SOLAW TR04B

Soil carbon sequestration

SOLAW Background Thematic Report - TR04B

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Abbreviations and acronyms

ACC	Abrupt climate change
BMP	Best management practice
BNF	Biological nitrogen fixation
C	Carbon
Ca^{+2}	Calcium ion
$CaCO_3$	Calcium carbonate
CBM	Coal bed methane
CEC	Cation exchange capacity
CH4	Methane
CO_2	Carbon dioxide
CSS	C capture and storage
EOR	Enhanced oil recovery
g	Gram
GCC	Global carbon cycle
GHGs	Greenhouse gases
GM	Genetically modified
ha	Hectare
INM	Integrated nutrient management
kg	Kilogram
LCA	Life cycle analysis
m	Metre
Mg	Megagram
Mg^{+2}	Magnesium ion
$MgCO_3$	Magnesium carbonate
MMV	Measurement, monitoring and verification
MRT	Mean residence time
N	Nitrogen
N_2O	Nitrous Oxide
NPP	Net primary productivity
NT	No-till
P	Phosphorus
Pedon	The smallest unit of soil containing all the soil horizons of a particular soil type
Pg	Pectagram
Ppm	Parts per million
RMPs	Recommended management practices
S	Sulpher
SIC	Soil inorganic carbon
SOC	Soil organic carbon
SOM	Soil organic matter
Yr	Year
Zn	Zinc

Introduction

This report describes the technical potential of C sequestration in soils, discusses technological options that are available for realizing the potential, and outlines the challenges of turning world soils into sinks for atmospheric CO_2. The goal is to collate, review and synthesize important information on soil C sequestration to enhance the credibility and integrity of the scientific information (Sills, 2010).

An increase in the atmospheric concentration of carbon dioxide (CO_2) (from 280 parts per million (ppm) in the pre-industrial era to 390 ppm in 2010, an enrichment of 39 percent) and other greenhouse gases (GHGs, such as nitrous oxide [N_2O] and methane [CH_4)], may accentuate radiative forcing and alter the Earth's mean temperature and precipitation (IPCC, 2007). The atmospheric concentration of CO_2 at 390 ppm as a volume is equivalent to ~590 ppm as a mass The mass of the atmosphere is 5.14×10^{18} kg (Trenberth *et al.,* 1988). Therefore, the total mass of CO_2 is 3 030 Pectagrams+ (Pg), which is equivalent to 825 Pg of carbon. Because of this strong impact on radiative forcing, there is increasing emphasis on identifying strategies that will reduce the rate of enrichment of atmospheric CO_2 by offsetting anthropogenic emissions. The focus, therefore, is on sequestration of CO_2 from the atmosphere or point sources. Anthropogenic sources include the combustion of fossil fuel, cement manufacturing, deforestation and the burning of biomass, and land-use conversion including drainage of peatlands, soil tillage, animal husbandry, etc.

There is a strong interest in stabilizing the atmospheric abundance of CO_2 and other GHGs to mitigate the risks of global warming. The Conference of the Parties (COP)-15 arrived at the Copenhagen Accord, which suggests reducing net emissions to hold the increase in global temperature below 2 °C (UNFCCC, 2009). Although disappointing, the Accord provides opportunities for limiting warming (Ramanathan and Xu, 2010). Its acceptance implies that CO_2 concentration needs to be limited to below 441 ppm by 2100 by reducing CO_2, CH_4 and N_2O emissions and by offsetting emissions through sequestration of carbon in soils and other terrestrial and inland aquatic ecosystems.

Three strategies are available for lowering CO_2 emissions to mitigate climate change (Schrag, 2007): (i) reducing global energy use; (ii) developing low or no-C fuel; and (iii) sequestering CO_2 from point sources or atmosphere using natural and engineering techniques. Between 1750 and 2003, anthropogenic emissions were estimated at 292 Pg from the combustion of fossil fuels (Holdren, 2008), and at 136 ±30 Pg from land-use change, deforestation and soil cultivation (IPCC, 2001). Currently, approximately 8.3 Pg C yr^{-1} is emitted by fossil fuel combustion (IPCC, 2007; WMO, 2010) and 1.6 Pg C yr^{-1} by deforestation, land-use change and soil cultivation. The total for anthropogenic emissions is 9.9 Pg C yr^{-1}, of which 4.2 Pg C yr^{-1} is absorbed by the atmosphere and 2.3 Pg C yr^{-1} by the ocean. The remainder may be absorbed by unidentified terrestrial sinks.

The global carbon cycle

There are five global C pools, of which the largest oceanic pool is estimated at 38 000 Pg and is increasing at the rate of 2.3 Pg C yr^{-1}. The geological C pool, comprising fossil fuels, is estimated at 4 130 Pg, of which 85 percent is coal, 5.5 percent is oil and 3.3 percent is gas. Proven reserves of fossil fuel include 678 Pg of coal (3.2 Pg yr^{-1} of production), 146 Pg of oil (3.6 Pg yr^{-1} of production) and 98 Pg of natural gas (1.5 pg yr^{-1} of production) (Schrag, 2007). Currently, coal and oil each account for approximately 40 percent of global CO_2 emissions (Schrag, 2007). Thus, the fossil fuel pool is depleting as a result of fossil fuel combustion, at the rate of 8.3 Pg C yr^{-1}.

The third largest pool is in the soil, pedologic and is estimated at 2 500 Pg to 1 m depth. This pool has two distinct components: soil organic C (SOC) pool estimated at 1 550 Pg and soil inorganic C (SIC) pool at 950 Pg (Batjes, 1996). The SOC pool includes highly active humus and relatively inert charcoal C. It comprises a mixture of: (i) plant and animal residues at various stages of decomposition; (ii) substances synthesized microbiologically and/or chemically from the breakdown products; and (iii) the bodies of live micro-organisms and small animals and their decomposing products (Schnitzer, 1991). On the basis of the mean residence time (MRT) or ease of decomposition, the SOC pool can be grouped into three categories: labile with an MRT of days to years, intermediate with MRT of years to decades and centuries and passive with MRT of centuries to millennia.

The SIC pool includes elemental C and carbonate minerals such as calcite, and dolomite, and comprises primary and secondary carbonates. The primary carbonates are derived from the weathering of parent material. In contrast, the secondary carbonates are formed by dissolution of CO_2 in soil air into dilute carbonic acid and its interaction with calcium (Ca^{+2}) and magnesium (Mg^{+2}) brought in from outside the local ecosystem (e.g. calcareous dust, irrigation water, fertilizers, manures). The SIC is an important constituent of soils in arid and semi-arid regions.

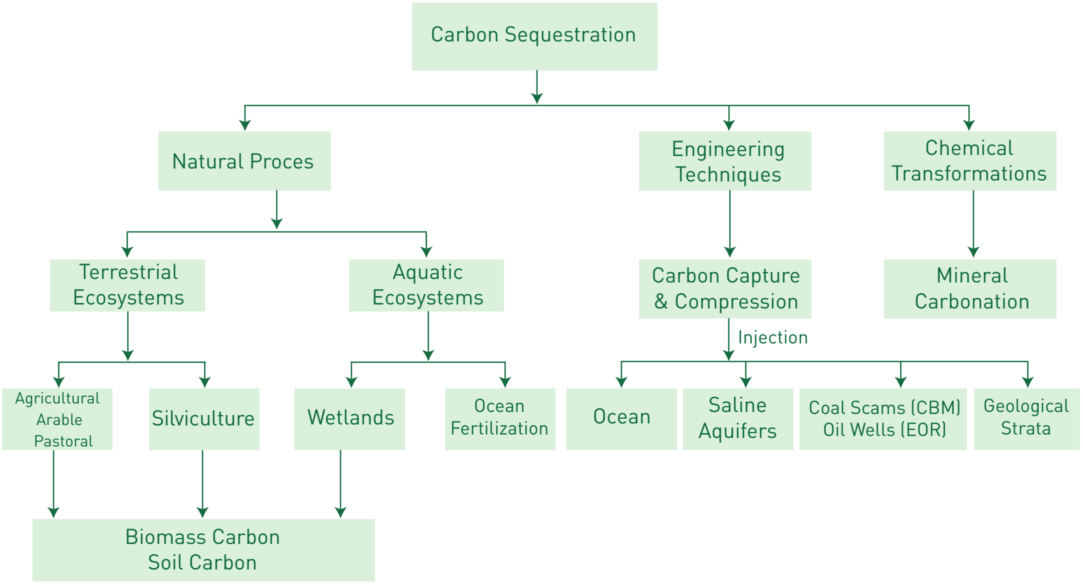
The fourth largest pool is the atmospheric pool comprising ~800 Pg of CO_2-C, and is increasing at the rate of 4.2 Pg C yr^{-1} or 0.54 percent yr^{-1}. The smallest among the global C pools is the biotic pool, which is estimated at 620 Pg, comprising 560 Pg of live biomass and 60 Pg of detritus material. The pedologic and biotic C pools together are called the terrestrial C pool estimated at approximately 3 120 Pg.

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

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

The atmospheric pool is connected to the oceanic pool, which absorbs 92.3 Pg yr^{-1} and releases 90 Pg yr^{-1} with a net positive balance of 2.3 Pg C yr^{-1}. The oceanic pool will absorb approximately 5 Pg C^{-1} yr^{-1} by 2100 (Orr *et al.*, 2001). The total dissolved inorganic C in the oceans is approximately 59 times that of the atmospheric pool. On the scales of millennia, the oceans determine the atmospheric CO_2 concentration, not vice versa (Falkowski et al., 2000).

