Chapter 2

Soil organic carbon sequestration in agriculture: Issues and priorities

A.K. Nayak[1*], Mohammad Shahid[1], A.K. Shukla[2], Anjani Kumar[1], R. Raja[1], Rahul Tripathi[1] and B.B. Panda[1]
[1]Central Rice Research Institute, Cuttack, Odisha, India
[2]Indian Institute of Soil Science, Bhopal, Madhya Pradesh, India
[*]e-mail: aknayak20@yahoo.com

Following the unprecedented expansion and intensification of agriculture in India, there is clear evidence of a decline in the organic carbon (OC) contents in many soils as a consequence; on the other hand it has been reported that good farming practices such as balanced fertilization and addition of crop residues either maintains or results in build up or depletion of soil organic carbon (SOC) stock (Swarup et al., 2000; Kong et al., 2005). The process of decline of organic matter is accelerated by the process of nutrient depletion, soil erosion and other forces of land degradation. In India, addition of organic matter was considered so important that numerous studies with organic manures were conducted in early saventies. The primary purpose was to determine their nutrient equivalence in comparison to chemical fertilizers. Despite the fact that organic manures contain almost all the essential plant nutrients and produce other non-nutrient benefits also, their value was principally assessed in terms of N only (Katyal, 1993; Tandon, 1997). The benefits of SOC are linked closely to the fact that it acts as a storehouse for nutrients, is a source of soil fertility, and contributes to soil aeration, thereby reducing soil compaction. Other benefits are related to the improvement of infiltration rates and increase in storage capacity for water. Furthermore, it acts as energy source for soil microorganisms. On the other hand intensive rice-based systems as reported from long-term experiments are showing symptoms of 'fatigue', witnessed by stagnating or declining yields (Dawe et al., 2000; Narang & Virmani 2001; Ladha et al., 2003). The depletion of soil fertility, associated with a reduction in quantity and/or quality of soil organic matter are some of the reasons attributed to this decline in yield (Ram 1998; Dawe et al., 2003).

Irrespective of its potential benefits to productivity and profitability, organic carbon might be sequestered by vegetation and soils, as a possible way of mitigating some detrimental effects of global climate change. Soils, managed agricultural soils in particular, represent a potentially significant low to no cost sink for greenhouse gases (GHGs) (Lal, 2004a; Pacala & Socolow, 2004). The great majority of agronomists and soil scientists agree that most agricultural soils can store more carbon and even a modest increase in carbon stocks across the large land areas used for agriculture would represent a significant mitigation of GHG emissions. Nevertheless, there are much uncertainty and debate on the total potential of soils to store additional carbon, the rate at which soils can store carbon, the permanence of this carbon sink, and best way to monitor changes in soil carbon stocks (Sanderman et al., 2010).

This chapter primarily discusses global organic carbon stocks with special reference to India, functions of organic carbon *vis-a-vis* agriculture, SOC sequestration and GHG mitigation potential, commoditization of SOC, stability and turnover of SOC, management options to make agri-

cultural land to store additional SOC along with a summary of field evidence for stocks changes in India. This is followed by a discussion of some of the difficulties in accurately measuring change in SOC stocks.

Soil organic carbon

Soils contain large amounts of carbon in both organic and inorganic forms. Organic C is found in soils in the form of various organic compounds, collectively called soil organic matter (SOM). Soil organic matter includes all living and non-living organic material in all stages of decomposition. The turnover rate of SOM varies due to complex physical, chemical and biological interactions in soil. World soil estimated up to 1 meter depth comprises about 1550 Pg (Pg = Petagram = 1×10^{15} g = billion ton) as organic C is about 2 times the atmospheric pool of 780 Pg, and about 2.5 times the biotic pool of 620 Pg (Lal, 2009). The sheer size of the soil carbon pool and the annual flux of carbon passing through the soil are two of the reasons that SOC can play a significant role in mitigating GHG emissions. Historically, approximately 78 Pg C has been lost from the global soil pool due to land-use conversion for agriculture with approximately 26 Pg attributed to erosion and 52 Pg attributed to mineralization (Lal, 2004b). These large historic losses and the concomitant potential to return to pre-clearing SOC conditions are precisely the reason many researchers believe there is great potential for agricultural soils to sequester large amounts of atmospheric CO_2 relative to current SOC levels.

The Indian situation

Total SOC pool in soils of India is estimated at 21 Pg to 30 cm depth and 63 Pg to 150 cm depth. The SOC pool in soils of India is 2.2% of the world pool for 1 m depth and 2.6% to 2 m depth (Lal, 2004c). It is home to 1.1 billion or 16% of the world population and also supports 500 million domestic animals. The land resources comprises 329 m ha of geographical area with only 161.8 m ha of arable land (11.8% of the world) of which 57.0 m ha (21.3% of the world) is irrigated, 68.5 m ha of forest and woodland (1.6% of the world), 11.05 m ha of permanent pasture (0.3% of the world) and 7.95 m ha of permanent crops (6.0% of the world). Approximately 12 m ha of land is under one or more than one form of degradation arising due to water erosion, wind erosion, salinity, alkalinity, etc. The large land base has a potential to sequester C and enhance productivity while improving environment quality. Hence SOC sequestration, is a truly win-win situation.

Soil organic carbon productivity function and societal value

Soil organic matter plays an important role in many physical, chemical and biological processes in soil; its depletion has numerous adverse ecological and economic consequences. Increase in SOC is accompanied by increase in crop yield and productivity both under fertilized and unfertilized field. Soil organic carbon pool is an important component in formation of both micro- and macro-soil aggregates. The degree of aggregation and the stability of aggregates is directly proportional to SOC concentration. The role of SOC in the formation of stable soil aggregates has major implications for soil structure and, therefore, on water infiltration, water holding capacity, aeration, soil strength and resistance to root growth, and surface crusting (Scholes et al., 1994). In situations where soil moisture or soil strength are major limitations to plant growth, the greatest impact of SOC can be on these physical components of soil fertility. Because of high aggregation, soils with high SOC concentration have high available water holding capacity, low susceptibility to soil erosion, and have low losses of plant nutrients into the ground water. Use efficiency of fertilizer, irrigation and other input is high in soils with high SOC concentration. The most important function of SOC in soil is as a reserve of the nutrients required by plants, and ultimately by the human population. It has a less direct, but nonetheless important effect on nutrient supply through its influence on cation exchange capacity and on the capacity to adsorb anions; and these functions have additional important implications for the impact of toxic ions

and biocidal agrochemicals (Woomer et al., 1994). All other factors remaining the same, soils with high SOC concentration have more agronomic/biomass productivity than those with low SOC concentration (Sandhu et al., 1996).

