshad and Martin, 2002). With multiparametric indices, standardization of soil quality attributes and creation of minimum dataset are important considerations (Nortcliff, 2002; Bastida et al., 2008; Rezaei et al., 2006). Some indices involve the soil management assessment framework (Andrews et al., 2004), microbiological and biochemical parameters (Arias et al., 2005; Hofman and Dusek, 2003), and can be used at plot or preferably at a watershed scale (Cambardella et al., 2004).

5 Soil Organic Carbon and Climate Change

As the largest C reservoir of the terrestrial biosphere, SOC pool strongly impacts and is impacted by the ACC. Ever since the dawn of settled agriculture around ten to twelve millennia ago, SOC pool has been a major source of plant nutrients required for crop and forage production. The other sources of plant nutrients include BNF by legumes and some tropical grasses, and the release by biomass burning following deforestation for new land development. Plowing and the attendant soil disturbances, along with drainage of wetlands, accentuate decomposition of SOC pool and the release of plant nutrients. With the average ratio of 12:1 for C:N, 50:1 for C:P, and 70:1 for C:S, mineralization of 1 megagram/hectare of SOC would release 83 kilogram of N, 20 kilogram of P and 14 kilogram of S. Repeated plowing, as is often done in low-input (and even some organic) systems, accentuates mineralization and release of essential plant nutrients. Estimated depletion of the global SOC pool upon conversion of natural to agroecosystems is estimated at 50 to 100 petagram (Lal, 1999, 2004b).

In conjunction with the release of essential nutrients through mineralization of soil organic matter (SOM), however, there is also emission of GHGs notably CO_2 but also CH_4 and N_2O. Decomposition of SOM increases emission of CO_2 under aerobic conditions and CH_4 under anaerobic environments. The rate of mineralization is temperature-dependent, and approximately doubles with every 10°Celsius increase in soil temperature (The Vant Hoff's Rule). Therefore, the projected warming may accentuate the mineralization, deplete the SOC pool and its dynamics, and exacerbate ACC. However, there are several uncertainties associated with the impact of ACC on SOC dynamics. Major questions are whether the projected ACC will: (1) amplify SOC depletion and enhance the positive feedback; (2) exacerbate soil erosion risks and increase GHG emissions from the SOC being transported by erosional processes (Lal, 2003; Van Oost et al., 2012); (3) accelerate the global C cycle along with the attendant ramifications; and (4) offset some of these adverse effects by enhancing NPP through the so-called CO_2 fertilization effect.

The projected ACC may also alter soil processes that impact SOC pool and its dynamics, such as increasing vulnerability to accelerated erosion. Some uncertainties with regards to soil processes include the following: (1) Will accentuation in beneficial pro-

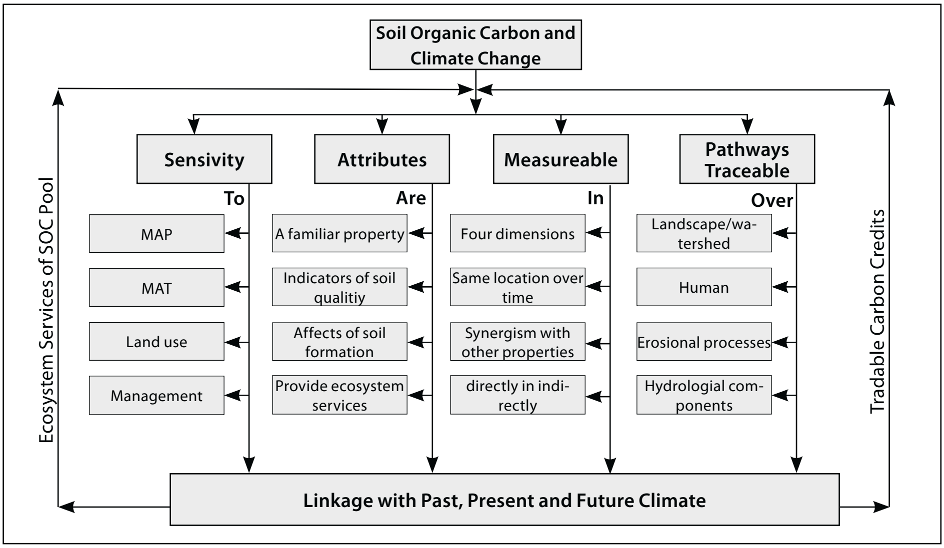

Figure 3: Soil Organic carbon as an indicator of climate change (MAP = mean annual precipitation, MAT = mean annual temperature).

cesses have mitigative impact by enhancing SOC sequestration and, thereby, increasing the land-based or terrestrial C sinks? (2) Will there be several adverse impacts on agronomic/biomass production (NPP) associated with increase in frequency and intensity of extreme events? (3) Will there be a confounding impact of SOC depletion on uptake/release of CH_4 and on nitrification/denitrification processes? (4) Will there be increased mortality of trees and perennial vegetation by increase in intensification of pests and diseases (McDowell, 2012)? Emissions of N_2O from soils are accentuated by use of fertilizers, both organic and inorganic. Manure management has been a source of N_2O emission for millennia prior to the use of nitrogenous fertilizers.