FIGURE 1: STRATEGIES OF CARBON SEQUESTRATION BASED ON NATURAL PROCESSES, ENGINEERING TECHNIQUES AND CHEMICAL TRANSFORMATIONS



Basic concepts of carbon sequestration

Atmospheric enrichment of GHGs can be moderated by either reducing anthropogenic emissions, or sequestering C in plant biomass or the soil. Transfer of atmospheric CO_2 into other pools with a longer MRT, in such a manner that it is not re-emitted into the atmosphere in the near future, is called sequestration. Depending on the processes and technological innovations, there are three main types of C sequestration (Figure 1): (i) those based on the natural process of photosynthesis and conversion of atmospheric CO_2 into biomass, soil organic matter or humus and other components of the terrestrial biosphere; (ii) those involving engineering techniques; and (iii) those involving chemical transformations (Lal, 2008).

The rate of enrichment of atmospheric CO_2 concentration can be reduced and moderated by its transfer to other pools by mitigative and adaptive options. Mitigative strategies involve those options that either reduce emissions or sequester C. Emission reduction includes those technologies that enhance energy-use efficiency, and involve low-C or no-C fuel sources. In general, natural processes of sequestering C into terrestrial and aquatic ecosystems are more cost-effective and have numerous co-benefits, such as enhancement of ecosystem services, as compared with engineering techniques and conversion of CO_2 into carbonates (Table 1; McKinsey and Company, 2009).

TABLE 1: COST OF CARBON SEQUESTRATION USING DIFFERENT TECHNIQUES

Technique/Strategy	Cost of abatement C / Đ (Mg C eq.)$^{-1}$
Tillage and residue management	-183.3
Waste recycling	-55.0
Degraded-land restoration	36.7
Second-generation biofuels	18.3
Pastureland afforestation	36.7

TABLE 1: COST OF CARBON SEQUESTRATION USING DIFFERENT TECHNIQUES (CONTINUE)

Technique/Strategy	Cost of abatement C / Đ (Mg C eq.)$^{-1}$
Degraded-forest restoration	44.0
Agriculture conversion	91.7
Biomass-co-firing power plant	110.0
Coal-C capture and sequestration	165.0
Gas plant capture and sequestration	220.0

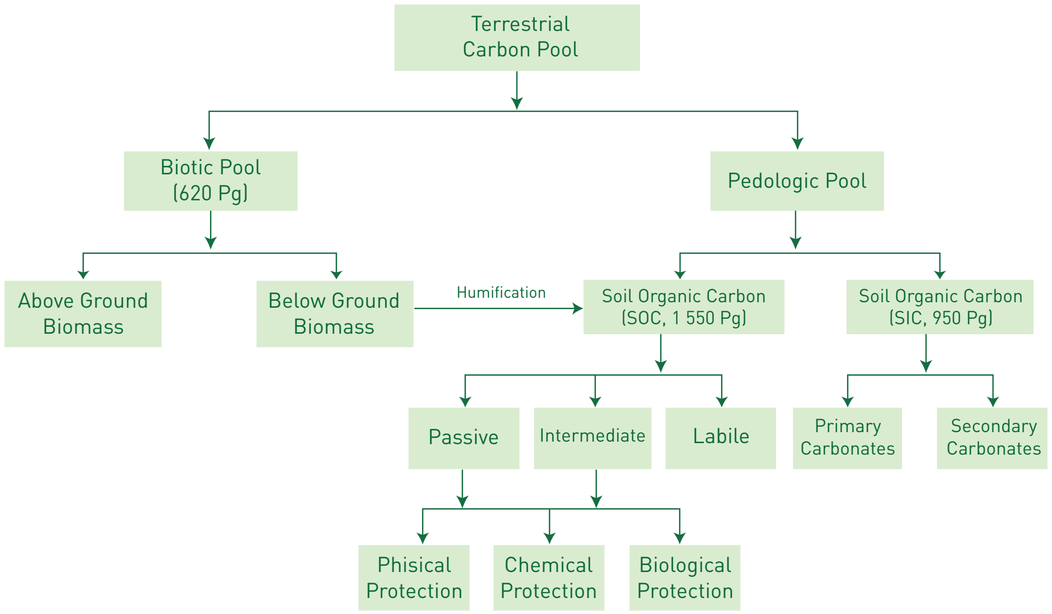
Source: adapted from McKinsey and Company, 2009)

The engineering techniques of C capture and storage (Lackner, 2003; Koonin, 2008; Broecker, 2008) involve injection of compressed and liquefied CO_2 beneath the ocean, into a saline aquifer or into a stable rock strata (Chu, 2009; Haszeldine, 2009). Injecting CO_2 into old oil wells can enhance oil recovery (EOR), and in unmineable coal seams it can displace coal bed methane (CBM). The principal concerns about geologic sequestration are the relatively high cost (McKinsey and Co., 2009; Al-Juaied and Whitmore, 2009), and the need for an established protocol for measurement, monitoring and verification (MMV). Despite the technical potential, the engineering techniques (geologic and oceanic sequestration) are still works in progress, and MMV protocol still needs to be developed and approved.

Mineral carbonation is the transformation of industrial CO_2 into calcium carbonate ($CaCO_3$), and magnesium carbonate ($MgCO_3$) and other minerals in the form of stable carbonates. It is a two-stage process comprised of scrubbing and mineral carbonation. Application of the slow natural processes under industrial conditions requires development of appropriate technology.

Transfer of atmospheric CO_2 into biotic and pedologic C pools is called terrestrial C sequestration (Figure 2).

FIGURE 2: INTERACTION BETWEEN THE PEDOLOGIC (SOILS) POOL AND THE BIOTIC POOL AS TWO DISTINCT BUT RELATED COMPONENTS OF THE TERRESTRIAL POOL



Of the 9.9 Pg C yr^{-1} emitted into the atmosphere, only 4.2 Pg of 43.75 percent of the anthropogenically emitted CO_2 remains in the atmosphere primarily owing to unspecified terrestrial sinks that sequester atmospheric CO_2 and play an important role in the global C cycle. Terrestrial ecosystems comprise a major C sink owing to the photosynthesis and storage of CO_2 in live and dead organic matter. Terrestrial C sequestration is often termed as a win-win or no-regrets strategy (Lal *et al.*, 2003) because of its numerous ancillary benefits (e.g. improved soil and water quality, restoration of degraded ecosystems, increased crop yield). It offers multiple benefits even without the threat of global climate change.

Sequestration of CO_2 by plants occurs both in terrestrial and inland aquatic ecosystems (or wetlands). CO_2 sequestration in terrestrial ecosystems is significant in protected areas and in extensively and intensively managed land-use systems, but to different degrees depending on vegetation, soil types and conditions. Managed ecosystems include the world's croplands, grazing lands, forest lands and urban lands. Restoration of degraded/desertified lands, and drastically disturbed ecosystems (i.e. mined lands) comprise an important sink for atmospheric CO_2. Important strategies for aquatic ecosystems are the management and restoration of wetlands (peat soils and their permanent vegetation). Although fertilization of oceans using iron is technically possible, there are environmental concerns (Kintisch, 2001).

Natural processes of C sequestration in terrestrial and aquatic ecosystems (e.g. soils, vegetation, wetlands) contribute to increased biomass, improved soil health and function, including nutrient cycling, water infiltration, soil moisture retention as well as water filtration and buffering in wetlands. Thereby these processes enhance the resilience of ecosystems and the adaptation of these systems to climatic disruptions with the attendant changes in temperature, precipitation and frequency and intensity of extreme events.

Most soils under the managed ecosystems contain a lower SOC pool than their counterparts under natural ecosystems owing to the depletion of the SOC pool in cultivated soils. The most rapid loss of the SOC pool occurs in the first 20-50 years of conversion from natural to agricultural ecosystems in temperate regions and 5 10 years in the tropics (Lal, 2001). In general, cultivated soils normally contain 50-75 percent of the original SOC pool. The depletion of the SOC pool is caused by oxidation or mineralization, leaching and erosion. Thus, soil C sequestration implies increasing the concentration/pools of SOC (and SIC as secondary carbonates) through land-use conversion and adoption of recommended management practices (RMPs) in agricultural, pastoral and forestry ecosystems and restoration of degraded and drastically disturbed soils. Formation of charcoal and use of biochar as a fertilizer is another option (Fowles, 2007). In contrast with geological sequestration, which implies injecting CO_2 at a depth of 1–2 km, the SOC sequestration involves putting C into the surface layer at a depth of 0.51 m using the natural processes of humification.