Soil organic carbon sequestration and greenhouse gas mitigation potential

A substantial portion of emitted carbon dioxide (CO_2) is sequestered in agricultural biomass and soil. The potential of agriculture (excluding bioenergy) to absorb large quantities of atmospheric CO_2 through soil carbon sequestration which has strong synergy with sustainable agriculture is widely being put forward as one of the mitigating options for climate change (Lal, 2002; Post et al., 2004). Thus, one of the more promising ways to reduce the rate of rise in atmospheric CO_2 is to encourage management policies that promote C sequestration in vegetation and ultimately in soils (Idso & Idso, 2002). Soils of India have lower SOC and hence there is a large sink capacity for atmospheric CO_2 sequestration. The IPCC 2nd assessment report estimated that the global potential CO_2 mitigation by agriculture could be in the range of 0.9–2.5 Gt C yr-1 (Gt = Giga tone = 1 x 10^9 t) including 0.5–1.6 Gt C yr-1 from biofuel production, 0.1 Gt C yr-1 from fuel savings and a limited restoration of previously cultivated wetland soils, the remaining 0.4–0.9 Gt C yr-1 mitigation potential from increased soil carbon sequestration. This does not mean that a sequestration potential of several hundreds of Tg C yr-1 would not be worth the trouble to realize, since such an improved soil humus management provides lots of other agricultural and environmental benefits and upset some of the GHG emissions from agriculture particularly rice.

It is estimated that globally, over the next century, agricultural soils could sequester 40 to 80 billion metric tons of carbon (Cole et al., 1997). Total potential of SOC sequestration in India is 12.7 to 16.5 Tg C yr-1 including 7 to 10 Tg C yr-1 for restoration of degraded soils and 6 to 7 Tg C yr-1 for adoption of recommended management practices (RMP) on agricultural soils (Lal, 2004c). The RMP related estimations are based on eco-region wise extrapolation and the rates of SOC sequestration from data of long-term experiments reported in the literature (Swarup, 1998). There could always be a possibility to have forward revision of these figures through adoption of varied innovative management practices and precision in estimation. The recent works on rate of carbon sequestration under different eco-regions in different cropping system with varied soil management options (Purukayastha et al., 2008; Kundu et al., 2007; Banger et al., 2009; Majumdar et al., 2008; Padre-Tirol et al., 2007; Nayak et al., 2009; Nayak et al., 2012) are some examples of technical potential of SOC sequestration. Similarly, different land degradation figure has been reported by various agencies due to use of different scale and methodologies, the first approximation of harmonized statistics shows that about 120.72 m ha as waste land and degraded land (Yadav & Sarkar, 2009), there is a need for its rehabilitation by different land use and soil management practices which could be an important sinks for carbon.

Soil carbon pools

Soil organic carbon can be partitioned into discrete pools according to its age or the amount of time it takes to turn over (Jenkinson & Raynor, 1977; Parton et al., 1987). Mean residence times of these pools are dependent on resistance to decay and the extent of protection against decomposition. The three main SOC pools are: (i) the active pool, with a turnover time in the order of weeks; (ii) the slow pool with a turnover time in the order of decades; and (iii) the passive pool with a turnover time in the order of millennia. The active pool is made up of readily oxidisable materials including, the microbial biomass carbon (MBC), light fractions of organic carbon (Soluble carbohydrates, extracellular enzyme, water extractable C), and is largely controlled by climate and residue inputs. About 10 to 30% active fraction is responsible for maintaining soil microorganisms.

The active soil C pool is most susceptible to soil management practices and is frequently used as an early indicator to SOM dynamics due to its faster turnover (Alvarez et al., 1998), so that changes caused by management or environmental stresses can be detected earlier in this pool

than in the SOC pool as a whole. This can be particularly important in cases where environmental conditions change over a relatively short time. The slow and/ or very slow pools contain moderately decomposable material within macro- and micro aggregates and particulate organic carbon (POC) of 50 μm- 2.0 mm in size (Parton et al., 1987). The passive or recalcitrant pool includes humic acid, fulvic acid, humin, organo-mineral complex formed from the turnover of microbial and slow SOC that are chemically resistant to, or protected from further microbial degradation (Schimel et al., 1994). Humic substances have a complex aromatic structure. Many of the carbon components have hydrocarbon-type structures, whose C-C bonds and C-O-C linkages are difficult to break, and thus are not easily decomposed. Therefore, humic substances represent C component's resistance to biological decomposition in soils.

Stability and turnover of soil organic carbon

Three main mechanisms of SOC stabilization have been proposed: (1) chemical stabilization, (2) physical protection and (3) biochemical stabilization (Christensen, 1996; Stevenson, 1994). Largely chemical stabilization is the result of physico-chemical interaction of SOC with soil minerals through the process of cation bridging, ligand exchange and hydrogen bonding. It depends on various factors, including the characteristics of the organic matter, reactivity and specific surface of soil minerals, base-cation status, presence of Fe and Al oxides, pH, and redox conditions (Sollins et al., 1996; Baldock & Skjemstad, 2000; Von Lutzow et al., 2006). Physical protection of C is intimately tied to processes responsible for creation, turnover, and stabilization of soil aggregates at multiple, often hierarchical, scales (Tisdall & Oades, 1982; Jastrow & Miller, 1998; Six et al., 2004) which make the substrate spatially inaccessible to microbes and enzymes. However, its relevance is mainly limited to topsoil horizons. Biochemical stabilization is understood as the stabilization of SOC due to its own chemical composition (e.g. recalcitrant compounds such as lignin and polyphenols) and through chemical complexing processes (e.g. condensation reactions) in soil. There is an important class of biochemically recalcitrant compounds, generically termed black carbon, formed as result of fire (Lehmann et al., 2008) that can constitute a significant fraction of SOC in most soils.

Soil organic carbon cannot increase forever; it can only reach a certain balanced level (Hassink, 1996). The equilibrium point of SOC over a long time can be affected by many factors including climate, vegetation type, nutrient availability, disturbance, land use, and management practices (Six & Jastrow, 2002). Although tropical conditions favor SOC decline, its level seldom reaches a stage of complete exhaustion. Rather, SOC levels in cultivated soils tend to attain a steady state, described as a lower equilibrium limit (Buyanovsky & Wagner, 1998). There is also an upper limit for SOC that is the equilibrium content typical for a virgin ecosystem. If SOC loss by erosion is negligible, then SOC level in a properly managed soil fluctuates between these two extremes. Cultivation alone tends to stabilize the SOC at the lower equilibrium level, but SOC additions and fertilizer applications tend to shift the equilibrium towards the upper limit.

Hence, similar management practices may result in positive sequestration in one soil that is far from its maximum C stabilization level, while no change in another soil that is much closer to its upper equilibrium point. With the same input of organic material in terms of quantity and quality, clay soils contain more organic matter than sandy soils (Jenkinson, 1988). The annual change of SOC is equal to the annual mineralization amount minus the annual accumulation. Thus, a zero annual change of SOC can be interpreted as having reached a balance because total mineralization must be equal to total accumulation. Therefore, if the actual annual mineralization rate can be determined, it is possible to calculate the requirement of organic materials to reimburse the SOC lost by mineralization in the field, thereby maintaining SOC equilibrium (Chun-Yan et al., 2006). The mean residence times of SOM vary from less than one year to a few hundred years, if properly managed, the soil and plant have a significant potential to act as temporary carbon sinks. The human-induced carbon sinks, however, require a continuous effort, not only in order to be established, but also to be maintained.

