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

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OUTLINE

Key Words: Food security, environment quality, soil restoration, global C cycle, soil C sequestration

List of Abbreviations

ACC = Abrupt climate change
AEC = Anion exchange capacity
AMF = Arbuscular mycorrhizal fungi
AWC = Available water capacity
BMP = Best management practices
BNF = Biological nitrogen fixation
CEC = Cation exchange capacity
EPA = Environmental Protection Agency
GCC = Global carbon cycle
GHG = Greenhouse gas
GPP = Gross primary productivity
MAP = Mean annual precipitation
MAT = Mean annual temperature
MBC = Microbial biomass carbon
Mg = Megagram (1 metric ton)
Mha = Million hectares
MRT = Mean residence time
NBP = Net biome productivity
NEP = Net ecosystem productivity
NGO = Non-government organization
NPP = Net primary productivity
NT = No-till
Pg = Petagram (10^{15} = 1 Gigaton)
POM = Particulate organic matter
SA = South Asia
SIC = Soil inorganic carbon
SOC = Soil organic carbon
SOM = Soil organic matter
SSA = Sub-Saharan Africa
UN = United Nations
ZND = Zero net deforestation
ZNE = Zero net emissions
ZNLD = Zero net land degradation

ABSTRACT:

World soils constitute the largest terrestrial reserve of carbon (C). Estimated at 4000 Pg (1 Pg = 10^{15} g) to 3-m depth, it plays a major role in the global C cycle and is closely linked with the atmospheric (790 Pg) and the biotic (620 Pg) pools. Two types of C are: soil organic C (SOC) and soil inorganic (SIC). 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 Pg. Agroecosystems with SOC pool below the critical level (1.5% to 2%) 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 (ACC). The technical potential of C sequestration in world cropland soils is 0.4-1.2 PgC yr^{-1} 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 1 to 2 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 ~30% 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 Pg 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 (Gelisols), and may create a major positive feedback releasing C and nitrogen (N). Thawing of permafrost could release up to 436 PgC and 29 PgN 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% since the Industrial Revolution. 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 U.S. in 2012 (Lal et al. 2012). 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 on-going 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, 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 interphase 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). 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 ~1500 Pg to 1-m depth (Batjes 1996) and 2344 Pg to 2-m depth (Jobbágy and Jackson 2000). Soil inorganic carbon (SIC) pool is estimated at 720 Pg to 1-m depth (Batjes 1996) and 950 Pg to 2-m 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 1500 PgC, which is equivalent to the present pool of world soils to 1-m depth (Batjes 1996). Thus, the total soil C pool may exceed 4000 Pg to 3-m depth. There is a strong need to improve estimates of the global soil C pool (Milne et al. 2011, Schmidt et al. 2011). In comparison, the biotic C pool comprises of 620 Pg of which 60 Pg represents the detritus material, and the atmospheric C pool of about 790 Pg (WMO 2011). The latter is increasing at the annual rate of about 2.3 pmmv or 3.3 Pg C (WMO 2011). Principal sources of atmospheric emission of CO_2-C are fossil fuel combustion (~10 PgC yr^{-1}) and land use conversion (~1.3±0.4 PgC yr^{-1}) (LeQuéré et al. 2009) (Fig. 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 PgC, additional loss since 1750 is estimated at about 156 Pg (Fig. 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 2006, 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% (Lal 2004b), may be as much as 30 to 50 MgC ha^{-1} or 50-100 PgC 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. 2012) is an important strategy to mitigate the ACC.

The gross primary productivity (GPP) is estimated at 123 Pg yr^{-1}, of which 60 Pg is respired by plants and leaving net primary productivity (NPP) of 63 Pg yr^{-1}. Accounting for the heterotrophic metabolism, the net ecosystem productivity (NEP) is about 10 PgC yr^{-1}. A large proportion of NEP is lost because of land use, fire and other perturbations. The net biome productivity (NBP) is estimated at 0.3 to 5.0 Pg with an average value of about 3 Pg yr^{-1} (Jansson et al. 2010). 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 10-12 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 (i) increase in global temperature, and (ii) increase in atmospheric concentration of CO_2 from 180 ppmv to 280 ppmv. Along with the increase in mean global temperature by as much as 5°C, the increase in atmospheric CO_2 concentration enhanced biomass production of C_3 plants (e.g., wheat, barley) dramatically and that of C_4 plants (e.g., 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 ha (Mha). The agricultural area increased to 930 Mha for population of ~1 billion in 1800, and to 4738 Mha for population of 7 billion in 2010.

Challenges to achieving food security for projected population of 9.2 billion by 2050 include land degradation already estimated at 3500 Mha (23.5% of Earth’s land area) (Bai et al. 2008) and affecting an additional 5-10 Mha yr^{-1}, urbanization needing 3 Mha yr^{-1} of agricultural land, land area needed for establishing biofuel plantations, and mitigating the climate change. While food grain production must be increased 70% by 2050, it is also widely believed that 1°C increase in mean temperature can reduce global grain yield by 10-17%. Thus, over and above the sustainable intensification of land already allocated to agroecosystems, additional land area would be needed to meet the food demands of increasingly affluent population with growing preference towards animal-based diets.

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 geo-engineering 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% yr^{-1} between 2007 and 2011 (Seck et al. 2012), compared to merely 1.6% yr^{-1} 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 availability of 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 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% to -15%, with -18% in northern West Africa, -13% in southern West Africa, and -15% 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 Mg of rice will be needed by 2035 to feed the growing population (Seck et al. 2012). In SSA, on the contrary, 30 million Mg more rice will be needed by 2035—an increase of 130%, and about one-third of this extra need is for Nigeria. Globally, rice production will have to be increased by 1.2% to 1.5% or an average yield increase of 0.6 Mg ha^{-1}. In SSA, yield of food crops are projected to decline from 8% to 22% 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 Sankar 2012). Maize, which supplies 30% of the food calories to >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 South Asia. The annual rate of increase in grain yield of lentil has been hardly 8.6 kg ha^{-1}yr^{-1} 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 Mg ha^{-1} for wheat and 3.8 Mg ha^{-1} for rice in India, and that of 3.8 Mg ha^{-1} for corn in SSA. The yield gap can be abridged by a adopting of 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. Four Ps of bridging the yield gap are :1) "<u>Policy"</u> specifically focused on soil quality improvement through enhancing the SOC pool,2)"<u>People</u>" with passion for soil improvement and scientific/traditional knowledge for good governance,3)"<u>Procedure</u>" consistent and pragmatic in implementing the policy, and 4)"<u>Pricing</u>" based on societal value of the scarce resource. Similarly, three Cs of bridging the yield gap are:1)" <u>Commitment </u>" of the people involved, 2)"<u>Continuity</u> "of the program over long time, and 3)"Coherence" in program implementation. These Ps and Cs are especially relevant to bridging the yield gap in South Asia and SSA.

The world population is projected to grow from ~7 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, Brazil, Bangladesh, Indonesia and Pakistan) account for half of the world population but have finite natural resources (low per capita arable land and renewable freshwater). 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 (3 to 4 decades or up to 2050), important issues are: (i) how to adapt agriculture to an uncertain climate, (ii) how to synchronize responses to local vulnerabilities with global disparities, and (iii) how to prioritize the adaptions strategies (Iglesias et al. 2011). It is in the 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 (Fig. 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 MPa 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 agro-ecosystems to pedological/agronomic droughts, such as the one experienced in the USA during 2012 (Lal et al. 2012). 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 losses 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 structures, microbial biomass (MBC) which affects C turnover and rhizospheric processes including nitrification/denitrification. The overall improvement in soil quality also enhances ecological processes 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 (Fig. 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 growing perennial grain crops is also being considered (Glover et al. 2010, 2012)

There is a wide range 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 10 to 12 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 Mg ha^{-1} of SOC would release 83 kg of N, 20 kg of P and 14 kg of S. Repeated plowing, as is often done in low-input 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 Pg (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°C increase in soil temperature (The Van't 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.