Technical potential of soil carbon sequestration using recommended management practices

Transfer of atmospheric CO_2 into the pedologic pools by use of judicious management of soils and vegetation, involves numerous agronomic interactions. Principal agronomic techniques include:

- reduction or elimination of mechanical tillage and adoption of no-till (NT) or minimum till;
- use of crop residues or synthetic materials as surface mulch in conjunction with incorporation of cover crops into the rotation cycle;
- adoption of conservation-effective measures to minimize soil and water losses by surface runoff and accelerated erosion bioengineering;

- enhancement of soil fertility through integrated nutrient management (INM) that combines practices for improving organic matter management (in situ), enhancing soil biological processes involving biological nitrogen fixation (BNF), and mycorrhizae, and additions of organic wastes (biosolids, slurry) and synthetic fertilizers;

- conservation of water in the root zone to increase the green water component by reducing losses through runoff (blue water) and evaporation (grey water), and increasing use efficiency through application of drip irrigation/fertigation techniques;

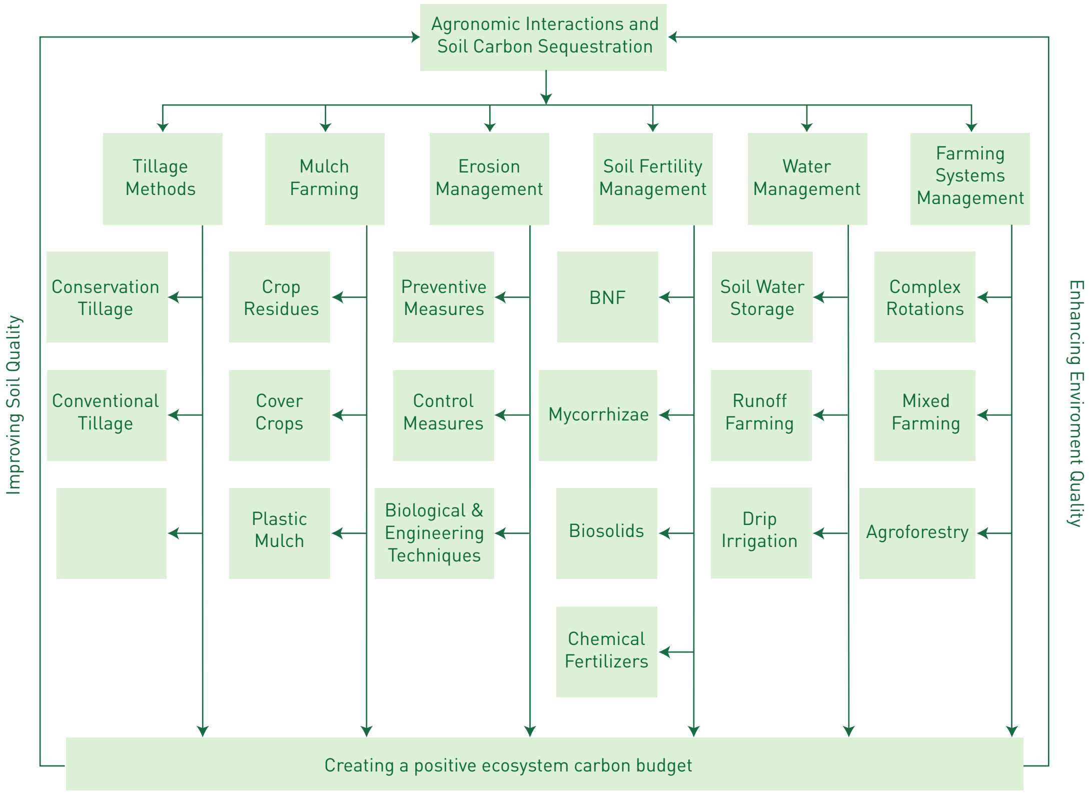
- improvement of grazing systems that enhance the diet of livestock and reduce their enteric emissions; and

- better use of complex farming systems including mixed crop-livestock and agroforestry techniques that efficiently use resources, enhance biodiversity and mimic the natural ecosystems.

The objective of these agronomic interactions (Figure 3) is to create a positive C budget, and improve the quality and productivity of natural resources. The overall goal of sustainable management of soil, water and biological resources is to strengthen and accelerate the coupled cycles of H_2O, C, N, P, and S. Strengthening of these interlinked cycles enhances the resulting ecosystem services by increasing the soil C pool, improving soil biological activity, increasing net primary productivity (NPP), decreasing losses from erosion and leaching, and increasing the humification efficiency.

Strategies for increasing the SOC pool are outlined in Figure 3.

FIGURE 3: **RECOMMENDED MANAGEMENT PRACTICES TO SEQUESTER CARBON IN SOILS**



There is a wide range of degraded soils with a depleted SOC pool. Important among these are those degraded by erosion, nutrient depletion, acidification and leaching, structural decline and pollution/contamination. Restoring degraded soils and ecosystems is a strategy with multiple benefits for water quality, biomass productivity and for reducing net CO_2 emissions. Grainger (1995) estimated that there are approximately 750 million ha of degraded land in the tropics with the potential for afforestation and soil quality enhancement. The sequestration potential is approximately 0.5 Megagram (Mg) ha^{-1} yr^{-1} as SOC and an additional 1.0 Mg ha^{-1} yr^{-1} as biomass, a terrestrial C sequestration potential of 750 million ha is approximately 1.1 Pg C yr^{-1}. Lal (2001) estimated the SOC sequestration potential of 0.4-0.7 Pg C yr^{-1} through desertification control in soils of arid and semi-arid regions. Similar estimates were provided by Squires *et al.* (1995).

West and Post (2002) assessed the SOC sequestration rate upon conversion of plow tillage to no-till (NT) farming after analysis of data from 67 long-term experiments from around the world. They reported the mean rate of SOC sequestration of 570 ± 140 kg C ha^{-1} yr^{-1}, which may lead to the new equilibrium SOC pool in 40–60 years. Lal (2004 a, b) estimated the global SOC sequestration potential, 0.4–1.2 Pg C yr^{-1} or 5-15 percent, of global fossil fuel emissions. Pacala and Socolow (2004) estimated that conversion of plow tillage to NT farming on 1 500 million ha of cropland along with adoption of conservation-effective measures could lead to sequestration of 0.5–1 Pg C yr^{-1} by 2050.

Adopting the INM strategy is essential to SOC sequestration. The humification process can be severely constrained by the lack of N, P, S and other building blocks of soil humus (Himes, 1998). The efficiency of C sequestration is reduced when C and N are not adequately balanced (Paustian *et al.*, 1997). Therefore, the SOC sequestration rate is enhanced by an increase in the application of biomass C (Janzen *et al.*, 1998) and N (Halvorson *et al.*, 2002). Liebig *et al.* (2002) observed that high N rate treatments increased SOC sequestration rates by 1.0-1.4 Mg C ha^{-1} yr^{-1} compared with unfertilized controls. Malhi *et al.* (1997) reported that SOC sequestration depended both on the rate and the source of N application. In Victoria, Australia, Ridley *et al.* (1990) observed that application of P and lime increased the SOC pool in the 0–10 cm layer by 11.8 Mg ha^{-1} over a 68-year period at an average rate of 0.17 Mg C ha^{-1} yr^{-1}.

Application of manure and other organic amendments is another important SOC sequestration strategy. The data from Morrow plots in Illinois indicated that manure plots contained 44.6 Mg ha^{-1} more SOC than unmanured control (Anderson *et al.*, 1990). Several long-term experiments in Europe have shown that the rate of SOC sequestration is greater with application of organic manure than with chemical fertilizers. Increase in the SOC pool in the 0–0.3 m depth after long-term use of manure when compared with chemical fertilizers was 10 percent over 100 years in Denmark (Christensen, 1996), 22 percent over 90 years in Germany (Korschens and Muller, 1996), 100 percent over 144 years at Rothamsted, United Kingdom (Jenkinson, 1990) and 44 percent over 21 years in Sweden (Witter *et al.*, 1993). In Hungary, Arends and Casth (1994) observed an increase in SOC concentration by 1.0–1.7 percent after manuring. Smith *et al.* (1997) estimated that application of manure at the rate of 10 Mg ha^{-1} to cropland in Europe would increase the SOC pool by 5.5 percent over 100 years. In Norway, Uhlen (1991) and Uhlen and Tveitnes (1995) reported that manure application would increase SOC sequestration at the rate of 70–227 kg ha^{-1} yr^{-1} over 37–74 year period.

Soils under diverse cropping systems generally have more SOC than those under monoculture (Drinkwater *et al.*, 1998; Buyanoski and Wagner, 1998). The increase in the SOC pool in subsoil under perennial/forest land use is another option that is used to enhance and increase MRT of C sequestered in the terrestrial ecosystems (Lorenz and Lal, 2005). Elimination of summer fallow is another strategy that is used to minimize losses from the SOC pool (Delgado *et al.*, 1998; Rasmussen *et al.*, 1998). Growing a winter cover crop enhances soil quality through SOC sequestration.

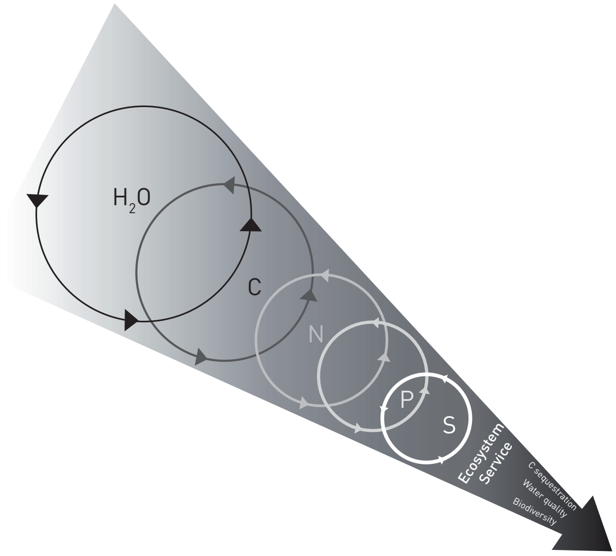
In the United Kingdom, Fullen and Auerswald (1998) reported that grass leys set aside increased SOC concentration by 0.02 percent yr^{-1} for 12 years. In Australia, Grace and Oades (1994) observed that the SOC pool in the 0–10 cm layer increased linearly with an increase in the frequency of pasture in the crop rotation cycle. In comparison with continuous cropping, incorporation of cover crops into the rotation cycle enhanced SOC concentration in the surface layer by 15 percent in Sweden (Nilsson, 1986), 23 percent in The Netherlands (Van Dijk, 1982) and 28 percent in the United Kingdom (Johnston, 1973) over 12–28 year period. Similar results were reported by Lal *et al.* (1998) for cropland in the United States.