Mechanism of soil organic carbon sequestration

Soil carbon sequestration refers to the storage of carbon in a stable form. It occurs through direct and indirect fixation of atmospheric CO_2. Direct soil carbon sequestration occurs by inorganic chemical reactions that convert CO_2 into soil inorganic carbon compounds such as calcium and magnesium carbonates. Direct plant carbon sequestration occurs as plants photosynthesize atmospheric CO_2 into plant biomass. Subsequently, some of this plant biomass is indirectly sequestered as SOC during decomposition processes of aboveground residues, belowground residues-accumulation of SOC due to the humification after plant death and rhizodeposition of root exudates and other root-borne organic substances released into the rhizosphere during plant growth as well as sloughing of root hairs and fine roots by root elongation. In total, various rhizodeposits accounting for up to 7 to 15% of net primary productivity (NPP) (Swinnen et al., 1995). Root exudates probably do not directly contribute much to soil C stocks as most of these low-molecular weight exudates have half-lives of only 20 to 40 minutes in soil (Boddy et al., 2007). In addition to this mycorrhizal fungi also contributes soil carbon stocks. Associations between plant roots and arbuscular mycorrhizal fungi (AMF) are ubiquitous in agroecosytems. Estimates of the amount of C allocated to fungal associates range from 4 to 20% of NPP (Graham, 2000) with a large fraction of this C supporting the growth
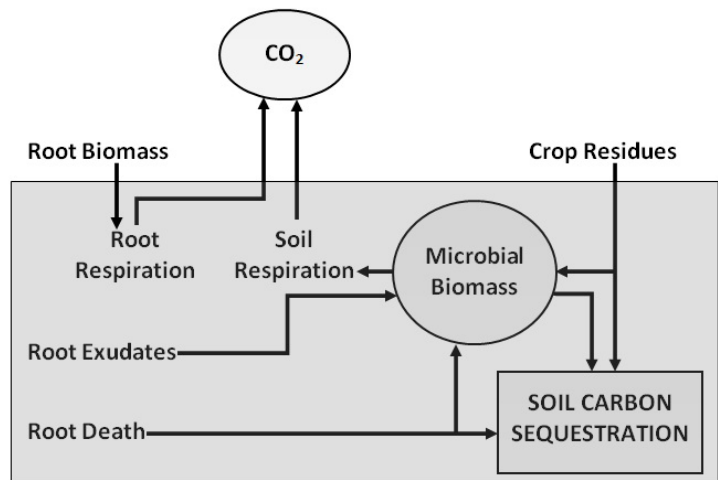

FIGURE 1. *Schematic diagram of soil carbon sequestration*

of new hyphae which have been estimated to have a turnover rate of days to months, while the direct contributions to C stocks from hyphal turnover appears small (Zhu and Miller, 2003), the indirect effects that hyphal growth has on soil structure and aggregate stability can have significant impacts on total SOC stocks (Miller & Jastrow, 1990). However, a glyco protein like substances produced by hyphae termed as glomalin is having very slow decomposition. Photosynthetically active soil microflora also contribute some of the carbon inputs to the soil. The amount of carbon sequestered at a site reflects the long-term balance between carbon uptake and release mechanisms (Fig. 1). Many agronomic, forestry, and conservation practices, including suitable management practices, lead to a beneficial net gain in carbon fixation in soil**.**

Commoditization of soil organic carbon

Soil organic matter is therefore one of our most important national resources; its unwise exploitation has been devastating; and it must be given its proper rank in any conservation policy. There is a need for determining a just value of soil organic carbon as commodity which can be traded like any other farm product. Under valuing a resource can lead to its abuse. It is important to identify criteria for determining the societal value of soil C for soil quality enhancement and ecosystem service, and using it for trading purposes**.** Carbon credits and its marketing are one such international attempt to mitigate the growth in concentrations of GHGs by commoditizing the carbon. Soil and biotic carbon is treated as a tradable commodity under clean development mechanism (CDM) of the Kyoto Protocol.

Clean development mechanism

Kyoto Protocol 1997 establishes the CDM, an institutional framework for direct foreign investments in GHG mitigation projects in developing countries. The objective of the CDM is to stimulate sustainable development in the developing countries, where the CDM projects will be implemented, the so-called host countries, and to give industrialized countries with high mitigation costs access to low-cost GHG offsets (formally Certified Emission Reductions, or CERs, in the Kyoto Protocol) in developing countries. With the CDM, the industrialized countries could count emission reductions and C-sink enhancement in developing countries against their commitments to reduce their GHG emissions. Recently political pressure to include soil activities under the Kyoto Protocol has been growing (New Scientist, 1998), even though the issue is a contentious one for the Parties to the UNFCCC (Nature, 2000). Article 3.3 of the Protocol explicitly mentions emissions from sources and removals by sinks as a direct consequence of human intervention affecting land-use changes, deforestation, reforestation and afforestation undertaken since 1990. Article 3.4 identifies agricultural land as a possible C source which should be included in the emission inventories that are prepared regularly by the UNFCCC Parties. However, the Protocol does not include provisions for national crediting for C sequestration in agricultural soils. During the first five-year commitment period (2008-2012) of the Kyoto Protocol, afforestation and reforestation projects will be eligible for crediting under the CDM. Other sink activities, such as forest conservation and soil C sequestration, will not be eligible. Still, soil C sequestration could become eligible for crediting under the CDM during subsequent commitment periods (Ringius, 2001).

Baseline, permanence and leakage

Baseline establishment is one of the key requirement i.e. carbon emission by sources or reduction by sinks in the absence of the CDM project. Baseline could be based on the most likely land use at the start of project. Additionality is defined as how much of the sequestration is a result of project implementation, beyond the estimated sequestration that would occur without the project. Permanence refers to the life span of the sequestered carbon; that is, whether the additional carbon sequestered at a site can be considered long-term or permanent with a low potential for later release or re-emission. It is evident that soil C re-accumulation schemes would need to be in place over long time-scales, raising the issue of whether C stocks are permanent or potentially reversible. How could stocks be protected against subsequent destructive interference resulting in losses? In this context, it should be realized that below-ground C normally is more protected than above-ground C during fire and other destructive events. Moreover, forests might be felled at a later point, but it is unlikely that agriculture will be reverted back to forests in India. Neither is it likely that farmers who benefit economically from conservation tillage will switch back to intensive tillage practices. More work is needed on the question of permanence of soil C sequestration. For instance, certain types of contracts may help to reduce the risk of reversal of C sequestration (Marland et al., 2001; Ellis, 2001). Carbon sequestration in soils might avoid problems of leakage because of its potential local benefits. The term leakage refers to the situation where a project unintentionally shifts an undesirable activity from the project site to another site, for instance a forest conservation project that prevents deforestation within the project area, and instead increases deforestation outside this area. However, soil C sequestration systems are less likely to create leakage effects because they will frequently be more desirable than alternative land-use systems.