2007)?, (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 processes 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?, and (3) will there be a confounding impact of SOC depletion on uptake/release of CH_4 and on nitrification/denitrification processes?, and (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 Fig. 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 (e.g., 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 ($\delta^{13}C$) 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 (Fig. 3).

6. Converting Soils of Agroecosystems from Carbon Source to Sink

The historic land use and management have created a large C sink capacity, estimated at 50 to 100 PgC, in world soils. Therefore, recarbonization or greening of the terrestrial biosphere (Lal et al. 2012) 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:

(a) Creating a Positive Soil Carbon Budget:

Technological options for enhancing input of biomass-C in soil are outlined in Table 4 and Fig. 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): (i) managing of soil environment via conservation tillage, mulching and use of organic and inorganic amendments, (ii) managing soil fauna for enhancing activity and species diversity, and

(iii) 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 toe slope 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 20th century, has been an important determinant of the SOC pool and its dynamics (Kaplan et al. 2011). Within arable land use, 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 switch grass, and *Miscanthus* (Hansen et al. 2004), agroforestry systems such as with leguminous trees including *Gliricidia* and *Faidherbia* (Sileshi et al. 2012), and establishing perennial grains (Glover et al. 2010, 2012).

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).

(b) 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 land use conversion, soil drainage, plowing, soil erosion etc. Therefore, adoption of a judicious land use 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 (Fig. 4, right side). Important among these is the formation and stabilization of microaggregates (<250μm). 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.

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: (i) persistent binding agents (e.g., humified SOM and polyvalent metal cation complexes, oxides and highly disordered aluminosilicates) bind primary particles and silt-size (<20μm) aggregates into stable microaggregates, (ii) stable micro-aggregates (20-250μm) 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 <50μm within the macro-aggregate (Oades, 1984). Similar to aggregation, there also exist hierarchical pore categories (Elliot and Coleman, 1988): (i) macropores, (ii) pore space between macroaggregates, (iii) pores between microaggregates but within macroaggregates, and (iv) 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. (Fig. 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 Fig. 6 outline specific needs for measurements of SOC for agronomic, climatic ecological purposes.

With reference to agricultural land use, SOC concentration (reported as % by weight, g kg^{-1}) can be measured in the root zone 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 and reported in terms of C density (kg m^{-2}) or the cumulative pool (MgC ha^{-1}). Rather than plot scale, measurements of SOC pool with reference to ACC are needed at the watershed, state or national scale. These measurements can be made at longer time scale of two, five or ten-year period, and are often related to emissions of GHGs (e.g., CO_2). With reference to assessing the ecological footprint of a land use or production system, measurements of SOC pool and the rate of its change (depletion, accretion) are also made for the entire soil profile or solum. These measurements are made at the biome/ecosystem level, are related to ecosystem services, and made on long-term (2, 5, 10 years etc.) basis (Fig. 6). Significant advances have been made in techniques of SOC measurements for different uses as discussed herein (Chatterjee et al. 2009).

8. The Soil Carbon Dilemma

Because SOC sequestration is important to enhancing soil and environment quality of degraded ecosystems, it is also essential to improving agronomic production and advancing/achieving global food security. Furthermore, increasing SOC pool is also critical to adapting agroecosystems to uncertainties associated with ACC and extreme events (Lal 2004b, Batjes 1998). Yet, there are questions regarding the importance of SOC sequestration on mitigating the ACC supposedly by offsetting anthropogenic emissions by fossil fuel combustion.

(i) Challenges of Enhancing the SOC pool: The SOC sequestration has potential and challenges. Yet, its maintenance to above the threshold level (1.5-2.0%) in the root zone is essential to enhancing NPP by improving soil quality and use efficiency of inputs (Lal 2006, 2010a, c, d). Improvement in soil quality by increase in SOC pool in the root zone is a well-established scientific principle, and is not debatable.

Nonetheless, there are several debatable issues that require an objective discourse. First and foremost, there is a menu of options, and there exists neither a panacea nor a silver bullet. Further, most technological options are soil/site/ecoregion specific (Fig. 4, left side). For example, NT system enhances SOC pool in some soils but in others either a measurable increase in SOC pool occurs only in the surface layer or it leads to depletion in the sub-soil layers (Baker et al. 2007, Blanco-Canqui and Lal 2008). There are also implications of ACC to the tillage practices (Ugalde et al. 2007). Regardless of the magnitude and direction of changes in SOC pool, the hidden C costs of NT farming are often lower than those of plow till because of elimination of primary and secondary tillage (Lal 2004a), and reduction in risks of soil erosion. The effect of N fertilization, whether it enhances sequestration or accelerates decomposition, is another debatable issue (Khan et al. 2007). Similarly, there are concerns about the bacterial and fungal contributions to C sequestration in soils of agroecosystems. Despite the protective effects of encapsulating SOC within stable aggregates (Six et al. 2006), it has been reported that the native SOC pool is decomposed and respired back to the atmosphere and that arbuscular mycorrhizal fungi (AMF) stimulates additional decomposition leading to a net depletion of the SOC pool (Kowalchuk 2012, Cheng et al. 2012). Because of the finite capacity, concerns about saturation of the soil C sinks have also been raised (Canadell et al. 2007). These debatable issues need to be considered at scientific, political and outreach levels.

(ii) Soil Carbon Pool and Budget: Estimates of the global soil C pool are highly variable, and depend on the depth of measurement, and on credible assessment of all components. For example, it is widely believed that the SOC pools of peatlands and especially those of permafrost are grossly underestimated. Jungkunst et al. (2012) reported that SOC pool of peatlands might be as much as 1,500 Pg. The concept "what can't be measured can't be managed," necessitates obtaining credible estimate of SOC pool. Similar to the concerns about pool, there are also numerous uncertainties regarding the estimate of GHG fluxes (CO_2, CH_4) from world soils. The ACC is likely to exacerbate soil erosion risks (O'Neal et al. 2005). Yet, the fate of C transported by erosion, and whether it is a source (Lal, 2003) or sink (Van Oost et al. 2007), need to be resolved through sound experimentation and use of accepted terminology. The SOC pool is extremely sensitive to mean annual precipitation (MAP) and the mean annual temperature (MAT) (Jenny 1928, 1941, 1980a). The SOC pool increase with increase in MAP and decreases with increase in MAT (Amundson 2001). Therefore, the projected increase in global MAT will adversely impact the SOC pool. In this regards, the SOC pool in soil of higher latitudes/altitudes and permafrost are highly vulnerable to the projected increase in MAT.

(iii) Soil Carbon Sink Capacity: Upon conversion to restorative land use and adoption of BMPs, most agricultural and degraded/depleted soils can be sink for atmospheric CO_2. Some recently developed or young soils may also be accumulating SOC by weathering of the parent material and progressive deepening of the soil solum. Alleviation of soil-related constraints (e.g., acidity, alkalinity, low P, elemental toxicity, aridity) through judicious management can enhance SOC pool even beyond the antecedent levels under natural vegetation. However, there can be a rapid turnover of SOC even in soil under re-established forests (Richter et al. 1999). The technical or potential soil C sink capacity is estimated at 50-100 Pg, and the rate of sequestration may be 0.4-1.2 PgC yr^{-1} in world's croplands (Lal, 2010b), 0.3-0.5 PgC yr^{-1} in grazing lands (Lal, 2010a), 0.2-0.3 PgC yr^{-1} in eroded land (Lal, 2001), and 0.3-0.7 PgC yr^{-1} in salt affected soils (Lal, 2010b). These rates are achievable under ideal conditions with regards to an optimal supple of all the building blocks (C, N, P, S) clay+silt contents, deep solum, and favorable MAP and MAT regimes.