The rate of sequestration ranges from negative or zero under arid and hot climates to approximately 1 000 kg C ha^{-1} yr^{-1} under humid and temperate climates (Lal, 2004b, 2005a,b,c). Normal rates of SOC sequestration on agricultural soils are 200–500 kg C ha^{-1} yr^{-1}. High rates are obtained with NT farming, retention of crop residue as mulch, growing cover crops in the rotation cycle and adopting complex farming systems including agroforestry, INM including manuring and restoration of degraded soils by afforestation.

Adoption of RMPs on agricultural and forest soils is a win-win strategy (Follett, 2001; Lal *et al.*, 2003; Lal, 2004a,b, 2006). While improving soil quality and agronomic productivity, agricultural intensification after adoption of RMPs can improve water quality, reduce non-point sources pollution by decreasing dissolved and sediment loads, and decreasing the net rate of CO_2 emissions through SOC sequestration. It is a natural process (Morris, 2006). However, in order to stabilize the sequestered SOC, it is important to understand the stabilizing mechanisms (Six et al., 2002), limitations of biophysical ecosystems in C sequestration (Schlesinger, 1999; Sauerbeck, 2001), and the relevant economic and policy issues (McCarl and Schneider, 2001).

The term 'technical potential of C sequestration' refers to the theoretical maximum sink capacity of a specific pool to which atmospheric CO_2 can be transferred for safe storage and retention over a long period. With specific reference to the C sequestration in soil, the technical potential refers to the C sequestration in soils and wetlands (peat soils) or aquatic ecosystems equivalent to the loss of ecosystem C pool through historic land use and management and soil degradation. The vegetation, and more specifically forests, store atmospheric CO_2 as lignin/suberin and other relatively resistant polymeric C compounds. The forest C is sequestered as harvestable timber and biomass in other woody plants and the below-ground root biomass. The terrestrial NPP may increase with an increase in atmospheric CO_2 because of the 'CO_2 fertilization effect'. The latter implies an increase in NPP at higher atmospheric CO_2 concentration in C-3 plants provided that H_2O, N and other nutrients are in adequate supply. It is in this context, that moderating the coupled cycling of H_2O, C, N, P and S, etc. is important for maximizing the NPP (Figure 4).

FIGURE 4: **MANAGING CYCLING OF WATER, CARBON, NITROGEN, PHOSPHOROUS AND SULPHER TO ENHANCE SOIL QUALITY AND ACCENTUATE ECOSYSTEM SERVICES**



It is argued that the potential CO_2 fertilization effect may peak around the middle of the twenty-first century (~2050). The technical potential of C sequestration in terrestrial ecosystems by 2150 is equivalent to an atmospheric drawdown of 50 ppm of CO_2 (Hansen et al., 2008).

Besides SOC sequestration, there are numerous practices that lead to reduced emissions. The objective is to minimize the use of energy-intensive inputs (e.g. fertilizers, chemical, irrigation, machinery), by reducing losses and enhancing efficiency (Table 2).

TABLE 2: **FOSSIL-FUEL-BASED INPUT FOR MODERN AGRICULTURE**

Agriculture process	Specific activity
1. Seed-bed preparation	Tillage methods (plowing, chiseling, harrowing)
2. Weed/pest control	Intercultivation, herbicides, spraying
3. Soil-fertility management	Fertilizers, applying fertilizers
4. Harvesting	Combine, silage, hay bailing, transport
5. Grain drying	Heating, transport, lifting, storage
6. Marketing	Loading, transport storage
7. Value addition	Processing, packaging, storage, transport

Energy-intensive practices include seedbed preparation, pest management, soil-fertility improvement, and harvesting and grain drying. Improving use efficiency is essential to reducing emissions. Emissions can be drastically reduced by increasing production from existing land so that any additional deforestation can be avoided (Table 3). Converting tropical forest and peatlands to cropland (or energy plantations) creates a large C debt, which may take decades or centuries to repay (Fargione et al., 2008).

TABLE 3: CUMULATIVE AVOIDED EMISSIONS FROM LAND-USE CONVERSION

Land-use	Conversion to	Avoided emissions (Mg C /ha /30 yr
Tropical forest	(Mg C /ha /30 y	(Mg C /ha /30 yr
Tropical cropland	(Mg C /ha /30 y	(Mg C /ha /30 yr
Temperate cropland	(Mg C /ha /30 y	(Mg C /ha /30 yr
Temperate cropland	(Mg C /ha /30 y	(Mg C /ha /30 yr

Source: calculated from Righelato and Spracklen, 2007

Challenges of enhancing soil carbon storage

C sequestration in soils, and other terrestrial ecosystems, have both mitigation and adaptation implications. The mitigation impacts of innovative agricultural systems accrue from the net reduction in GHG emissions. The adaptation impacts of adopting improved soils and crop management systems are based on the reduction of the adverse effects of projected climate change. Yet, there are numerous challenges to realizing the mitigation and adaptation benefits of adopting agricultural innovations.

The importance of applying crop residues as an amendment to enhance the SOC pool has long been recognized (Melsted, 1954; Tisdale and Nelson, 1966). However, the nutritional requirement (e.g. N, P and S) for humification of biomass C and conversion into stable humic substances and organo-mineral complexes is not widely understood. Himes (1998) observed that additional amounts of N, P and S are required to convert biomass C into humus. Jacinthe and Lal (2005) also showed that application of N increased the humification efficiency of wheat straw in a long-term mulching experiment conducted in central Ohio.

Using the data from Morrow plots in Illinois, Khan et al. (2007) reported that use of fertilizer N promoted the decomposition of both crop residues and SOM content. These authors observed no convincing evidence of increase in the SOC pool in fertilized subplots, despite an increase in the input of the biomass-C. On the contrary, a noticeable decline in the SOC pool occurred after the application of fertilizer. However, Drinkwater et al. (1998) showed that in organic systems (without use of chemical fertilizers), legume-based cropping systems reduced C and N losses, presumably because of an increase in N availability after biological N fixation (BNF).

This important issue of the elemental requirements for SOC sequestration needs to be resolved for soil type, crop rotations and tillage method. Soil-specific and demand-specific (yield of grains and biomass, and desired rates of SOC sequestration) rates of N application are required to minimize losses, reduce environmental pollution (leaching of nitrates and emission of N_2O) and maximize energy efficiency. Biological controls of terrestrial C sinks (Schulze, 2006) and their management strategies must be identified. Innovative techniques must be developed to deliver water and nutrients directly to plant roots at the right time (and in the right formulation and amount) so that their use efficiency is high.

An increase in the SOC pool is essential to advancing global food security, especially for increasing agronomic yields in the developing countries of sub-Saharan Africa and South Asia (Lal, 2004a; 2006). However, despite the multiple benefits, the total sink capacity of biotic/terrestrial C sequestration is low and estimated at about 50–100 Pg over 50 to 100 year period (by the end of the twenty-first century). The sink capacity is limited by several interactive factors including the magnitude of historic C loss, higher rate of decomposition because of change in climate, and the more severe problems of erosion and leaching (Lal, 2009c).

Further, C sequestered in the terrestrial ecosystems can be re-emitted with a change in land use, conversion to plow-based systems, soil drainage and adoption of extractive farming practices. There is also a concern regarding the temperature-sensitivity of soil C with global warming and the positive feedback to climate change (Davidson and Janssens, 2006). There are associated C costs of farm operations related to fertilizers and pesticide use, tillage, irrigation and other farm operations (Lal, 2004b) in terms of fuel/energy, emission from the manufacture of nitrogenous fertilizers and so forth. This highlights the need for both sound cost/benefit analysis at the farming system level and assessment of the value chain and opportunities in improving C balance for the main commodities.

Significant advances in understanding the processes leading to SOC sequestration can be made using modern innovations in nanotechnology, biotechnology and information technology. A combination of nanotechnology and biotechnology can provide useful tools for restoring degraded soils and ecosystems and enhancing the SOM pool. Some possible innovations include nano-enhanced products (e.g. nanofertilizers and nanopesticides) with a nanobased smart delivery system (use of halloysite) to provide nutrients at the desired site, time and rate to optimize productivity.

Using such nanoscale formulations of agricultural chemicals can enhance the use efficiency of input, and minimize losses into the environment. Nanoporous materials (e.g. hydrogels and zeolites) can store water in the soil during the rainfall season and release it slowly during the dry season; thus minimizing the adverse effects of drought stress. With remote sensing of edaphic conditions, automatic release of targeted input (nanoscale precision farming) can effectively and efficiently alleviate soil-related constraints. However, C input into deep subsoil may lead to priming of old or passive C (Fontaine et al., 2007), which is an important topic needing additional research.