Soil carbon trading

One carbon credit is equal to one ton of CO_2, or in some markets, CO_2 equivalent gases. Certified emission reductions (CERs) are a type of emissions unit (or carbon credits) issued by the CDM Executive board for emission reductions. Greenhouse gas accounting for soil carbon in agriculture under the Kyoto Protocol is based on the rate of change in carbon stock. Therefore, if

conventional practice causes a decline and the new practice reduces the rate of loss, credit can be earned. This is a real reduction in emissions that could be counted under an emissions trading scheme.

Though, the Kyoto Protocol does not include provisions for national crediting for C sequestration in agricultural soils, many Nation States, MNCs invest in carbon sequestration efforts outside Kyoto. This meets Corporate Social Responsibility and also legislations as in California that requires carbon emission reductions or sink enhancement. This ensures the relaxed conditions of additionality, leakage, low transaction costs. It is estimated that conversion of all crop lands to conservation tillage in United States could sequester 25 Gt C over next 50 years. Some farmers have started receiving payments from coal burning utilities in emission trading arrangements brokered through Chicago Climate exchange (Baker et al., 2007) and payment are based on the premises that conservation tillage sequester the equivalent of 0.5 t CO_2 ha^{-1} yr^{-1}. Small and marginal farmers constitute major chunk of land holders in India. Aggregating small land holders (1-5 acre farm size) to make a meaningful transaction is a challenge for paying the benefit of carbon credits. However reputed organization can verify the activity undertaken for C sequestration or reducing C emission and award the VERs (verified emission reduction), which in turn can be traded. However there are many questions remained to be answered before soil carbon trading is reality in agriculture and these are:

a.   Will agricultural soils be approved as means to meet GHG emissions commitments?

b.   Will incentives be adequate so that landowners will maintain practices that sequester C?

c.   Can incentives be designed so that countervailing C losses aren't stimulated?

d.   How will emissions reductions be integrated into total fabric of agricultural policy?

e.   How will international agricultural activities come into play?

Management practices and soil carbon sequestration

The carbon storage below ground in the form of soil organic material may increase agricultural productivity and resilience to climate change. Many promising practices for soil carbon sequestration have been identified (Kimble et al., 2002). Long term studies have shown that improved fertilizer management, manuring and compost application, residue incorporation, crop rotation, green manuring, reduced tillage, adjusting irrigation method, restoration of waste land and agro-forestry enhance C storage. These practices not only promote sustainable agriculture but also mitigate the impact of climate change through both carbon sequestration and minimized emissions of GHGs. A single land use or management practice will not be effective at sequestering C in all regions (Lal et al., 1998). The cropping systems and the management practices that could provide C input higher than the above critical level are likely to sustain the SOC level and maintain good soil health in the subtropical regions of the Indian subcontinent (Mandal et al., 2007). For example, a legume-based cropping system accumulates carbon at a lower rate than a cereal-based system, as its residues decompose more rapidly, and a soil under continuous flooded rice (rice-rice) accumulates carbon at a higher rate than under a rice-wheat rotation that is aerobic for part of the time. Long term experiments on rice based system has shown that balanced fertilization with NPK, however, caused an enrichment (9.3-51.8% over the control) of SOC, its extent being influenced by the cropping systems (Mandal et al., 2007). Similarly in long term rice-wheat experiment conducted in different agro-climatic zones of India, indicated that application of 50% NPK + 50% N through FYM in rice, 100% NPK in wheat (NPK + FYM), sequestered 0.39 0.50, 0.51 and 0.62 Mg C ha^{-1} yr^{-1} over control (no NPK fertilizers or organics), respectively at Ludhiana (Trans Gangetic Plains), Kanpur (Upper Gangetic Plains), Sabour (Middle Gangetic Plains) and Kalyani (Lower Gangetic Plains) (Nayak et al., 2012). In India each year 19.6 m t of straw of rice and wheat are burnt. If used as recycled biomass, this potentially translates into 3.85 m t of organic carbon, 59,000 tonnes of nitrogen, 2,000 tonnes of phosphorous

and 34,000 tonnes of potassium and could be one of the potential options for improving the SOC stocks of soil. Saline and sodic soils are of widespread occurrence in the arid and semiarid regions of northern India, limiting the productivity of more than 2.5 m ha of otherwise arable lands in the Indo-Gangetic plains (Abrol & Bhumbla, 1971). Afforestation and reclamation of these lands through agroforestry systems have been reported to increase SOC content and improve the biological properties of sodic soils (Singh, 1996; Singh & Singh, 1997). When sodic soil was reclaimed and restored, we estimated SOC sequestration rate of 0.826 Mg C ha^{-1} yr^{-1} under *Prosopis juliflora* plantations and 0.689 Mg C ha^{-1} yr^{-1} under rice-wheat system (A.K. Nayak, personal communication 18 Feb, 2012). If offset payments to agricultural activities and payments to the carbon credit gained so in developing countries are allowed under a new climate change agreement, there is significant potential for mitigation activities involving land use including practices such as conservation agriculture, improved nutrient and water management and conversion of low-productivity crop land to pasture or agriculture and, in some cases, to forests.

Converting harvestable biomass to more recalcitrant C rather than completely combusting it offers a new approach to terrestrial sequestration as a potential side benefit of bioenergy production and is called Biochar or Biomass carbonization. With low-temperature pyrolysis, biomass is carbonized by heating under low-oxygen conditions while producing liquid and gaseous biofuels. Since combustion would not be complete, char-like substances would also be produced (Post et al., 2009). There is a scope for converting 19.6 million tonnes of straw of rice and wheat which are burnt annually in India into chemically stable forms – through biochar a clean process where heat and combustible gases are captured and used and C is stored in soil. Recent developments in genomics provide an unprecedented opportunity to identify genes, enzymes, biochemical pathways, and regulatory networks that underline rate-limiting steps in C acquisition, transport, and fate-and thereby yield new approaches to enhance terrestrial C sequestration. An investment in these new approaches to increase biomass production in agricultural crops and fast-growing trees in managed plantations is required to tap the potentials.

Measurement, monitoring and verification of soil organic carbon

To monitor carbon changes in soil and biotic pool, there is a need to improve the accuracy and costs of soil carbon sampling and measurement methodology. Stocks of organic C in soils are determined from two variables, namely SOC concentration and bulk density. Determination of organic carbon concentration is usually done by wet oxidation (Walkley & Black, 1934) or dry combustion (Wang & Anderson, 1998). The wet oxidation method is known to underestimate the amount of organic C in most samples so a correction factor needs to be applied. The magnitude of the correction factor is known to vary across soil types. Despite more accurate methods being available, the Walkley-Black technique is still used in some laboratories, particularly in India. Significant progress has been achieved during the past 10 years toward refining, enhancing, and adapting the method for measuring and monitoring soil carbon sequestration at field and regional scales. It is now possible to measure soil carbon changes as small as 1 Mg C ha^{-1} in a period of 3 years (McConkey et al., 2000) or estimate it with the use of simple or complex simulation models (Paustian et al., 1997; Smith, 2007). Measurement needs to be corrected and the measurement process needs to be unbiased, and more accurate measurements will be more broadly accepted. Article 3.4 of the Kyoto Protocol states that "uncertainties, transparency in reporting, and verifiability" should all be accounted for when monitoring carbon sink activities (Smith, 2004).