(iv) The CO_2 Fertilization Effect: The beneficial effect of CO_2 fertilization, especially in C_3 plants, depends on a range of other extraneous factors (Lenka and Lal 2012). Important among the extraneous factors are optimal supply of N, and water. Furthermore, the response to CO_2 enrichment may not be linear, there may be a time lag, and also some indirect effects such as acclimation, homeostasis, ecosystem stoichiometry, and shift in species composition (Rustad 2006).

(v) Availability of water and nutrients: Carbon sequestration in soil and vegetation is a resource-limiting process. The process can be severely constrained by the lack of sufficient water and nutrients (e.g., N, P, S). Availability of water nutrients is a major constraint to enhancing biomass production, and thus to SOC sequestration. Rockström et al. (2012) estimated that achieving global food security and maximizing C sequestration in terrestrial ecosystems would require increasing water consumption of 2600 km^3 yr^{-1} by an additional 3250 km^3 yr^{-1}. The global safe operating space for fresh water use it 5000 km^3 yr^{-1} compared with the projected use of 5850 km^3 yr^{-1}. Rockström and colleagues conclude that food, being essential and the highest priority, C sequestration may not be realistic as a major mode of ACC mitigation.

(vi) Recalcitrance of Soil Carbon and the Microbial Control: Rather than the focusing recalcitrance on organic substances (e.g., cutin, lignin or suberin content), there is a growing awareness about the microbial control on decomposition and C cycling in soil. It is the physical access of microorganisms to the occluded or sorbed substrates, which is the rate limiting control (Schimel and Schaeffer 2012). The hierarchy model of aggregations has been renamed the “onion layering” model (Sollins et al. 2006). With a long turn over time of millennia (Trumbore 2009), decomposition may not depend on biochemical recalcitrance (Dungait et al. 2012), and is unlikely to be due to biological constraints, but because of physical inaccessibility.

(vii) Multiple uses of crop residues: recycling crop residues and other agricultural by-products is essential to sequestering C in soils. Harvesting crop residues for biofuels can deplete SOC pool (Lal 2008a, Blanco-Canqui and Lal 2008). We can either have alcohol or humus (Jenny 1980b), but not both. Prudent management of waste is essential to meet the challenge of climate change (Mondini et al. 2007, Schepers and Lynch 2007).

9. Soil Governance for Enhancing Ecosystem Services

The term soil governance refers to application of scientific/traditional knowledge to soil management through public scrutiny. It is a societal discourse to sustainable development and involves close cooperation and interaction among scientists, experts, politicians and local actors. Enhancing soil security is at the core of the societal discourse, because in the long run, it determines the national security.

Soil governance relates to decisions that define expectations, grants power and validates performance. It refers to management of leadership processes with specific reference to sustainable management of soil resources. The SOC concentration and dynamics, being integral to numerous goods and service provisioned by soil, judicious governance of soil in general, but that of SOC in particular, is essential. It is in this connection that there is a need for consistent management and cohesive policies at local, regional, national and global levels.

There is a strong interaction between soil quality/SOC concentration, ACC and global food security. Food insecurity affects about 1 billion people (FAO 2009, 2010), most of them residing in developing countries of SA, SSA, West Asia/North Africa, Central America and the Caribbeans. Because the majority of the poor (and food-insecure) may be dependent on agriculture, soil degradation and severity of ACC may exacerbate the food system risks. The attendant volatility in food price may bring social disturbances and political unrest in the short to long-term (Alpas and Kiymaz 2011). Therefore, improving earth/soil system governance is pertinent to judiciously navigating the anthropocene (Biermann et al. 2012). The strategies of sustainable development must be directed towards changing course and steering away from the critical tipping points of land degradation, deforestation, depletion of SOC pool, emission of GHGs from the terrestrial biosphere, and thawing of permafrost in soils. However, being complex and highly interactive, can earth system interactions be effectively governed (Nilsson and Persson 2012), especially with reference to ACC and food insecurity? Implementing action plans of planetary stewardship must define the entry points into the vicious cycle and develop institutional framework for sustainable development. The goal is to change course from sustainable management to sustainable governance of soil and natural resources (Rist et al. 2007). The change in emphasis towards sustainable governance encourages a wider societal debate so that principal stakeholders can deliberate and negotiate the norms, rules and protocols. By doing so, earth systems interactions can be governed. Nonetheless, these remain to be major political and institutional challenges.

Biermann et al. (2012) emphasized key role of United Nations institutions in Earth system governance, and proposed the following building blocks:

1. Assignment of U.N. Organizations to have mandate for agenda setting, norm development, compliance management, science assessment, and capacity building (such as a UN-EPA),
2. Integration of the social, economic and environmental pillars of sustainable development from local to global levels,
3. Integration of sustainability governance by governments to close the remaining regulatory gaps at the global level, especially in deployment of emerging technologies (e.g., conservation agriculture, bioengineering, geo-engineering),
4. Emphasis on planetary concerns in economic governance, such as mainstreaming environmental goals into global trade, investments and finance regimes by discriminating between products on the basis of production processes,
5. Strengthening of inter-governmental institutions and raising of important questions of legitimacy and accountability, and
6. Implementation of policies and norms to ensure equity and fairness to be at the heart of the durable international framework for sustainable development.

Implementing an effective soil governance beyond Rio+20 requires objectivity through changes in societal values, stewardship of finite and fragile soil resources, engagement of the civil society organizations, focus of the private sector on green economy, and limiting human demands on natural resources.

10. Towards Achieving Carbon Neutral Management of Agroecosystems

With the severe threats of ACC caused by anthropogenic emissions, there is a growing interest in identifying and implementing strategies of zero net deforestation (ZND), zero net land degradation (ZNLD), and zero net emissions (ZNE) at a building or community (university campus) level. The goal of ZNLD (Lal 2012a) has been initiated by UNCCD. In the same context, the focus on agricultural land use is to achieve C-neutral management of agroecosystems (Lal 2012a). The stagey is to increase agronomic production, while off-setting C-based inputs (fertilizers, pesticides, tillage, etc.) by C sequestration in soil and vegetation. A series of steps needed towards this goal are outlined in Fig. 7. The first step is to identify BMPs for land use, soil/crop/livestock management, and inputs required on biome (soil, climate, vegetation) basis. The second step is to validate and fine-tune these BMPs for site-specific situation using the concepts of precision farming. The stagey is to adapt BMPs to alleviate soil and ecological constraints to enhancing productivity. The third and fourth steps relate to soil governance (refer Section 9 above) for implementation of BMPs. It involves: (i) developing channels of communication with policy makers, and (ii) starting discussions/dialogue with all stakeholders (e.g., farmers, extension/outreach personnel, NGOs) to facilitate adoption of BMPs. The final step is to make provisions for payments to land managers for creating new and strengthening of existing ecosystem services. Rather than subsidies, payments for provisioned ecosystem services are a useful strategy to incentivizing land mangers (Fig. 7).