Similar to nanotechnology, biotechnology has numerous applications that assist understanding and management of pedospheric properties and processes. Relevant examples of such applications include:

- enhancing the SOC pool in terrestrial ecosystems (soils, trees and wetlands) by using genetically modified (GM) plants characterized by a favourable root:shoot ratio and harvest index with a large biomass production, and a deep root system containing recalcitrant compounds (e.g. phenolics);

- expanding the land base by bringing new land under production, which was hitherto not been cultivable, by growing specifically improved crops/cultivars, and restoring degraded ecosystems through bioremediation of contaminated soils;

- growing efficient plants with high BNF capacity, built-in resistance to drought (aerobic rice), anaerobiosis, nutrient/elemental imbalance, unfavorable soil pH/reaction, etc.; and

- developing plants that emit chemical stress signals that can be remotely sensed and treated with targeted inputs to alleviate the stress prior to severe adverse effects on production.

Co-benefits of terrestrial sequestration

There are numerous co-benefits related to enhancing the quantity and quality of the soil C pool. There is a critical/threshold level of the SOC pool below which soil ecological processes are adversely affected by associated negative impacts on numerous ecosystem services. The critical level of SOC concentrations in the root zone of some soils of the tropics is 1.1 percent (11 g/kg) (Aune and Lal, 1998). Enhancement of the SOC pool in degraded/desertified soils can lead to improvements in soil quality (structure, aeration, water-holding capacity, CEC, habitat for soil organisms, etc.), with numerous ancillary or co-benefits.

Important among the co-benefits are:

- reduced plant water stress as a result of enhanced available water capacity in the root zone;
- increased nutrient (N, P, S. Zn, etc.) retention and availability through enhancement of both the intensity and capacity factors;
- enriched species diversity of soil biota, and activity of macrofauna with regards to biotillage effects (e.g. missing, aerating) and microbial biomass/activity, i.e. decomposing, BNF (Rhizobium) and enhancing nutrient uptake especially P (mychorrhizal fungi);
- increased germination, good stand establishment and better plant growth;
- increased water infiltration capacity and reduction in surface runoff or overland flow;
- reduced risk of soil erosion, decline in dissolved and suspended soil particles and nutrients in surface runoff, and reduction of non-point source pollution;
- decreased risk to fish and other aquatic life owing to oxygen depletion in rivers, estuaries and coastal waters;
- increased use efficiency of inputs (e.g. fertilizers, irrigation) through reduction in losses of nutrients and water;
- increased NPP and agronomic yields of crops and livestock/land area, and
- mitigation of climate change by off-setting anthropogenic emissions through C sequestration in trees and soils.

Thus, in general, there is an overall increase in ecosystem services, through the restoration of SOM including a notable improvement in aesthetic value (fewer dust storms, less waterlogging, less prone to flooding, more vegetation). The economic value of the soil is improved by its improved productive potential and the ability of the ecosystems to adapt to climatic variability/disruptions is enhanced. Above all, the increase in SOM concentration is also related to the urgent and important issue of global food security.

Achieving global food security

There are more than 1 billion food insecure people in the world, and the global population is expected to increase by another 2.5 billion to 9.2 billion by 2050. In addition to caloric intake, there is the widespread problem of hidden hunger (Lal, 2009b). A healthy human diet must contain seven macro-elements (Na, K, Ca, Mg, S, P, Cl) and 17 micro-elements (Fl, Zn, Cu, Mn, I, F, B, Sc, Mo, Ni, Cr, Si, As, Li, Se, V, Co). Improving soil quality by increasing SOM is essential for the retention and availability of these elements. Advancing food security will require an increase in cereal production of 70 percent between 2010 and 2050, and the doubling or tripling of agronomic production in most developing countries (Lele, 2010). Thus, the global cereal demand is expected to increase at the rate of 1.75 percent yr^{-1} (Table 4). It is widely recognized that the United Nations Millennium Development Goals will not be met by 2015 (Sastre, 2008).

TABLE 4: GLOBAL FOOD DEMAND BY 2025

Parameter	1995	2025	2050	Annual rate of change (Percentage/yr^{-1})
Population (109)	5.7	7.9	9.2	1.12
Cereal demand (106) Mg	1 657	2 436	3 255	1.75
Area under cereals (Million ha)	506	609	625	0.43
Cereal yield (Mg ha^{-1})	3.3	4.0	5.2	1.04

Source: recalculated from Cassman et al., 2003; Wild, 2003

Note: Cereals include rice, wheat, and maize, which provide 60 percent of all human calories.

The global average cereal yield must be increased accordingly, especially in developing countries. National average crop yields in sub-Saharan Africa and Southern Asia are low compared with those in developed countries. Crop yields are low and highly variable on dryland/rainfed cropping systems, because of drought stress caused by variable and uncertain monsoon rains. The problem of low yields is exacerbated by the severe problem of soil degradation by erosion, depletion of the SOC pool and essential plant nutrients, and either unavailability or lack of access to essential inputs for the resource-poor and low-income farmers. Negative nutrient balance is a problem at the continental scale in sub-Saharan Africa (Anonymous, 2006; Henoa and Baanante, 2006; Vitousek et al., 2009).

While GM crops, organic farming (Tester, 2009), and bio-engineered crops (Skostad, 2009) can be used to enhance crop yields, it is important to realize that there is no viable substitute for judicious soil management. The strategy is to use modern and innovative technologies that sequester C in soils (NRC, 2009), enhance soil/ecosystem/social resilience (Walker and Salt, 2006), and make every drop of rain count towards minimizing drought stress. In this regard, the importance of aerobic rice (especially in the rice-wheat system of South Asia) cannot be overemphasized (Peng et al., 2006; Bouman et al., 2007), because it can conserve water resources.

Innovative technology engaged to meet the future demands must also meet the following criteria:

- limit atmospheric CO_2 concentrations through agricultural ecosystems and land-use conversion (Wise et al., 2009);
- enhance or maintain ecosystem services and minimize their vulnerability to global abrupt climate change (ACC) (Schröter et al., 2005);
- enhance stability and diversity of ecosystems (Ives and Carpenter, 2007); and
- restore degraded soils and ecosystems (Lal, 2009a).

Farming soil carbon

Despite the low cost and numerous co-benefits of C sequestration in soils, there is a great need to promote C sequestration in agricultural soils globally, especially in developing countries. Indeed, the rate of adoption of RMPs for soil C sequestration by farmers, ranchers and foresters is low, especially in developing countries. Even with more than 50 years of research on no-till farming and conservation agriculture, the data in Table 5 show that these practices are adopted on ~7 percent of the world's cropland areas (111 million ha out of 1 500 million ha) (Derpsh, 2007, Kassam et al., 2009; Derpsch et al., 2010). Thus, there is a great need to promote adoption of RMPs that can potentially increase agronomic production (crop, livestock and forest productivity) while improving soil and environment quality, enhancing the resilience of ecosystems and reducing vulnerability, and mitigating climate change with soil C sequestration.

TABLE 5: AREA UNDER NO-TILL FARMING IN DIFFERENT COUNTRIES

	Area under no-till (10^6 ha)	
Country	**2004-2005**	**2009**
United States	25.30	26.50
Brazil	23.60	25.50
Argentina	18.27	19.72
Canada	12.52	13.48
Australia	9.00	17.00
Paraquay	1.70	2.40
China	0.10	1.33
Kazakstan	-	1.20
Indo-Gangetic Plains	1.90	-
Bolivia	0.55	0.71
South Africa	0.38	0.37
Spain	0.30	0.65
Venezuela	0.30	0.30
Uruguay	0.26	0.66
New Zealand	0.20	0.16
Finland	-	0.20
France	0.15	0.20
Chile	0.12	0.18
Colombia	0.10	0.10
Ukraine	-	0.10
Others	1.00	-
Total	**95.75**	**110.76**

Source: recalculated from Cassman et al., 2003; Wild, 2003

One option is to trade C sequestered in soils (and trees), similar to trading of any other farm produce (i.e. corn, soybean, milk, poultry). Trading C credits, through cap-and-trade, would create another income stream for land managers, and it would be an important incentive for investment in soil restoration. The cost of C sequestration by C capture and storage (CCS or engineering) techniques is about US$100/Mg of CO_2 (US$0.367/kg C) (McKinsey and Company, 2009). Even if land managers were compensated at the net price of US$0.10/kg C, it could generate US$30 to US$50/ha/year for C sequestration at the rate of 300 kg to 500 kg C/ha/yr (Lal, 2004a).

In order for C sequestration to become operational and practical, a mechanism should be put in place to reward farmers/land managers so that transaction costs and political obstacles to directing payments to farmers could be minimized. In addition, the MMV process should be established. This additional income would create a strong incentive for the adoption of RMPs by small-size landholders and resource-poor farmers/land managers in developing countries and would promote change to a restorative and more productive land use. Payments for ecosystem services through trading C are a better option than providing subsidies or emergency aid (more sustainable, less risk of increasing dependency or disrupting local markets). Thus, farming C is an important strategy to use to break the agrarian stagnation in sub-Saharan Africa where cereal grain yields have stagnated below 1 Mg/ha (1 tonne/ha) since the 1960s.

Besides direct payments for ecosystem services, improvements in soil quality through SOC sequestration would also enhance agronomic production. An increase in the SOC pool by 1 Mg C/ha in the root zone can increase grain yield by 20–70 kg/ha for wheat, 10–50 kg/ha for rice, 30–300 kg/ha for corn and 10–20 kg/ha for beans (Lal, 2006a). Improving soil quality through an increase in the SOC pool is an important strategy that can bring the green revolution to the smallholders of sub-Saharan Africa (Lal, 2010a).