Recently several instruments have been developed for *in-situ* measurements of soil carbon which include laser-induced breakdown spectroscopy (Cremers et al., 2001), inelastic neutron scattering (Wielopolski, 2000), and diffuse reflectance IR spectroscopy (Christy et al., 2006) in the near-infrared and mid-infrared wavelength regions of 400–2500 and 2500–25,000 nm, respectively. Measurement and monitoring approaches using current or advanced methods need to be integrated to field-level and regional scales using computer simulation and remote sensing on some dynamic and geographically appropriate basis (Paustian et al., 1997; Smith, 2007). For

trading purpose uncertainties in measurement, transparency in reporting, and verifiability should be accounted for when monitoring carbon sink activities.

Monitoring soil carbon changes at the project level are potentially costly and highly variable in carbon stocks on micro and macro scales due to multiple pools and small incremental changes anticipated. Hence estimation of soil carbon change could be undertaken by: 1) using SOC stock change values for specific practices reported in literature based on research studies; or 2) using process-based models of soil carbon dynamics, parameterised from experimental data; or 3) through a combination of baseline measurement to assess the vulnerability of soil carbon pools, and modeling informed by baseline measurements and understanding of the factors driving soil C dynamics.

Calculation of soil organic carbon stocks

Carbon results are generally reported in metric tons of CO_2 equivalents and compared to reference sample data to determine carbon additionality potential. Equations for conversion of carbon (C) results to CO_2 equivalents (Tian et al., 2009) are as follows:

Where %C = Mean percent organic carbon over the depth interval & treatment unit of interest

$$\text{SOC stock (Mg SOC ha}^{-1}) = \frac{\%C}{100} \times BD \times AD \times \frac{1000 \text{ m}^2}{\text{ha}}$$

BD = Mean bulk density (in Mg m^{-3})

AD = Soil depth interval of interest (in m)

Conversion to CO_2 equivalents in Mg (metric tons) per hectare:

Quantitative and reliable assessment methods of SOC are required to characterize soil properties and ecosystem functions. Soil organic C is a dynamic pool, and net changes in C sequestra-

$$\frac{\text{Mg CO}_2}{\text{ha}} = \frac{44 \text{ g/mole CO}_2}{12 \text{ g/mole C}} \times \frac{\text{Mg C}}{\text{ha}}$$

tion often are more informative than absolute quantities. It is important to quantify temporal changes, whether caused by ecosystem development or by management practices, because they manifest changes in crucial properties of ecosystems (properties of soils) and of the ecosphere (atmospheric CO_2) (Ellert et al., 2002). Soil based approaches typically integrate various pieces of information, such as (i) temporal changes in SOC at single point, (ii) spatial variation in SOC distribution and associated cycling processes within landscape, (iii) geographical data on key variable such as land use, plant cover, soil properties, and climatic regime.

Modelling of soil organic carbon stock changes

Over the years, several review studies on soil carbon dynamics have been carried out to establish the state-of-the-art, identify shortcomings in the current modeling approaches for estimating and projecting SOC changes. Jenkinson (1990) classified SOM models based on the number of pools as single homogenous, two and multi-component models. Paustian (1994) grouped multi-component models into organism-oriented and process-oriented, based on soil biology and biochemical processes. McGill (1996) grouped 10 process-oriented multi-component models based on relevant attributes, such as their static and dynamic nature, spatial and temporal scale, soil properties and homogeneity of soil horizons, and effect of microbial biomass on dynamics of organic matter. Smith et al. (1999) reviewed SOM models for tropical ecosystems, covering model

use, input requirements, and outputs. Ma & Shaffer (2001) reviewed nine U.S. soil nitrogen dynamics models, as did McGechan & Wu (2001) for European models. They compared the descriptions of soil carbon and nitrogen dynamics in these models and the effect of various environmental factors on these processes. Grace & Merz (2001) classified models based on their main disciplinary orientation into ecological or agro-ecosystem models and agricultural or agronomic models, based on the data used for their calibration. RothC and Century (Cerri et al., 2004), have been demonstrated for several agricultural systems/ soil type combinations in India and abroad. Some of the SOM models and their characteristics for predicting SOC changes are given in Table 1.

TABLE 1. *Characteristics of various soil organic matter models for predicting soil organic carbon change*

Model	Land use system	Pool	Component
CANDY	Arable	3 OM pool (active, stable, inert)	C and N Sub model
CENTURY	Grass land, arable, forest	2 litter pool (AOM metabolic AOM structural) 3 SOM pool (active, passive, slow)	Forest sub-model, grass and crop sub-model, simulates the dynamics of C, N, P and S
DNDC	Arable	4 OM pool (litter, MBC, active humus, passive humus)	Soil physical environment, plant growth, organic matter decomposition, and denitrification
NCSOIL	Arable	2 residue pool , 4 SOM pool	NCSOIL is a stand-alone model
ROTHC	Soil in various system	Same as CENTURY	Does not contain a sub-model for plant production
SOMM	Forest	3 OM pool (litter, decompose dlitter, topsoil humus)	Stand-alone model
Verberne	Grass land	3 FOM pool (decomposable, structural, resistant), SOM Pool (nonprotected, protected, stabilised)	Soil water sub-model, soil organic matter sub-model, and soil N sub-model
Hybrid	Ecosystem	Same as CENTURY	Stand-alone model
ICBM	Arable	Two compartment model does not include plant processs	Stand-alone model

OM=Organic matter, SOM=Soil organic matter, AOM = Added organic matter, FOM =Fresh organic matter

Conclusions

Many of the management options discussed in the paper tend to increase overall sustainability of existing agricultural systems and as such are required to be adopted in respective agro-ecological situations in India. As a society, we will have to assess whether or not it is acceptable to compromise productivity of certain crops because they are not C neutral or net carbon storing. Overall, it is suggested that farming practices that increase soil C accumulation without compro-

mising yield should be encouraged. However many mitigation options in the agricultural sector have numerous co-benefits in terms of food security, environmental sustainability and farm profitability, we believe that governmental policies that promote adoption of these best management practices should be pursued regardless of the final status of agricultural soils in any carbon pollution reduction scheme. Continued efforts should be made for evaluating different agro-technologies having high sequestration potential and low global warming potential without compromising the yield. Due to the complex nature of agriculture in India, quantitative predictions of SOC sequestration rates will likely always entail a large degree of uncertainty. For proper accounting at regional and national scale, there is a need for robust modeling coupled with detailed measurements in representative systems combined with verification of management practices and yields via reporting and remote sensing with some economic discounting to factor in verification uncertainty. Developing mechanisms and procedures for carbon trade negotiations and formulation of protocols under CDM projects for making other sink activities in our country such as forest conservation and soil C sequestration eligible for carbon credit is needed so that the farmers and land managers can be benefited and this can futher be extended to cover degraded and desertified soils. The political and economic problems associated with implementing soil C sequestration programs and its trading worldwide needs to be studied.