11. Are Soil Carbon Sinks Solution to Global Warming?

The importance of soil humus as a national asset has long been recognized (Allision 1973). In the USDA Handbook #7, Albrecht (1938) stated that, "Soil organic matter is one of our most important natural resources; its unwise exploitation has been devastating; and it must be given its proper rank in any conservation policy as one of the major factors affecting the level of crop production in the future." During the energy crisis of 1970s, when crop residues were also being seriously considered as fuel source, Jenny (1980b) opined "I am arguing against indiscriminate conversion of biomass and organic wastes to fuels. The humus capital, which is substantial, deserves being maintained because good soils are a national asset." Despite the recognition of the significance of humus and its benefits, there have been little attempts to identify and implement policy interventions to enhance and sustain SOC pool at national and global levels.

Numerous solutions have been proposed to reduce risks of ACC (Pacala and Socolow 2004, Jacobson 2009, etc.). Despite the proposed numerous options of geo-engineering etc., it is the relevance of natural fixes (e.g., C sequestration in terrestrial ecosystems or land-based sinks) that require special attention. Coupled C and N cycles are closely linked to biota (Harte 2001), and bind C with biota across space and across time (Janzen 2004). Recycling of C is the rule in all biotic processes. Howard (1940) stated that, "the wheel of life is made up of two processes—growth and decay. The one is the counter part of the other." In the same vane, Dyson proposed that, "The CO_2 generated by burning of fossil fuels can theoretically be controlled by growing trees." Dyson (2008) further affirmed this belief by stating, "if we control what plants do with carbon and can restore the pool in the terrestrial biosphere, the fate of CO_2 in the atmosphere is in our hands."

An answer to the question—can we manage ecosystems to hold more C (Janzen 2004)—requires an objective and critical evaluation. It has been argued that it is the decay of SOM that drives numerous biological transformations and rhizospheric processes. About 75 years ago, Albrecht (1938) stated that, “attempting to hoard as much organic matter as possible in the soil, like a miser hoarding gold, is not the correct answer. Organic matter functions mainly as it is decayed and destroyed. Its value lies in its dynamic nature.” Hence, the question—shall we hoard SOC or use it? (Janzen 2005).

The answer to this question lies in developing and implementing strategies that achieve both—using it and also hoarding some of the SOC in soil for rainy days and posterity. Read (2008) proposed a global program of “biosphere C pool management” (BCSM) by increasing land’s sustainable productivity through judicious investments at a scale similar to those for getting oil and other fossil fuels. By taking more CO_2 out of the atmosphere than when under current land use and management, the C thus photosynthesized should be conserved carefully through deployment of bio-based negative emission systems. A strategy of this nature would enable use of the essential products (e.g., food, feed, fiber, fuel) but a large part of the NPP would be conserved to create a large atmospheric draw down. Indeed, Hansen et al. (2008) proposed that the terrestrial biosphere (soil and biota) is the logical strategy where the humanity should aim. McKinsey & Co (2009) has documented that SOC sequestration in terrestrial ecosystems is the most cost-effective option, especially when compared with geological sequestration in rock strata and saline aquifers.

Despite the vast potential of C sequestration in soil and vegetation (terrestrial ecosystems), the option has not been strategically considered by policy makers. The Kyoto Treaty has not implemented it whole-heartedly, and the Rio+20 paid a mere lip service. The lack of support may be attributed to some commonly raised concerns about SOC sequestration (refer section 8). These concerns include the following (Post et al. 2009): finite and temporary /transient nature; difficulties in measurement, monitoring and verification; leakages elsewhere; and diversion from the real issue of finding alternatives to fossil fuels. Yet among several wedges proposed (Pacala and Socolow 2004), an important is SOC sequestration through conservation tillage as a significant option. Despite the concerns, the potential of soil/terrestrial sequestration is strategically too important to be ignored. It is a win-win option because of numerous co-benefits, especially the beneficial impact on soil quality. Regardless of the need to adapt/mitigate ACC, enhancing SOC pool in agricultural soils is essential to feeding world's population of 7 billion in 2011 and 9.3 billion by 2050.

Hansen et al. (2007) estimated that terrestrial sequestration has a capacity to create a draw down of atmospheric CO_2 by 50 ppm over 100 to 150 years. This is a conservative estimate; the actual potential may be double than this. In addition to SOC, there also exists the potential of SIC sequestration (Lal 2001, Sahrawat 2003), which should not be ignored because of the large areas involved. Even the draw down of 50 ppm, being a natural and cost-effective fix with numerous ancillary benefits, is not small. Rather than a drawback, the dynamic nature of SOC pool is an advantage for agronomic ecosystems. More importantly, the SOC sequestration buys us time until alternatives to fossil fuel take effect. Proven soil/land management options (Table 4) exist. Promoting a widespread adoption of these options over several decades until 2050 creates a bridge to the future.

12. Conclusion: Mitigating Global Warming and Achieving Food Security by Sustainable Soil Management and Improving Agriculture

Improved agriculture must be integral to any solution to addressing ACC and improving the environment. In view of the impacts of present and future climate variability on agriculture (Maracchi et al. 2005), it is important to look into the future of agriculture in a changing climate (Iglesias et al. 2011). Modern agriculture must produce more food to feed the growing population (Beddington et al. 2012), both locally and globally. Local food production, to reduce food mileage and enhance self-reliance depends on quality of local soil resources. With ever decreasing per capita land area globally, sustainable intensification for increasing productivity per unit area and time primarily depends on soil quality and its humus capital. Minimizing food systems risks threatening the global poor with low purchasing power, depends on soil resources and their resilience against ACC and other perturbations. Adaptation of agroecosystems to ACC, and mitigation of human-induced warming depends on prudent governance that enhances C sequestration in world soils (Fig. 8). There exists a close link between food security, climate change and SOC-moderated quality of soil and water resources. Availability and renewability of fresh water resources, for agricultural and all other uses, is moderated by quantity and quality of SOC resources. Indeed, numerous ecosystem services, essential to human well-being and nature conservancy, are provisioned by the quantity and quality of humus capital of local, regional and global soil resources (Table 5).

Complex problems of planetary nature require a multitude of solutions. There is neither a panacea nor a silver bullet. Instead, there is a menu of technological options. It is in this context that the importance of enhancing and sustaining C pools in world soils is crucial. A uniquely crucial attribute of the SOC pool is its pivotal role in simultaneously addressing food security, climate security, and water security. In the era of global inter-dependence and of urgent, growing need for peace and political stability, the importance of restoring and sustaining SOC pool is more than ever before.

As soils degrade and desertify, as agronomic productivity sputters, as food production lags behind the demands, as hunger and malnutrition adversely affect human health and wellbeing, as natural waters pollute and contaminate, as climate warms and species disappear, and as environment deteriorates and jeopardizes the ecosystem services, there will be a growing realization among scientists and policy makers that taking soils for granted and depleting SOC pool have been the root cause of the downward spiral.

If soils and their SOC pools are not restored, crops will fail even if rains do not; hunger will perpetuate even with emphasis on biotechnology and genetically modified crops; civil strife and political instability will plague the developing world even with sermons on human rights and democratic ideals; and humanity will suffer even with great scientific strides. Political stability and global peace are threatened because of soil degradation, food insecurity, and desperateness. The time to act is now (Lal 2008b).