Need for new tools to measure SOM dynamics

Most measurements of the SOM pool and fluxes are made at a point scale or pedon level, which is the smallest unit of soil containing all the soil horizons of a particular soil type. The impacts of soil C sequestration on ecosystem services must, however, be assessed at the farm, landscape or watershed scales. This means that assessment of the components of ecosystem C budget, using life cycle analysis (LCA) for RMPs versus traditional practices, must be done at the landscape or watershed scale. Such an attempt must include both direct and hidden C costs of all inputs (Table 2) and the fate of C transported by leaching, runoff and sediments and mineralization. A holistic approach to ecosystem C budget would involve full LCA of RMPs versus traditional systems overtime. Besides research on biophysical processes, an economic assessment of SOM-enhancing techniques is also needed (Landers, 2001). Standardized and cost-effective methodology is needed to assess the net C flux from all managed ecosystems (West and Marland, 2004).

Credible measurement of the SOM pool and fluxes at a range of spatial and temporal scales is challenging. Soil scientists have monitored management-induced changes in SOM concentrations in the plough layer since 1850 (Manlay et al., 2007). However, assessment of changes in the SOC pool, and the fluxes in the context of soil C sequestration to offset anthropogenic emissions, requires a different protocol, precision and units of assessment (Mg C ha^{-1} vs g kg-1) to those needed for evaluating soil fertility on cropland soils. While recent developments in methods to measure SOC concentration in the field (Ebinger et al., 2006; Wielopolski, 2006) are noteworthy improvements, techniques must be developed to assess SOC pools over a short period of 1–2 years. An important question that needs answering (Smith, 2004) is: How long before a change in SOM can be detected? A methodology is needed to assess C cycling in the Earth’s system from the perspective of soil science (Janzen, 2004).

As with measurements of SOM concentrations, models of SOM pools and their dynamics have also been developed (Manlay et al., 2007). Whereas considerable progress has been made in predicting the SOM pool in relation to land use, management, soil properties and climatic factors (Nye and Greenland, 1960; Jenkinson and Rayner, 1977; Parton et al., 1987) and more recently with the development of EPIC, ROTH-C, CENTURY, C-QUEST models, etc. There is a great need to predict changes in soil structure and tilth characteristics, along with attendant changes in determinants of soil physical quality, with change in SOM pool and fluxes. Thus, models are needed to:

- understand processes and identify missing links;
- identify needs and determine the technical potential versus achievable potential in soil C sequestrtion;
- develop a framework for diverse management scenarios to optimize the net SOC pool; and
- identify multi-functional land-use/soil management systems in which soil C sequestration is an integral component.

In addition to the management-induced changes in SOM pool and fluxes, it is equally important to model SOM pool and flux in the context of several questions that remain to be addressed concerning climate change. On a global scale, will there be a positive feedback leading to acceleration of the rate of climate change? Alternatively, will the CO_2 fertilization effect and the shift in eco-regions/biomes towards the Earth's poles increase NPP and have a negative/mitigating impact on global warming? Will there be an increase or decrease in the SOC pool in the temperate regions (mid-latitude) with a modest increase in soil temperature?

Charcoal, biochar or black C has gained importance since the identification of terra preta do indio by the late Wim Sombroek in the Amazon (Morris, 2006; Mann, 2008). These are anthrosols made by some tribes in the Amazon, and are characterized by large patches of once agricultural/crop lands that the farmers enriched with charred biomass. Some of these dark and fertile patches contain three times as much N and P as the surrounding soil and 18 times as much SOC. Thus, many researchers argue that use of charcoal is a viable option for improving soil quality and enhancing the SOC pool. Indeed, there is some industry involvement in the manufacture of charcoal-based amendments (Woods et al., 2006). Rumpel et al. (2006) observed that some soils managed by slash-and-burn agriculture are enriched with black C or relatively recalcitrant charcoal.

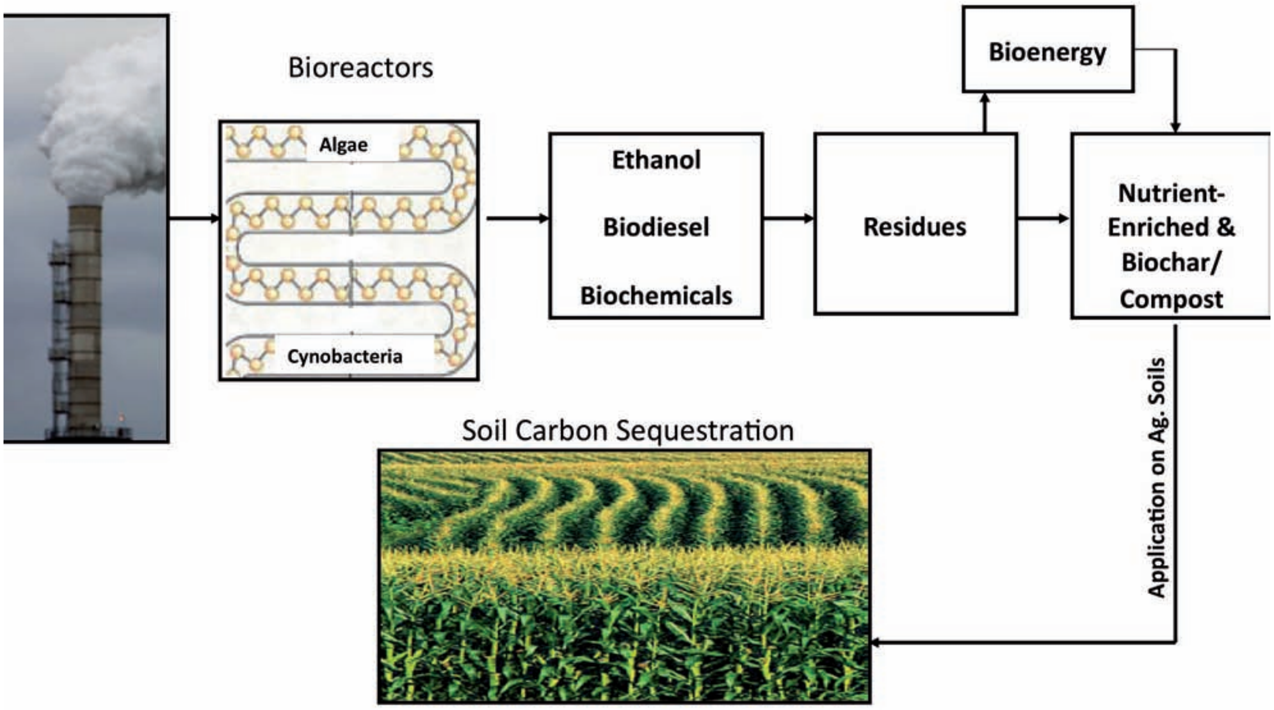
These researchers observed a positive correlation between SOC and black C concentrations. They measured the highest concentration of black C under the most intensively-operated slash and burn practice. Because of its concentration in the surface layer, the black C, similar to other SOC pools, is preferentially transferred to depositional sites by the processes of erosion. Steiner et al. (2007) observed that application of organic fertilizers and charcoal to a much-weathered central Amazonian upland soil increased soil fertility and crop yields. Thus application of charred biomass as a soil amendment/conditioner is one option that is being widely considered (Lehman et al., 2002; 2003; Sohi et al., 2009; Ramanathan and Xu, 2010).

Biofuels and soil carbon pool

Growing biofuel crops and using agricultural co-products (crop and animal residues) strongly impacts soil quality (Lal and Stewart, 2010). Development of clean sources of household fuel is an essential pre-requisite to reducing the use of animal dung (Venkatraman et al., 2005) and crop residues as fuels and applying these as amendments to improve soil quality. Animal dung and other agricultural/urban biosolids could be fed to a biodigester to generate electricity and the by-products synthesized into fortified compost for use as soil amendments. Because crop residues and animal dung are used as biofuel in rural Asia and Africa, such power generators must be developed at the village or community level. In addition, biofuel plantations could be established in rural areas to provide viable sources of clean cooking fuel either as a wood fuel or as a modern liquid fuel (e.g. cellulosic ethanol, biodiesel, etc.) and create employment opportunities.

Growth of cyanobacteria is a way to produce biomass (Figure 5). Rather than using woody perennials (e.g. poplar, willow, eucelyptars and mesquite) and warm season grasses (e.g. switchgrass and miscanthus), it may be prudent to grow algae and cyanobacteri to produce biomass. In addition to C, these organisms play an important role in the Earth's nitrogen (N) and sulfur (S) cycles and can be grown in bioreactors that do not compete with land, water and other scarce and non-renewable resources.

FIGURE 5: GROWING BIOMASS AND CYANOBACTERIA AS BIOFUEL FEEDSTOCKS FROM INDUSTRIAL CO_2 AND CITY WASTEWATER



Crop residues are being widely considered as a source of ligno-cellulosic biomass for conversion into ethanol (Somerville, 2006; Kennedy, 2007). However, few systematic and long-term studies have been designed to assess the impact of residue harvest on SOM concentration, and the rate of C sequestration and soil quality (Wilhelm et al., 2004). Serious concerns are being raised as to whether bio-energy produced from crop residues is effective in improving the C balance (Lal and Pimentel, 2007). The serious question that needs to be critically and objectively answered regards the amount of energy that can be produced without harming the environment (European Environment Agency, 2006). In Ohio, Blanco-Canqui and Lal (2007ab) reported that even 25 percent removal of corn stover from a long-term NT experiment resulted in a significant adverse impact on the SOM pool and soil quality. In addition to loss of nutrients contained in the residues (Singh et al., 2005). Long-term experiments need to be conducted on a wide range of soils and environments, which would then provide information on SOM dynamics under different scenarios of residue harvest.