References

Abrol, I.P., & Bhumbla, D.R. (1971). Saline and alkaline soils in India, their occurrence and management. *World Soil Resources, FAO Report*, 41, 42-51.

Alvarez, C.R., Alvarez, R., Grigera, M.S., & Lavado, R.S. (1998). Associations between organic matter fractions and the active soil microbial biomass. *Soil Biology and Biochemistry*, 30, 767-773.

Baker, J.M., Ochsner, T.E., Veterea, R.T., & Griffis, T.J. (2007). Tillage and soil carbon sequestration. What do we really know?. *Agriculture Ecosystems and Environment*, 118, 1-5.

Baldock, J.A., & Skjemstad, J.O. (2000). Role of the soil matrix and minerals in protecting natural organic materials against biological attack. *Organic Geochemistry*, 31, 697-710.

Banger, K., Kukal, S.S., Toor, G., Sudhir, K., & Hanumantharaju, T.H. (2009). Impact of long term additions of chemical fertilizers and farm yard manure on carbon and nitrogen sequestration under rice-cowpea cropping system in Semi-Arid Tropics. *Plant and Soil*, 318, 27-35.

Boddy, E., Hill, P.W., Farrar, J., & Jones, D.L. (2007). Fast turnover of low molecular weight components of the dissolved organic carbon pool of temperate grassland field soils. *Soil Biology & Biochemistry*, 39, 827-835.

Buyanovsky, G.A., & Wagner, G.H. (1998). Changing role of cultivated land in the global carbon cycle. *Biology and Fertility of Soils*, 27, 242-245.

Cerri, C.E.P., Paustian, K., Bernoux, M., Victoria, R.L., Melillo, J.M., & Cerri, C.C. (2004). Modeling changes in soil organic matter in Amazon forest to pasture conversion with the Century model. *Global Change Biology*, 10, 815-832.

Christensen, B.T. (1996). Carbon in primary and secondary organomineral complexes. In M.R. Carter, B.A. Stewart (Eds.), *Structure and organic matter storage in agricultural soils.* (pp. 97-165). Boca Raton, FL: CRC Press.

Christy, C.D., Drummond, P., & Lund, E. (2006). *Precision agriculture: Applications of an On the-Go Soil Reflectance Sensor*. Salina, Kans: Veris Technologies.

Chun-Yan, W.U., Chen, Y., Wang, J., & Wang, S. (2006). Estimation of turnover and equilibrium of soil organic matter using a mathematical approach. *Pedosphere*, 16(5), 634-645.

Cole, C.V., Duxbury, J., Freney, J., Heinemeyer, O., Minami, K., Mosier, A., Paustian, K., Rosenberg, N., Sampson, N., Sauerbeck, D., & Zhao, Q. (1997). Global estimates of potential mitigation of greenhouse gas emissions by agriculture. *Nutrient Cycling in Agroecosystems*, 49, 221-228.

Cremers, D.A., Ebinger, M.H., Breshears, D.D., Unkefer, P.J., Kammerdiener, S.A., Ferris, M.J., Catlett, K.M., & Brown, J.R. (2001). Measuring total soil carbon with laser-induced breakdown spectroscopy (LIBS). *Journal of Environmental Quality*, 30, 2202-2206.

Dawe, D., Dobermann, A., Ladha, J.K., Yadav, R.L., Bao, L., Gupta, R.K., Lal, P., Panaullah, G., Sariam, O., Singh, Y., Swarup, A., & Zhen, Q.X. (2003). Do organic amendments improve yield trends and profitability in intensive rice systems?. *Field Crops Research*, 83, 191-213.

Dawe, D., Dobermann, A., Moya, P., Abdulrachman, S., Singh, B., Lal, P., Li, S.Y., Lin, B., Panaullah, G., Sariam, O., Singh, Y., Swarup, A., Tan, P.S., & Zhen, Q.X. (2000). How widespread are yield declines in long-term rice experiments in Asia?. *Field Crops Research*, 66, 175-193.

Ellert, B.H., Janzen, H.H., & Entz, T. (2002). Assessment of a method to measure temporal change in soil carbon storage. *Soil Science Society of America Journal*, 66, 1687-1695.

Ellis, J. (2001). *Forestry projects: Permanence, credit accounting and lifetime*. Paris: OECD.

Grace, P.R., & Merz, S.K. (2001). Net Ecosystem Exchange workshop proceedings. CRC for Greenhouse Accounting, Canberra.

Graham, J.H. (2000). Assessing costs of *arbuscular* mycorrhizal symbiosis in agroecosystems. In G.K. Podila, D.D. Douds Jr. (Eds.), *Current advances in mycorrhizae research*. (pp. 127-139). St. Paul, MN: APS Press.

Hassink, J. (1996). Preservation of plant residues in soils differing in unsaturated protective capacity. *Soil Science Society of America Journal*, 60, 487-491.

Idso, S.B., & Idso, K.E. (2002). Global warming: Carbon sequestration to mitigate. In R. Lal (Ed.), *Encyclopedia of soil science*. (pp. 612-614). New York: Marcel Dekker.

Jastrow, J.D., & Miller, R.M. (1998). Soil aggregate stabilization and carbon sequestration: Feedbacks through organo-mineral associations. In R. Lal, J. M. Kimble, R. F. Follett, B.A. Stewart (Eds.), *Soil processes and the carbon cycle*. (pp. 207-273). Boca Raton, FL: CRC Press.

Jenkinson, D.S. (1990). The turnover of organic carbon and nitrogen in soil. *Philosophical Transactions of the Royal Society*, *London*, B329, 361-368.

Jenkinson, D.S. (1988). Soil organic matter and its dynamics. In A. Wild (Ed.), *Soil conditions and plant growth* (11th ed.). (pp. 564-607). UK: Longman Group.

Jenkinson, D.J., & Raynor, J.H. (1977). The turnover of soil organic matter in some of the Rothamsted classical experiments. *Soil Science*, 123, 298-305.

Katyal, J.C. (1993). Integrated nutrient management and supply: An overview. *Proceedings of Indian National Science Academy*, B59(3&4), 161-172.

Kimble, J.M., Lal, R., & Follett, R.R. (2002). Agricultural practices and policy options for carbon sequestration: What we know and where we need to go?. In R. Lal, J.M. Kimble, & R.F. Follett (Eds.), *Agricultural practices and policies for carbon sequestration in soil*. (p. 512). New York: Lewis Publishers.

Kong, A.Y.Y., Six, J., Bryant, D.C., Denison, R.F., & van Kessel, C. (2005). The relationship between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems. *Soil Science Society of America Journal*, 69, 1078-1085.