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TABLES

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

Biome	**Area (10^6ha)**	**Mean Soil Carbon Content ($Mg\ ha^{-1}$)**
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 2. Examples of regions and crops prone to food insecurity aggravated by the changing climate

	Country/Region	Crop	Climatic Factor	Time Period	Reference
1.	**China**	Winter wheat	Drought in winter wheat	Near future (10-30 yrs)	Song and Zhao (2012)
2.	**Russia/ Ukraine/ Kazakhstan**	Wheat	Climate variability	Next decades	Lioubimtseva et al. (2012)
3.	**Africa**	Rice	Coping with climate change	By 2035	Seck et al. (2012)
4.	**South Asia**	Dryland crops	Managing water and SNRM	Next decades	Venkaterswarlu and Shanker (2012)
5.	**Mexico**	Maize	Drying and warming trends (Highlands)	Near future	Shiefaw et al. (2011)
6.	**South Asia**	Lentil	Drought stress	2010-2050	Eskine et al. (2011)
7.	**West Africa**	Rainfed crops	Drought, warming	Near future effects: Sudano-Sahelian= -18% Guinean Zone = -13% Overall = -11%	Roudier et al. (2011)
8.	**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 3. Beneficial impacts of crop/animal residue retention for improving SOC concentration on soil processes and provisioning of ecosystem services

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 4. Technological options for soil carbon sequestration

	Land Use	Soil Management	Water Management	Crop/Livestock/Tree Species Management
1.	**Cropland**	• Conservation tillage: mulch farming, cover cropping, biochar application • Integrated nutrient management: composting, manuring, recycling agricultural waste, balanced nutrients • Precision farming: soil-specific management • Organic farming	• Minimizing runoff and evaporation losses • Enhancing plant available water capacity • Converting blue and grey water into green water • Water harvesting/recycling • Micro/drip irrigation • Water table management • Controlled drainage	• Complex rotations/systems • Improved varieties with deep/prolific root systems • Ley farming • Agroforestry systems • Agro-silvo-pastoral systems • Adapted animal and tree species • Multipurpose species • Perennial grains
2.	**Grazing Land**	• Soil fertility improvement • Erosion control • Soil compaction control	• Water harvesting and recycling • Reduce crusting (biological crust) • Recharge aquifer	• Improved pastures • Controlled grazing • Rotational grazing • Establishing fodder trees • Shelter belts
3.	**Forestland**	• Nutrient management • Soil compaction control	• Water conservation • Watershed management	• Adaptable species • Mixed plantations • Multipurpose trees • Stand management
4.	**Eroded Lands**	• Enhance soil structure • Improve soil fertility • Minimize crusting/compaction • Increase soil biodiversity (earthworms)	• Runoff management • Improving infiltration rate • Siltation/sedimentation ponds • Water conservation in the root zone	• Afforestation • Vegetation cover • Contour hedges/buffers • Shelter belts
5.	**Salt Affected Soils**	• Improve soil structure • Balanced nutrient application • Create negative salt balance • Improve SOC concentration	• Improve drainage • Leach salt out of the root zone • Reduce evaporation loss • Water table management	• Salt tolerant species/halophytes • Appropriate rotations and cropping systems
6.	**Depleted Soils**	• Apply biosolids • Improve soil fertility • Enhance bioturbation	• Conserve water in the root zone • Runoff management • Water harvesting and recycling	• Establish leguminous spp. • Complex systems
7.	**Wetlands**	• Preserve SOC pool • Reduce decomposition rate • Create favorable C:N:P:S ratio	• Rewetting drained wetlands • Water table management • Promote run on	• Establish native species • Diverse hydromorphic plants

Table 5. Soil carbon sequestration is a win-win strategy because it generates a multitude of goods and ecosystem services.

Provisioning	Moderating	Supporting	Cultural/ Scientific
1. Food and Biomass production	1. Temperature (heat capacity)	1. Agricultural biomass production	1. Scientific processes
2. Freshwater retention	2. Denaturing pollutants (microbial processes)	2. Activity and species diversity of soil biota	2. Recreational (Peat, swamps)
3. Pharmaceutical (Penicillin)	3. Decomposing waste		
4. Energy (peat)	4. Recycling elements		
5. Germ plasm/ seed bank	5. Carbon sequestration		
	6. Disease suppression		

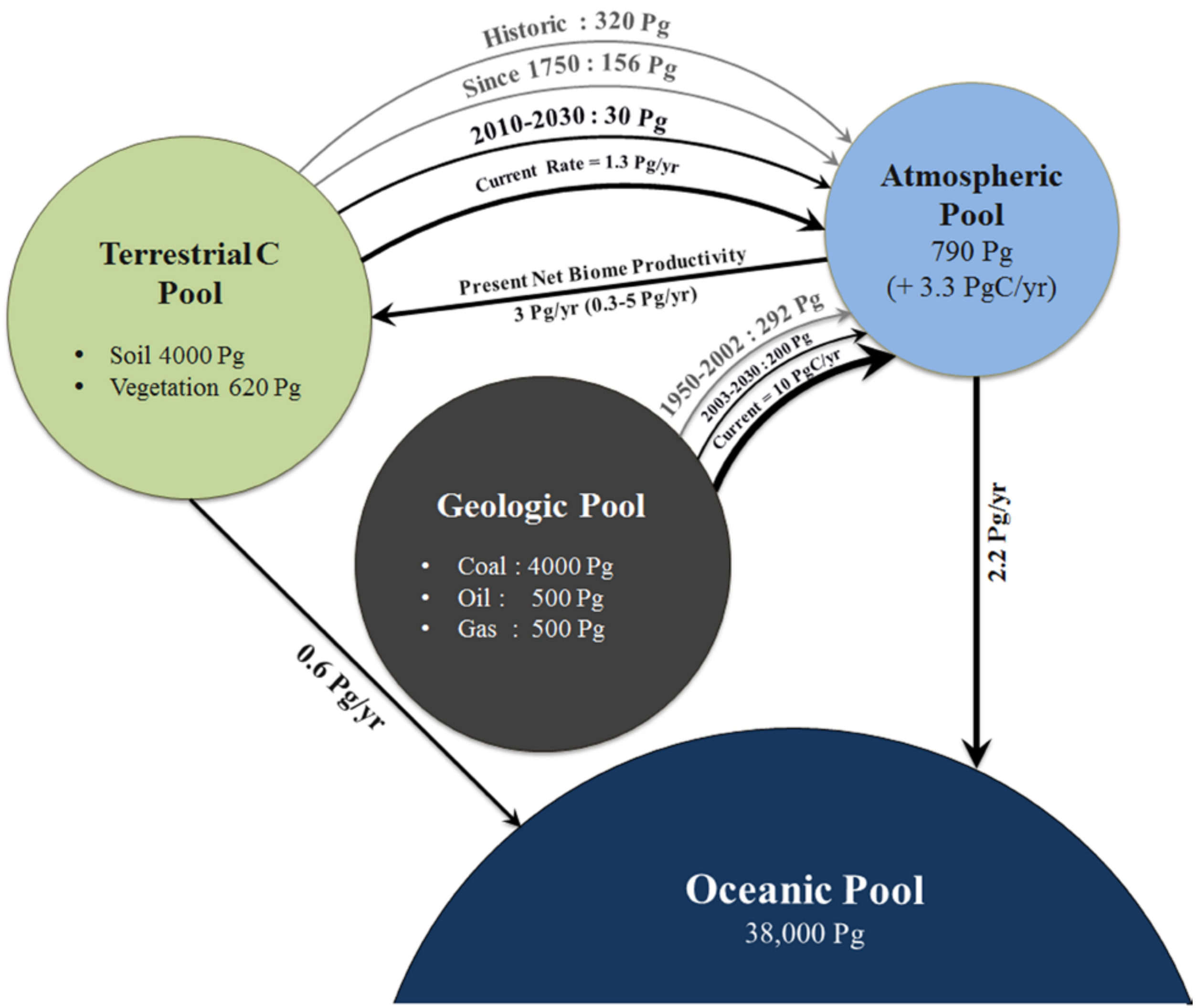

Fig. 1. Principal components of the global carbon cycle (Data cited in this diagram are from Ruddiman 2003, Holdren 2008, Jansson et al. 2010, Lal 2004b, WMO 2011, LeQuéré et al. 2009).