The impact of N application on the mineralization and humification of a large input of carbonaceous crop residues (e.g. corn, wheat, barley and rice rather than legumes such as soybeans, cowpeas, pigeon peas and alfalfa) is debatable. Khan et al. (2007) indicated the importance of the judicious management of N if crop (corn residues) are to be harvested for bio-energy production. The feasibility of using crop residues as a feedstock for production of cellulosic ethanol (Graham et al., 2007) needs careful and objective analyses. The promise of cellulosic ethanol must be objectively and critically assessed (Lal, 2010b). In addition to using cellulosic biomass as a feedstock for producing ethanol, biomass is being used for producing chemicals derived from cellulose and hemi-cellulose. Hayes (2006) reported that quantitative yields of levulinic acid, a promising feedstock chemical that can be used for fuel additives, polymers and plastics and numerous other essential chemicals, have been obtained in the 'Biofine' process (Hayes, 2006). Major concerns related to removing crop residues are reduced agronomic productivity; increased use of fertilizers and herbicides to compensate for the loss of nutrients; increased weed infestation in the residue-free soil and increased risk of soil erosion and non-point source pollution.

Yield gaps and best management practices (BMP)

The Green Revolution of the 1960s and 1970s, which broke yield barriers and saved hundreds of millions from starvation, occurred in regions characterized by deep soil, assured water supply from abundant rains or supplemental irrigation, and in the presence of strong institutional support and policy interventions that promoted adoption of BMPs. In comparison vast areas, characterized by soils of marginal quality, regions with predominantly rainfed or dry land farming, and small-scale farmers with less than 1 acre (2.47 acres = 1 ha) with no or poor access to markets and institutional support were by-passed by the above-mentioned Green Revolution. Yet, these regions have vast scope for increased food production because of the yield gap between BMPs traditional practices (Wani et al., 2009; Lal, 2010c) (Figure 6).

FIGURE 6: YIELD GAP BETWEEN BMPS AND TRADITIONAL TECHNOLOGIES

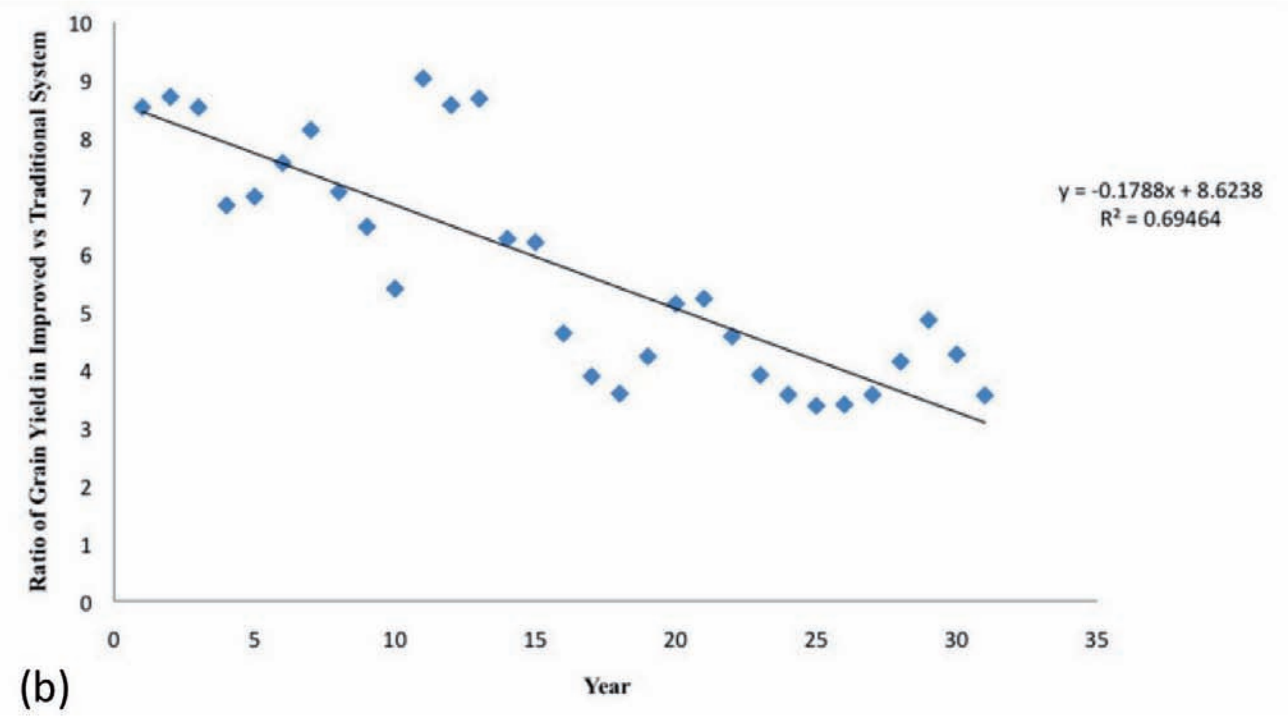
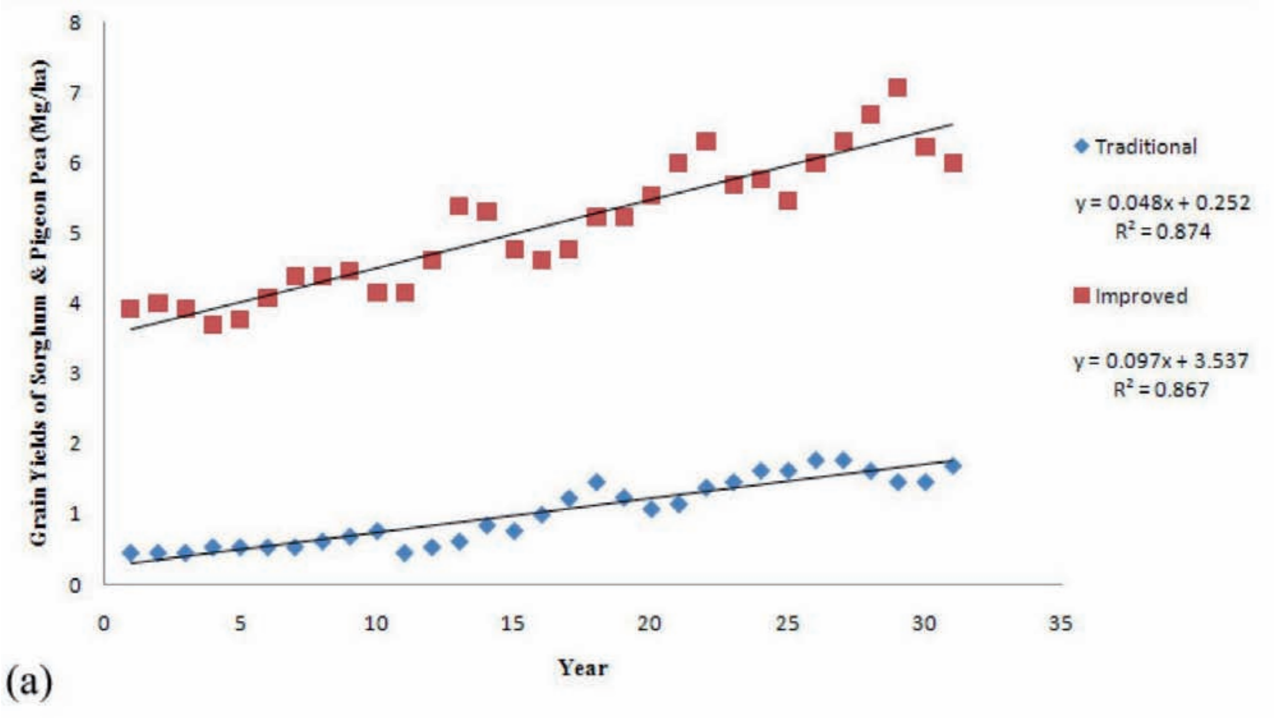


FIGURE 6: YIELD GAP BETWEEN BMPS AND TRADITIONAL TECHNOLOGIES (CONTINUE)



Source: recalculated from Cassman et al., 2003; Wild, 2003

However, the potential remains untapped because of issues related to the human dimensions. For example, the global area under NT farming (and conservation agriculture) is merely 111 million ha (Table 5). The rate of fertilizer application in sub-Saharan Africa is barely 8 kg/ha/yr (Figure 7) and only 5 percent of the irrigable land area is equipped for supplemental irrigation (Table 6). These regions are also home to most of the world's 1.02 billion food-insecure people, whose desperateness demands the widespread adoption of proven technologies required to bring about a quantum leap in food production.