Therefore, SOC pool and its dynamics can be an indicator of climate change. The outline in Figure 3 lists several reasons of using SOC as an indicator of past (paleoclimate) and future climate change. Important among these include the following: (1) a familiar soil attribute; (2) measurable in four dimensions (length, width, depth, time) both directly (dry/wet combustion) and indirectly (soil color, bulk density) and in-situ (inelastic neutron scattering) and ex-situ, on mass basis and volume basis, and repeatedly over time for the same location; (3) a property with a memory (δ13C) relevant to understanding the paleoclimate; (4) a characteristic usable in synergism with other indicators of climate change; (5) a parameter relevant to assessing other pedogenic (rate of soil formation)/rhizospheric (elemental and biomass transformation)/agronomic parameters (soil fertility, nutrient retention and supply); (6) a factor capable of enhancing provisioning of several ecosystem services (e. g., food security, water purification); (7) a component with well-defined properties (e. g., thermal capacity, surface area, charge density, affinity for water) and sensitive to climate change; (8) a tracer whose pathways can be followed over landscape, watershed etc.; (9) a property which responds to management; and (10) a characteristic that has economic/societal values, which can be traded in domestic and international markets (Figure 3).

6 Converting Soils of Agroecosystems from Carbon Source to Sink

The historic landuse and management have created a large C sink capacity, estimated at 50 to 100 petagram C, in world soils. Therefore, recarbonization or greening of the terrestrial biosphere (Lal et al., 2012b) can transfer some of the atmospheric CO_2 into the terrestrial C pool and also offset anthropogenic emissions.

There are two strategies of recarbonization: (1) creating a positive soil C budget so that the input of biomass C exceeds the losses by erosion, mineralization and leaching, and (2) enhancing the mean residence time (MRT) of C in soil. These strategies are briefly discussed below.

6.1 Creating a Positive Soil Carbon Budget

Technological options for enhancing input of biomass-C in soil are outlined in Table 4 and Figure 4. The overall strategy is to promote soil conservation, enhance productivity, and recycle crop and animal byproducts etc. Implementation of this strategy involves (Fernandes et al., 1997): (1) managing of soil environment via conservation tillage, mulching and use of organic and inorganic amendments; (2) managing soil fauna for enhancing activity and species diversity; and (3) managing timing of farm operations especially with regards to application and placement of amendments. Also important are the management options with regards to the landscape position. The SOC concentrations are usually the highest on northern slopes and toeslope positions (Burke et al., 1995). Feeding and casting activities of earthworms (i.e., bioturbation) strongly influence aggregation and SOM dynamics (Pulleman et al., 2004). The land use change, especially during the 20^{th} century, has been an important determinant of the SOC pool and its dynamics (Kaplan et al., 2011). Within arable landuse, important controls include the use of no-till (NT) or conservation tillage (Ding et al., 2002; Ugalde et al., 2007; Campbell et al., 2006), precision tillage (Farkas et al., 2009), waste management (Mondini et al., 2007; Schepers and Lynch, 2007), incorporation of cover crops within the rotation cycle (Ding et al., 2000) and establishment of biofuel plantations such as that of switchgrass and Miscanthus (Hansen et al., 2004), agroforestry systems such as with leguminous trees including *Gliricidia* and *Faidherbia* (Sileshi et al., 2012), and establishing perennial grain crops (Glover et al., 2010, 2012).