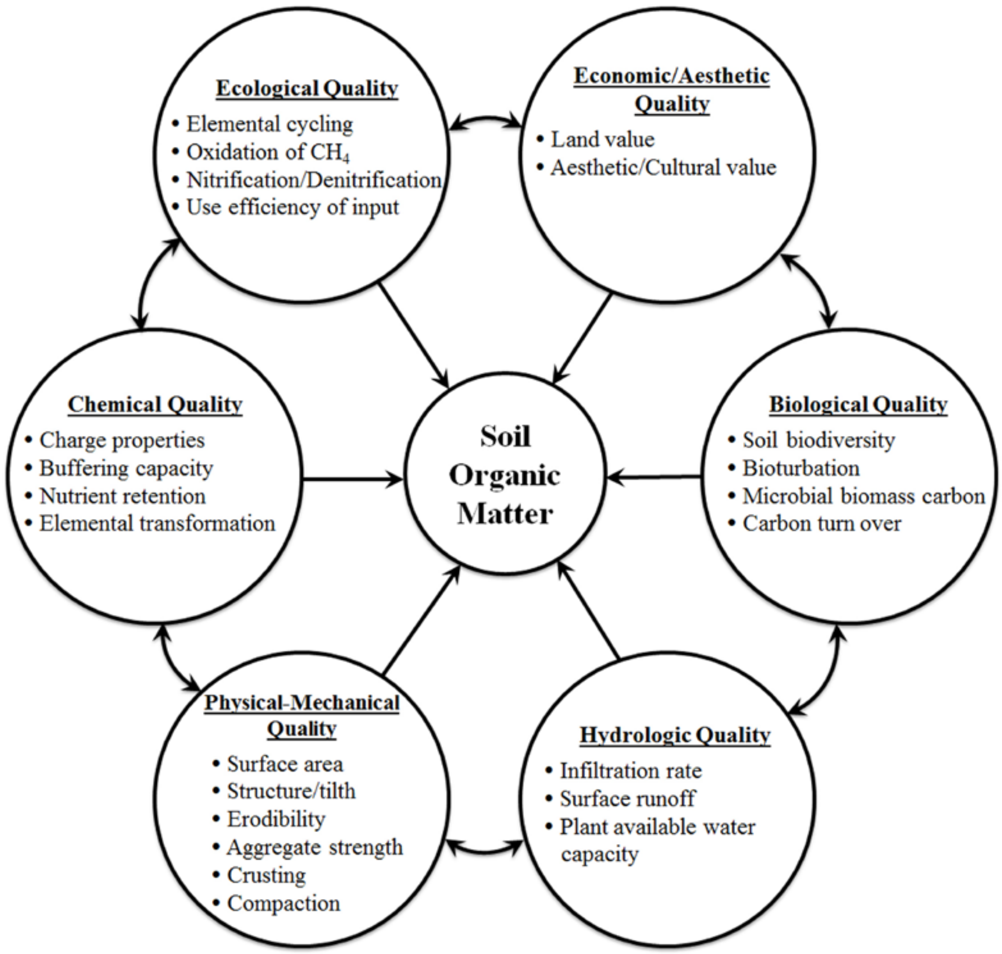

Fig. 2 Effects of soil organic matter content on soil quality.

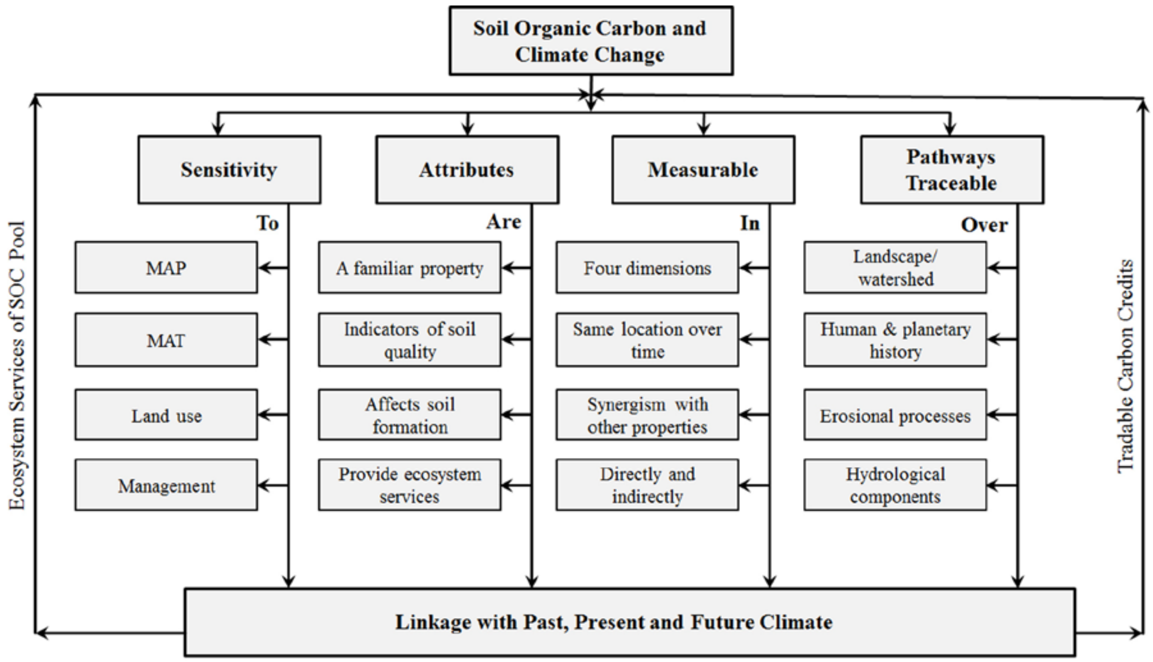

Fig. 3 Soil Organic carbon as an indicator of climate change (MAP= mean annual precipitation, MAT= mean annual temperature).