FIGURE 7: (A) WORLD AND (B) REGIONAL FERTILIZER CONSUMPTION

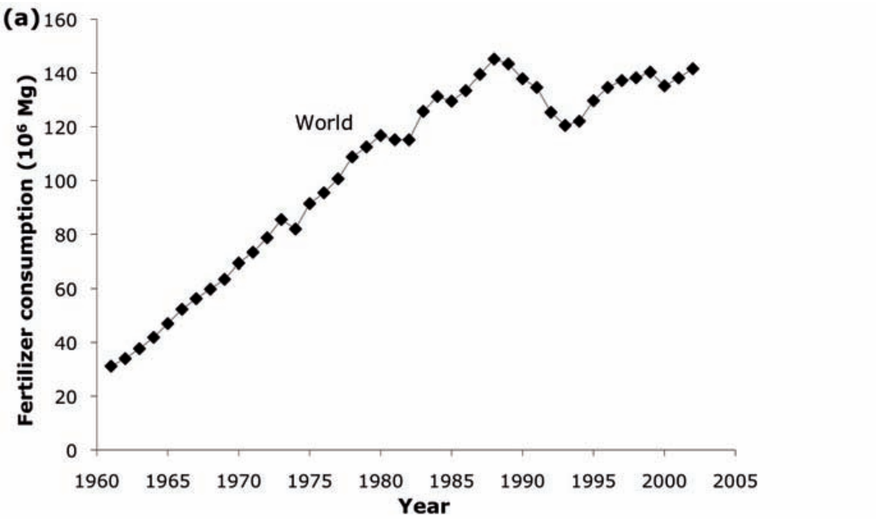
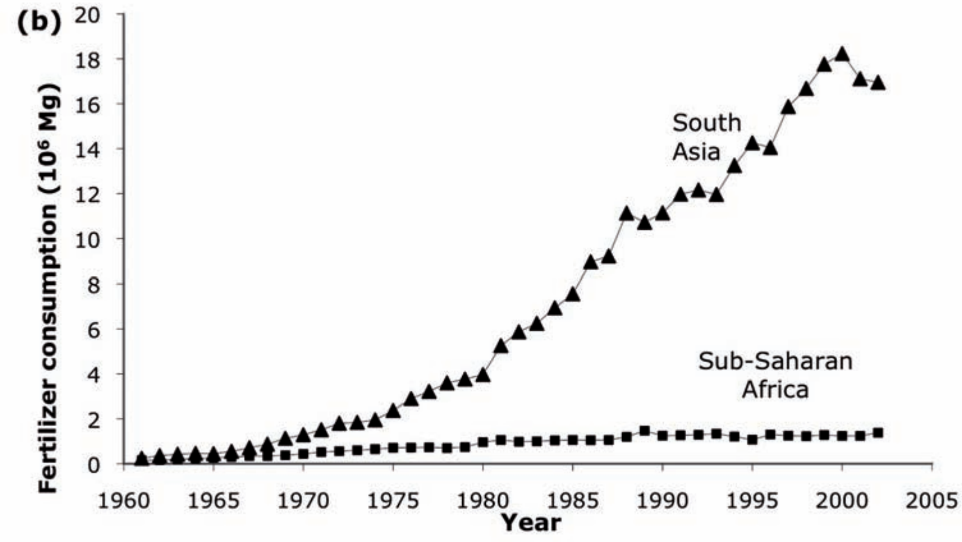


FIGURE 7: (A) WORLD AND (B) REGIONAL FERTILIZER CONSUMPTION (CONTINUE)



Source: Adapted from Lal, 2006 b

TABLE 6: CHANGES IN IRRIGATED LAND AREA IN COUNTRIES OF SUB-SAHARAN AFRICA FROM 1960 TO 2003

Country/ region	1961	1965	1970	1975	1980	1985	1990	1995	2000	2003
					Million ha					
Sub-Saharan Africa	3.45	3.69	3.997	4.353	4.849	5.308	5.781	6.442	6.903	7.023
Madagascar	0.30	0.33	0.330	0.465	0.645	0.826	1.000	1.087	1.086	1.086
Sudan	1.48	1.55	1.625	1.700	1.700	1.763	1.800	1.946	1.863	1.863
South Africa	0.808	0.890	1.000	1.017	1.128	1.128	1.200	1.355	1.498	1.498

Source: Recalculated from FAO, 2005; Lal, 2006b

Reasons best management practices are not adopted by resource-poor farmers

Resource-poor farmers, desperate as they are, follow extractive farming practices. Retention of crop residue as mulch on the soil surface is essential to most BMPs, yet crop residues are systematically removed for numerous competing uses including cattle feed, fuel, fencing, construction material and other household and industrial products. Fertilizers that are essential for enhancing crop yields are either prohibitively expensive, unavailable, or farmers are unsure of their effectiveness under uncertain climate conditions and the high risk of drought.

Improved varieties, high yielding and profitable as these may be under ideal/optional agronomic conditions of water and nutrients, may not produce the assured minimum yield that can be produced by traditional varieties under prevailing conditions characterized by the uncertainties of biotic and abiotic stress. Even if residue mulches are retained, NT systems cannot be adopted without the availability of reasonably priced effective weed control measures and appropriate seeding equipment that can facilitate sowing in an untilled seedbed covered with crop residues and other biomass. Then there is the question of mindset, and other issues pertaining to the human dimension (e.g. land tenure, gender issues, farm size, education), logistic support and infrastructure, especially access to market and institutional support (Lal, 2007).

Enhancing farm income

Poverty alleviation is important among several United Nations Millennium Development Goals, for it is poverty that is a principle constraint to the adoption of BMPs, which require capital investment to restore soil quality and to purchase needed off-farm inputs. The strategy is to enhance the purchasing power of the farming community to facilitate access and use of the inputs required for the adoption of BMPs. It would be prudent to pay farmers to provide ecosystem services that are of interest globally, rather than providing subsidies and emergency aid based on hasty responses. Provision of aid has proven ineffective in Africa and elsewhere because it creates dependency and suppresses initiative, while exacerbating corruption. (See Section on Farming soil carbon).

Ecosystem services, which are created through C sequestration in soil and terrestrial ecosystems, include the co-benefits of BMPs, such as mitigation of climate change, purification of water, denaturing of pollutants as well as the enhancement of biodiversity. Such payments for ecosystem services, dignified and honorable as they are, would create the much needed income stream that is essential for the alleviation of rural poverty while promoting the adoption of BMPs. Farming C is one important strategy that can be used to promote the adoption of BMPs by resource-poor farmers worldwide. Carbon could become a farm commodity that farmers could use as a source of income. Payments would come from the world community for ecosystem services provided by the farmers. This is an important strategy required for the promotion of BMPs, by resource-poor farmers around the world.

Policy implications

Enhancing C sequestration in soils and vegetation requires the adoption of BMPs and for land managers to convert to restorative land use. These practices include use of crop residues as surface mulch, adoption of complex crop rotations and diverse farming systems, use of INM strategies for recycling biosolids and other co-products, etc. There are numerous competing uses of crop residues including production of cellulosic ethanol, co-combustion with coal or wood as biofuel, and use as animal feed, or an industrial raw material. Thus, policy interventions are needed that would promote the use of crop residues and animal manure and other by-products as soil amendments.

Identification and implementation of such policies would reverse the trends of soil degradation, enhance the SOC pool and improve soil quality. In this context, the importance of compensating farmers for ecosystem services through farming C and trading C credits cannot be over-emphasized. This requires organizing small-scale farmers into associations or producers cooperatives to reduce the transaction costs of C trading, monitoring and accounting. In addition, small-scale farmers can be successfully linked to larger farm enterprises where transaction costs are reduced because of contract farming.

Furthermore, projected changes in climate may exacerbate the problems of low agronomic production in sub-Saharan Africa, South Asia and elsewhere in developing countries. Among the numerous causes of decling or stagnating yields in the rice–wheat system in Asia are severe soil degradation and high temperatures in early spring. Thus, policy interventions at regional, national and international levels are required to promote the adoption of RMPs. This, would enhance soil/ecosystem/social resilience (Walker and Salt, 2006) against climate disruption by increasing the terrestrial C pool, and improving the quality of soil, water and natural resources.

Conclusions

Atmospheric concentration of CO_2 at 390 ppm in 2010, and increase at the rate of 2.3 ppm/yr is exacerbating the risks of global warming, soil degradation and desertification and environmental pollution. C sequestration in soils and vegetation, with a technical potential of ~3 Pg C/yr with a drawdown of atmospheric CO_2 by 50 ppm by the end of the twenty-first century, is a cost-effective option with numerous ancillary or co-benefits especially through enhancement of ecosystem services. Important among the co-benefits of enhancing the SOC pool are improved soil quality and the attendant increase in agronomic production (Figure 8).

FIGURE 8: CO-BENEFITS AND ECOSYSTEM SERVICES CREATED BY SOC SEQUESTRATION

The latter is essential for advancing food and nutritional security especially in sub-Saharan Africa, South Asia and other regions faced food deficits and high levels of under- and malnutrition.

In addition to adequate calories, proteins, macroelements (7) and microelements (17) are also needed for a healthy human diet. Adoption of recommended management practices, especially by the small-scale land holders and resource-poor farmers who cannot afford to invest in soil restoration because of prohibitively expensive inputs, can be promoted by payments for ecosystem services. Farming C and trading of C credits sequestered in soils and trees, similar to trading of any other farm produce, can create another income stream for farmers. In comparison with engineering technologies of geologic or oceanic sequestration, C sequestration in soils and vegetation is a cost-effective option. It is a win-win strategy, a low hanging fruit, and an essential development option regardless of the debate on climate change. It is a strategy that humanity cannot afford to neglect. C sequestration enhances soil quality and the associated water and nutrient cycles and thereby it enhances the productive potential of the land – on which all terrestrial life depends.

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