Kundu, S., Bhattacharyya, R., Ved Prakash, Ghosh, B.N., & Gupta, H.S. (2007). Carbon sequestration and relationship between carbon addition and storage under rainfed soybean–wheat rotation in a sandy loam soil of the Indian Himalayas. *Soil and Tillage Research*, 92, 87-95.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R.,

Bhattarai, E.M., Das, S., Aggarwal,, H.P., Gupta, R.K., & Hobbs, P.R. (2003). How extensive are yield declines in long-term rice-wheat experiments in Asia?. *Field Crops Research,* 81, 159-180.

Lal, R. (2002). Carbon sequestration in drylands. *Annals of Arid Lands,* 38, 1-11.

Lal, R. (2004a). Soil carbon sequestration impacts on global climate change and food security. *Science,* 304, 1623-1627.

Lal, R. (2004b). Soil carbon sequestration to mitigate climate change. *Geoderma,* 123, 1-22.

Lal, R. (2004c). Soil carbon sequestration in India. *Climatic Change,* 65, 277-296.

Lal, R., Kimble, J.M., Follett, R.F., & Cole, C.V. (1998). *The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect.* Chelsea, Mich.: Ann Arbor Press.

Lal, R. (2009). Soil carbon sequestration for climate change mitigation and food security. *Platinum jubilee of ISSS Souvenir.* (pp. 39-46). New Delhi: Indian Society of Soil Science.

Lehmann, J., Skjemstad, J., Sohi, S., Carter, J., Barson, M., Falloon, P., Coleman, K., Woodbury, P., & Krull, E. (2008). Australian climate-carbon cycle feedback reduced by soil black carbon. *Nature Geoscience*, 1, 832-835.

Ma, L., & Shaffer, M.J. (2001). A review of carbon and nitrogen processes in nine U.S. soil nitrogen dynamics models. In M.J. Shaffer, L. Ma, S. Hansen (Eds.), *Modeling carbon and nitrogen dynamics for soil management.* (pp. 55-102). Boca Raton, FL: Lewis Publishers.

Majumdar, B., Mandal, B., Bandopadhyay, P.K., Gangopadhyay, A., Mani, P.K., Kundu, A.L., & Majumdar, D. (2008). Organic amendments influence soil organic carbon pools and rice-wheat productivity. *Soil Science Society of America Journal,* 72, 775-785.

Mandal, B., Majumder, B., Bandopadhyay, P.K., Hazra, G.C., Gangopadhyay, A., Samantaroy, R.N., Misra, A.K., Chowdhuri, J., Saha, M.N., & Kundu, S. (2007). The potential of cropping systems and soil amendments for carbon sequestration in soils under long-term experiments in subtropical India. *Global Change Biology,* 13, 357-369.

Marland, G., Fruit, K., & Sedjo, R. (2001). Accounting for sequestered carbon: The question of permanence. *Environmental Science and Policy,* 4, 259-268.

McConkey, B.G., Liang, L.Y., Padbury, G., & Heck, R. (2000). Prairie soil carbon balance project: Carbon sequestration from adoption of conservation cropping practices. *Final Report to GEMCo.*190, Saskatoon, Sask.

McGechan, M.B., & Wu, L. (2001). A review of carbon and nitrogen processes in European soil nitrogen dynamics models. In M.J. Shaffer, L. Ma, S. Hansen (Eds.), *Modeling carbon and nitrogen dynamics for soil management.* (pp. 103-171). Boca Raton FL: Lewis Publishers.

McGill, W. (1996). Review and classification of ten soil organic matter (SOM) models. In D.S. Powlson, P. Smith, J.U. Smith (Eds.), *Evaluation of soil organic matter models using existing long-term datasets.* (pp. 111-132). Proceedings of the NATO Advanced Research workshop, NATO ASI Series I, Vol. 38. Berlin: Springer Verlag.

Miller, R.M., & Jastrow, J.D. (1990). Hierarchy of root and mycorrhizal fungal interactions with soil aggregation. *Soil Biology & Biochemistry,* 22, 579-584.

Narang, R.S., & Virmani, S.M. (2001). Rice-wheat cropping systems of the Indo-Gangetic Plains of India. In *Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, and International Crops Research Institute for the Semi-Arid Tropics,* Patancheru, Andhra Pradesh, India, pp. 36.

Nature, 30 November 2000. *Critical politics of carbon sinks.* 408(6812), 501.

Nayak, A.K., Gangwar, B., Shukla, A.K., Mazumdar, Sonali. P., Kumar, Anjani., Raja, R., Kumar, Anil., Kumar, Vinod., Rai, P.K., & Mohan, Udit. (2012). Long-term effect of different integrated nutrient

management on soil organic carbon and its fractions and sustainability of rice–wheat system in Indo Gangetic Plains of India. *Field Crops Research,* 127, 129-139.

Nayak, P., Patel, D., Ramakrishnan, B., Mishra, A.K., & Samantaray, R.N. (2009). Long-term application effects of chemical fertilizer and compost on soil carbon under intensive rice–rice cultivation. *Nutrient Cycling in Agroecosystem,* 83, 259-269.

New Scientist, 21 November 1998. *Down to Earth.* 160(2161), 17.

Pacala, S., & Socolow, R. (2004). Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science,* 305, 968-972.

Padre-Tirol, A., Ladha, J.K., Regmi, A.P., Bhandari, A.L., & Inubushi, K. (2007). Organic amendments affect soil parameters in two long term rice-wheat experiments. *Soil Science Society of America Journal,* 71, 442-452.

Parton, W.J., Schimel, D.S., Cole, C.V., & Ojima, D.S. (1987). Analysis of factors controlling soil organic matter levels in great plains grasslands. *Soil Science Society of America Journal,* 51, 1173–1179.

Paustian, K. (1994). Modelling soil biology and biochemical processes for sustainable agriculture research. In C.E. Pankhurst, D.M. Doube, V.V.S.R. Gupta, P.R. Grace (Eds.), *Soil Biota: Management in sustainable farming systems.* (pp. 182-193). Canberra: CSIRO.

Paustian, K., Andren, O., Janzen, H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M., & Woomer, P. (1997). Agricultural soils as a C sink to offset CO_2 emissions. *Soil Use and Management,* 13, 230-244.

Post, W.M., Izarurralde, R.C., Jastrow, J.D., McCarl, B.A., Amonette, J.E., Bailey, V.L., Jardien, P.M., West, T.O., & Zhou, J. (2004). Enhancement of carbon sequestration in U.S. Soils. *BioScience*, 54, 895-908.

Post Wilfred, M., Amonette, J.E., Birdsey, R.G., Charles, T., Izaurralde, R.C., Jardine, P.M., Jastrow, J., Lal, R., Marland, G., McCarl, B.A., Thomson, A.M., West, T.O., Wullschleger, S.D., & Metting, F.B. (2009). Terrestrial biological carbon sequestration: Science for enhancement and implementation. In *Carbon sequestration and its role in the global carbon cycle.* (pp. 73-88). Geophysical Monograph Series, 183.