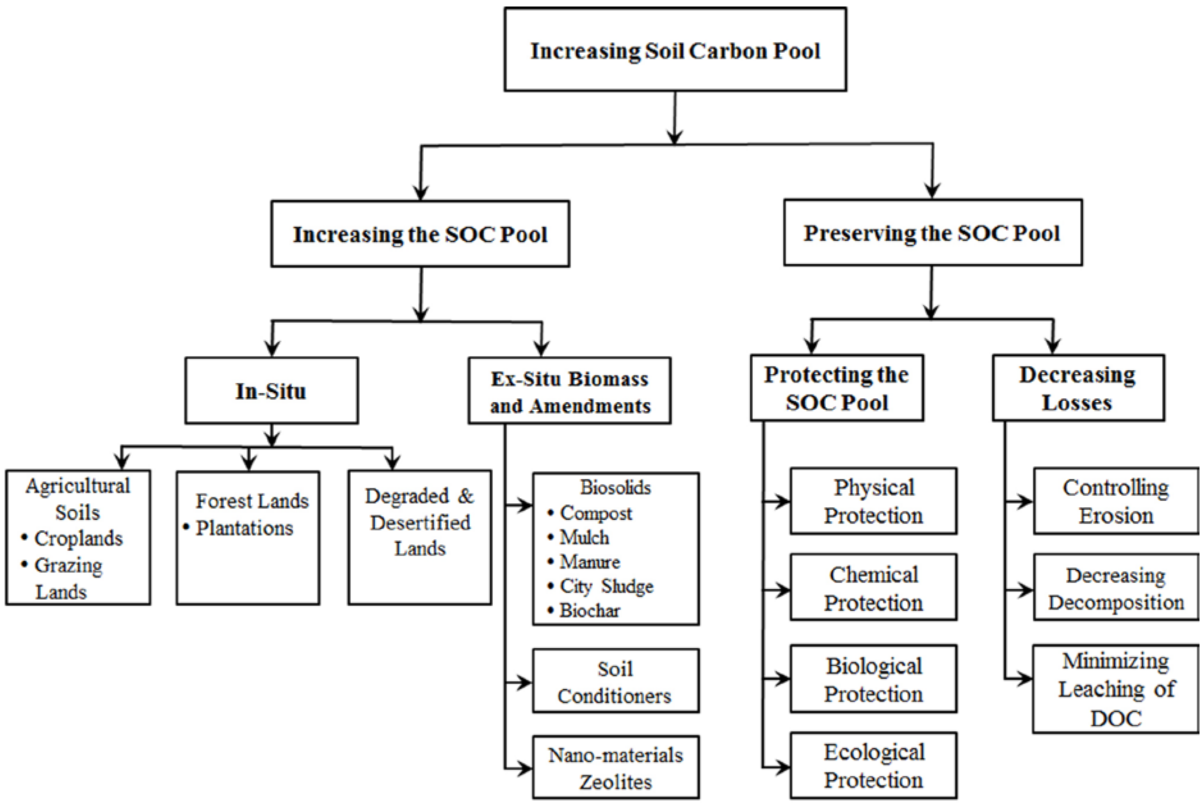

Fig. 4 Principal strategies of converting soils of agroecosystems from C source to sink.

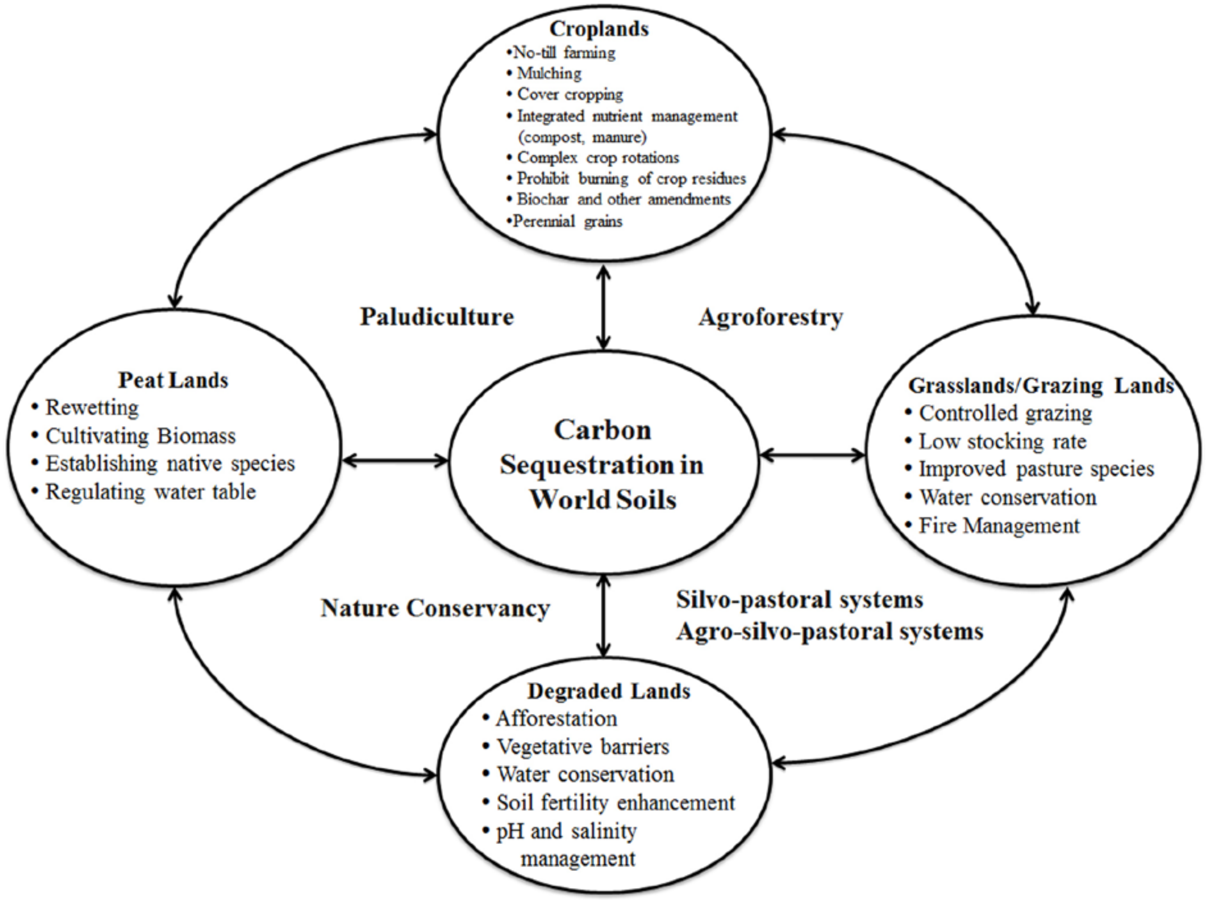

Fig. 5 Priority biomes and some recommended technological options for carbon sequestration in world soils.