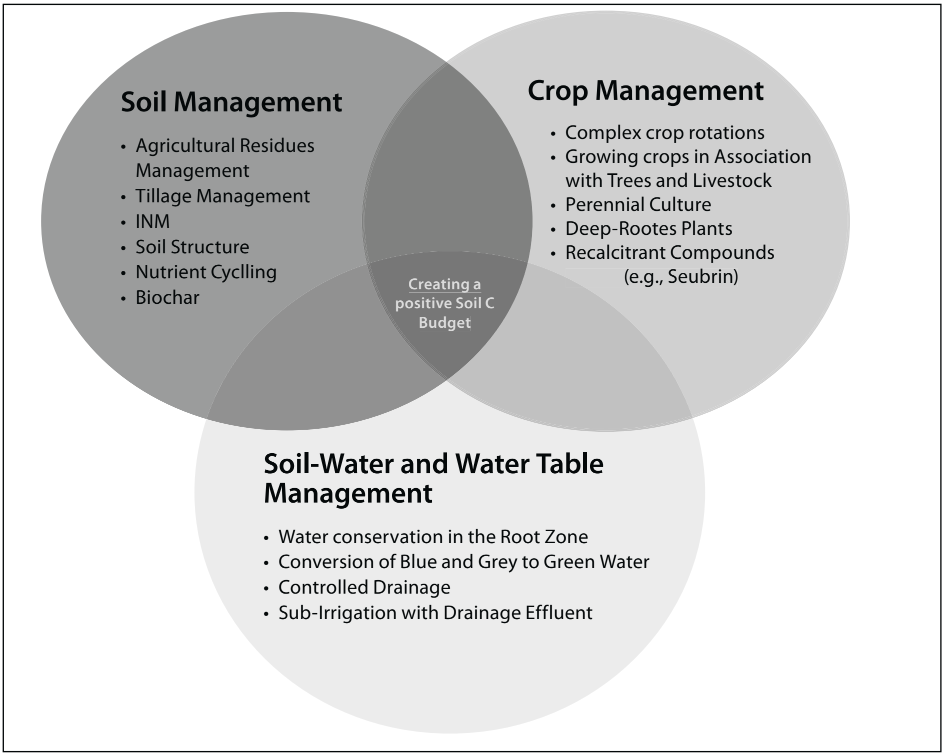

Figure 4: Principal strategies of converting soils of agroecosystems from C source to sink.

Uses of organic and inorganic amendments also impact the SOC dynamics. Positive effects of chemical fertilizers on enhancing SOC pool are widely documented, but especially so in the North China Plains (Mo et al., 2005; Xu et al., 2006). Inorganic fertilizers are effective when used in conjunction with NT farming and manure/compost. (Thompson et al., 2006). Restoration and vegetation/water management of wetlands also enhance C sequestration in these ecosystems (Bernal and Mitsch, 2012).

6.2 Stabilization of Soil Carbon Pool and Increasing the Mean Residence Time

Increasing the SOC pool is the first step, and retaining it in the soil so that it is not re-emitted in to the atmosphere is another. The SOC pool is extremely sensitive to perturbations such as landuse conversion, soil drainage, plowing, soil erosion etc. Therefore, adoption of a judicious landuse and of BMPs is essential to minimizing loss of SOC sequestered. Effective erosion control, by a judicious combination of biotic and engineering techniques, is essential to minimizing the losses. There is a range of mechanisms that protect SOC against microbial processes (Figure 4, right side). Important among these is the