Purukayastha, T.J., Rudrappa, L., Singh, D., Swarup, A., & Bhadraray, S. (2008). Long-term impact of fertilizers on soil organic carbon pools in maize-wheat-cowpea cropping system. *Geoderma,* 144, 370-378.

Ram, N. (1998). Effect of continuous fertilizer use on soil fertility and productivity of a *Mollisol*. In A. Swarup, R.D. Damodar & R.N. Prasad (Eds.), *Long-term soil fertility management through integrated nutrient supply.* (pp. 229-237). Bhopal, India: Indian Institute of Soil Science.

Ringius, L. (2001). What prospects for soil carbon sequestration in the CDM? COP-6 and beyond. *Energy & Environment,* 12, 275-285.

Sanderman, J., Farquharson, R., & Baldock, J. (2010). Soil carbon sequestration potential: A review for Australian agriculture. A report prepared for Department of Climate Change and Energy Efficiency, pp. 89.

Sandhu, K.S., Benbi, D.K., & Prihar, S.S. (1996). Dryland wheat yields in relation to soil organic carbon, applied nitrogen, stored water and rainfall distribution. *Fertilizer Research,* 44, 9-15.

Scholes, R.J., Dalal, R., & Singer, S. (1994). Soil physics and fertility: The effects of water, temperature and texture. In P.L. Woomer, M.J. Swift (Eds.), *The biological management of soil fertility.* (pp. 117-136). Chichester: John Wiley and Sons.

Schimel, D.S., Braswell, B.H., Holland, E.A., McKeown, R., Ojima, D.S., Painter, T.H., Parton, W.J., & Townsend, A.R. (1994). Climatic, edaphic and biotic controls over storage and turnover of carbon in soils. *Global Biogeochemical Cycles*, 8, 279-293.

Singh, B. (1996). Influence of forest litter on reclamation of semiarid sodic soils. *Arid Soil Research and Rehabilitation,* 10, 201-211.

Singh, G., & Singh, N.T. (1997). Effect of land use practices on organic carbon dynamics of sodic soils. In R. Lal, J. Kimble, R. Follett (Eds.), *Soil properties and their management for carbon sequestration*. (pp. 89-105). USDA-Natural Resources Conservation Service, National Soil Survey Centre.

Six, J., & Jastrow, J.D. (2002). Organic matter turnover. In R. Lal (Ed.), *Encyclopedia of soil science*. (pp. 936-942). New York: Marcel Dekker Inc.

Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research,* 79, 7-31.

Smith, G.A. (2007). Harnessing farms and forests in the low carbon economy: How to create, measure, and verify greenhouse gas offsets. In Z. Willey, W. Chameides (Eds.), *Harnessing farms and forests in the low carbon economy: How to create, measure, and verify greenhouse gas offsets*? (pp. 220). Durham, NC: Duke University Press.

Smith, P. (2004). Monitoring and verification of soil carbon changes under Article 3.4 of the Kyoto Protocol. *Soil Use and Management,* 20, 264-270.

Smith, P., Falloon, P., Coleman, K., Smith, J.U., Piccolo, M., Cerri, C.C., Bernoux, M., Jenkinson, D.S., Ingram, J.S.I., Szabó, J., & Pásztor, L. (1999). Modelling soil carbon dynamics in tropical ecosystems. In R. Lal, J.M. Kimble, R.F. Follett, B.A. Stewart (Eds.), *Global climate change and tropical soils*: *Advances in soil science.* (pp. 341-364). Boca Raton, FL: CRC Press Inc.

Sollins, P., Hofmann, P., & Caldwell, B.A. (1996). Stabilization and destabilization of soil organic matter: Mechanisms and controls. *Geoderma,* 74, 65-105.

Stevenson, F.J. (1994). *Humus chemistry: Genesis, composition, reactions*. New York: John Wiley & Sons.

Swarup, A. (1998). Emerging soil fertility management issues for sustainable crop productivity in irrigated systems. In A. Swarup, D.D. Reddy, R.N. Prasad (Eds.), *Long term soil fertility management through Integrated Plant Nutrient Supply.* (pp. 54-68). Bhopal, India: IISS.

Swarup, A., Manna, M.C., & Singh, G.B. (2000). Impact of land use and management practices on organic carbon dynamics in soils of India. In R. Lal, J.M. Kimble, B.A. Stewart (Eds.), *Global climate change and tropical ecosystems*. (pp. 261-281). Boca Raton, FL: CRC/Lewis Publishers.

Swinnen, J., Vanveen, J.A., & Merckx, R. (1995). Carbon fluxes in the rhizosphere of winter wheat and spring barley with conventional *vs* integrated farming. *Soil Biology & Biochemistry,* 27, 811-820.

Tandon, H.L.S. (1997). Organic residues: An assessment of potential supplies, their contribution to agricultural productivity and policy issues for Indian agriculture from 2000 to 2025. In I.S. Kanwar, J.C. Katyal (Eds.), *Plant nutrient needs, supply, efficiency and policy issues* (*2000-2025*). New Delhi, India: National Academy of Agricultural Sciences.

Tian, G., Granato, T.C., Cox, A.E., Pietz, R.I., Carlson, C.R. Jr., & Abedin, Z. (2009). Soil carbon sequestration resulting from long-term application of biosolids for land reclamation. *Journal of Environmental Quality,* 37, 1-14.

Tisdall, J.M., & Oades, J.M. (1982). Organic matter and water-stable aggregates in soils. *Journal of Soil Science,* 33, 141-163.

Von Lutzow, M., Kogel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B., & Flessa, H. (2006). Stabilization of organic matter in temperate soils: Mechanisms and their relevance under different soil conditions - A review. *European Journal of Soil Science,* 57, 426-445.

Walkley, A., & Black, I.A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science,* 37, 29-38.

Wang, D.L., & Anderson, D.W. (1998). Direct measurement of organic carbon content in soils by the Leco CR-12 Carbon Analyzer. *Communications in Soil Science and Plant Analysis,* 29, 15-21.

Wielopolski, L., Orion, I., Hendrey, G., & Roger, H. (2000). Soil carbon measurements using inelastic neutron scattering. *IEEE Trans. Nuclear Science,* 47, 914-917.

Woomer, P.L., Martin A., Albrecht A., Resch D.V.S., & Scharpenseel, H.W. (1994). The importance and management of soil organic matter in the Tropics. In P.L. Woomer, M.J. Swift (Eds.), *The biological management of soil fertility.* (pp. 47-80). Chichester: John Wiley and Sons.

Yadav, J.S.P., & Sarkar, D. (2009). Soil degradation with special reference to India. In *Platinum jubilee of ISSS Souvenir.* (pp.15-21). New Delhi: Indian Society of Soil Science.

Zhu, Y.G., & Miller, R.M. (2003). Carbon cycling by *arbuscular* mycorrhizal fungi in soil-plant systems. *Trends in Plant Science,* 8, 407-409.

*****