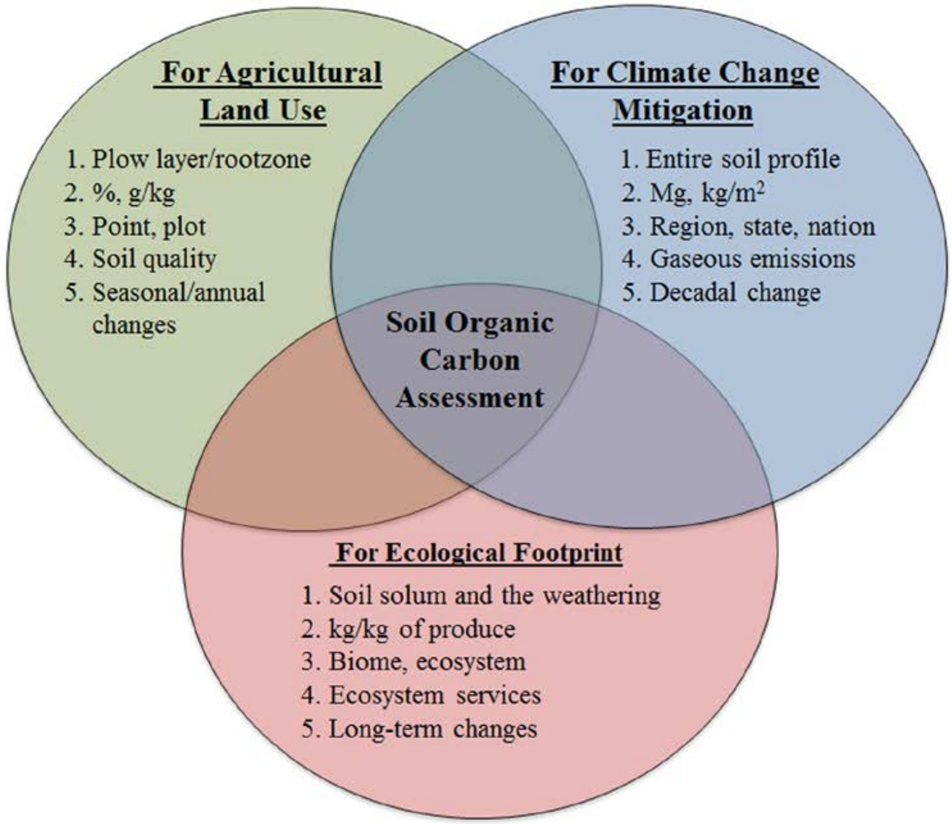

Fig. 6 Measurement of soil organic carbon for specific objectives

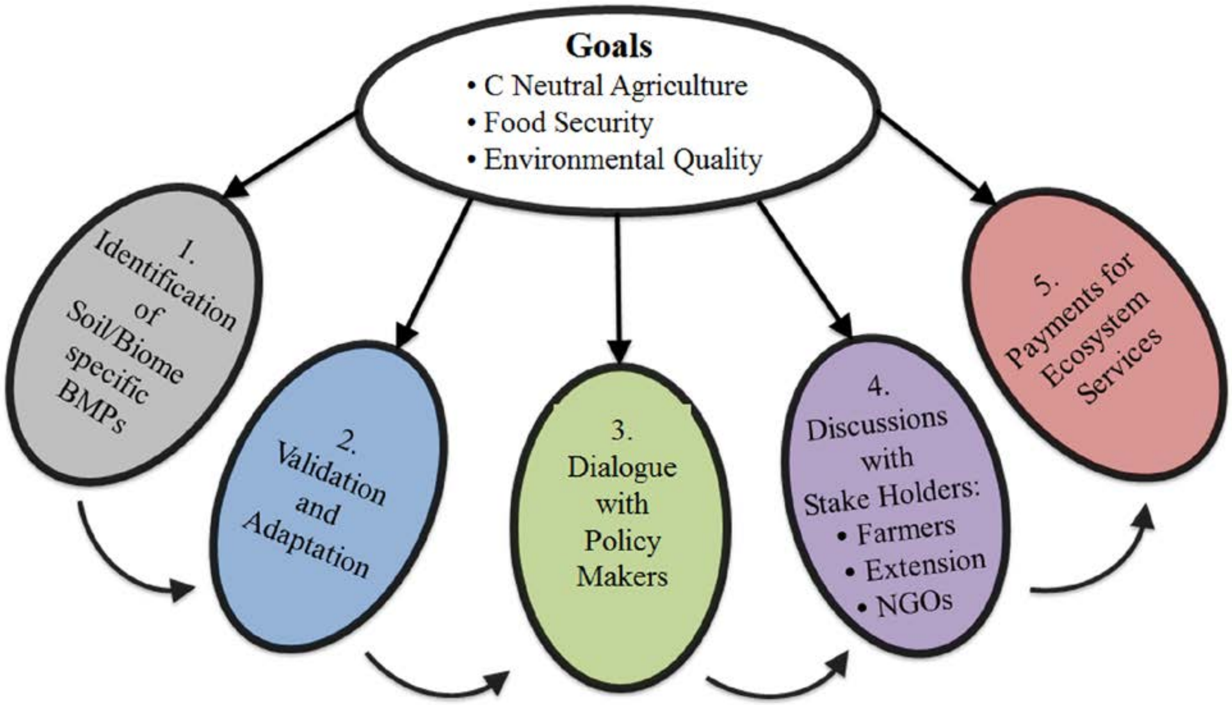

Fig. 7 Proposed steps on the timeline to achieve C-neutral inputs of production systems

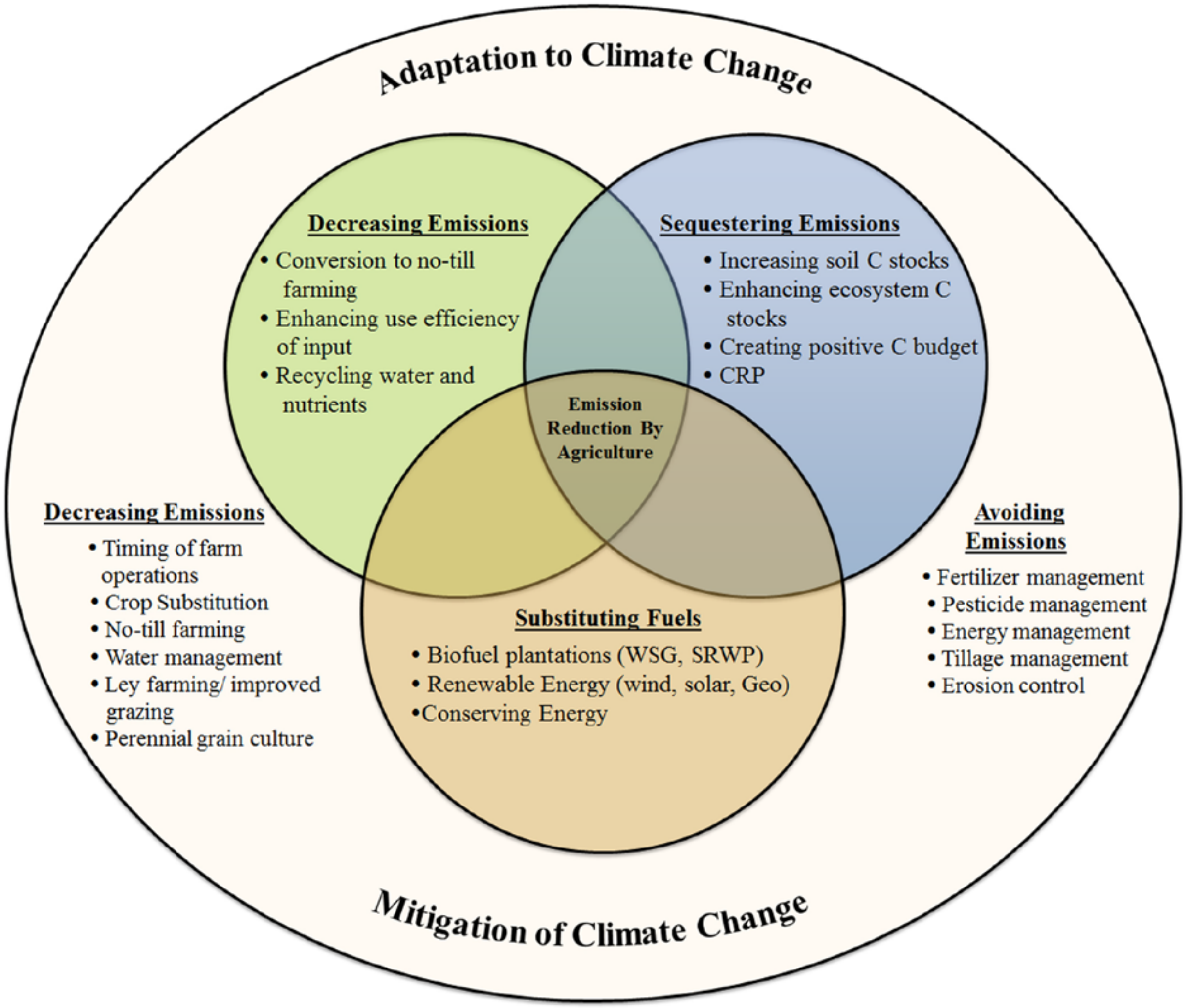

Fig.8 Technical options to develop climate-smart agriculture (WSG: warm season grasses, SRWP: short rotation woody perennials, CRP: conservation reserve program).