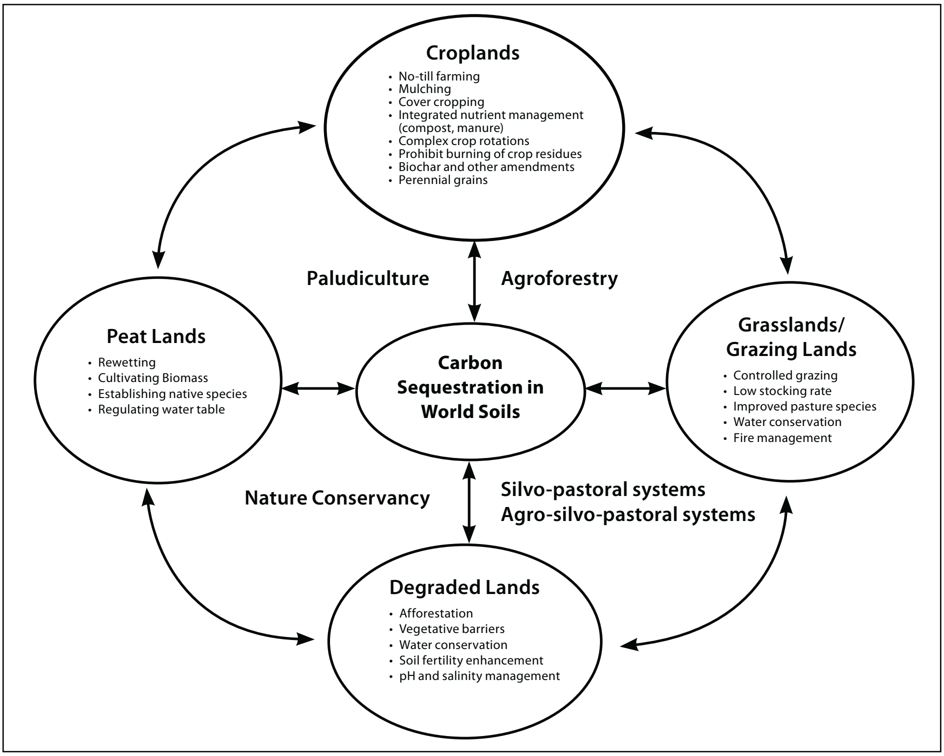

Figure 5: Priority biomes and some recommended technological options for carbon sequestration in world soils.

formation and stabilization of microaggregates (< 250 micronmeter). Growing crops and other plant species with a deep (tap) root system, and those which contain recalcitrant compounds (suberin), may reduce the vulnerability to decomposition. The existence of biochemically recalcitrant compounds is a debatable issue (Schmidt et al., 2011).

Formation of stable soil aggregates is an important mechanism of protection of SOC pool against microbial processes. Five mechanisms of formation of stable aggregates are: soil fauna, roots, microorganisms, environmental variables, and inorganic bonding agents (Six et al., 2004). In accord with the aggregate hierarchy concept (Tisdall and Oades, 1982), different binding agents act at different hierarchical stages of aggregation: (1) persistent binding agents (e. g., humified SOM and polyvalent metal cation complexes, oxides and highly disordered aluminosilicates) bind primary particles and silt-size (< 20 micronmeter) aggregates into stable microaggregates; (2) stable microaggregates (20 – 250 micronmeter) are bound together by fungal hyphae and roots (temporary binding agents) and by microbial and plant-derived polysaccharides (transient binding agents). In general, polysaccharides are binding agents on a scale of less than 50 mirconmeter within the macro-aggregate (Oades, 1984). Similar to aggregation, there also exist hierarchical pore categories (Elliot and Coleman, 1988): (1) macropores; (2) pore space between macroaggregates; (3) pores between microaggregates but within macroaggregates; and (4) pores within microaggregates. Pores of different sizes are habitat for microorganisms of different sizes. These hierarchical concepts apply only when the cementing agents are humic substances and organic materials (Oades and Waters, 1991). In addition, root-derived particulate organic matter (POM) and activity of earthworms and other soil biota play an important role in formation of aggregates and stabilization of SOC.

Priority biomes with a large soil C sink capacity are the depleted/degraded/desertified soils of croplands, grazing lands, wetlands, and those severely affected by degradation processes such as accelerated erosion, salinization, elemental imbalance, nutrient depletion, decline in soil structure etc. (Figure 5). Restoration of degraded soils and desertified ecosystems and of drained ecosystems is the highest priority. The C sink capacity of degraded ecosystems is large. Further, the rate of soil/biotic sequestration is more in cool and humid than in warm and dry climates (Lal., 2004b). Thus, priority biomes would include reforestation/afforestation in the humid tropics, temperate regions, and tropical wetlands/peat lands. Restoration of eroded and salinized soils is also a high priority. Enhancing SOC pool in agroecosystems is essential to improving use efficiency of inputs, increasing agronomic productivity and advancing food security (Table 4).

7 Soil Carbon Measurement

As an indicator of ACC and useful to provisioning of numerous ecosystem services, credible measurement of SOC pool is essential. Whereas the measurement of SOC pool in relation to management of soil fertility and agronomic productivity has been done since circa 1850, measurements of SOC pool are different for mitigation of climate change and assessment of ecological footprint of diverse production systems. The schematics in Figure 6 outline specific needs for measurements of SOC for agronomic, climatic and ecological purposes.

With reference to agricultural land use, SOC concentration (reported as percent by weight, gram/kilogram) can be measured in the rootzone or plow layer. These measurements can be made on seasonal or annual basis and related to use efficiency of input, crop/biomass yields and soil quality parameters. With reference to soil C sequestration to off-set anthropogenic emissions and mitigation of ACC due to enrichment of atmospheric CO_2, measurements of SOC pool should be made for the entire profile (1 to 2 meter depth) and reported in terms of C density (kilogram/cubic meter) or the cumulative pool (megagram C/hectare). Major issues are: (1) how to obtain reliable data on soil bulk density, and (2) how to capture spatial variability? Rather than plot scale, measurements of SOC pool with reference to ACC are needed at the watershed, state or national scale.