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Challenges and opportunities in soil organic matter research

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Summary

Soil organic matter (SOM) can be a source or sink for atmospheric CO_2 depending on land use, and management of soil, vegetation and water resources. SOM is a source of atmospheric CO_2, with the use of extractive farming practices that lead to a negative nutrient balance and exacerbate soil degradation. The historic loss of C from the SOM pool between the 1850s and 2000 is estimated at 78 ± 12 Gt compared with the emission of 270 ± 30 Gt from fossil fuel combustion. Despite its numerous direct and ancillary benefits, enhancing the SOM pool is a major challenge, especially in impoverished and depleted soils in harsh tropical climates. In addition to biophysical factors, there are also numerous social, economic and political constraints that limit increase in SOM pools. Conversion of plough-tillage to no-till farming, an important practice to enhance the SOM pool, is constrained by the limited access to herbicides and seed drill, and the competing uses of crop residues. Yet, enhancing the SOM pool is essential to restoring degraded soils, advancing food security and improving the environment. Important subjects among researchable topics include: assessing the rate of SOM accretion for a wide range of land use and management practices with reference to a baseline; evaluating the importance of biochar; measuring and predicting SOM at landscape and extrapolation to regional scale; establishing relationships between SOM and soil quality and agronomic productivity; determining on- and off-site effects of crop residues removal for ethanol/biofuel production; determining the fate of C in SOM translocated by erosional processes; evaluating nutrient requirements for increasing SOM in croplands; validating predictive models in tropical environments; and developing methodology for trading C credits.

Introduction

Important global issues of the 21st century are: (i) an increase in human population by an additional three billion by the middle of the 21st century, most of which is expected to occur in the developing countries; (ii) a decline in per capita availability of cultivable land and renewable fresh water resources; (iii) an increase in the atmospheric abundance of CO_2 (from 385 p.p.m. in 2008 and increasing at the rate of *c.* 2 p.p.m. year^{-1}) and other GHGs with the attendant risks of global warming; (iv) an increase in energy demand from 440 EJ in 2007 and growing at the rate of *c.* 2.5% globally; (v) an increase in food demand, especially in developing countries that are home to 850 million food-insecure people (Borlaug, 2007), and where the scarce natural resources (per capita land area and water) are already under great stress; and (vi) an increase in the extent and severity of the human-induced soil degradation (1.94 billion ha globally and increasing at the rate of 5–10 million ha annually) (Oldeman, 1994), with adverse impacts on ecosystems services and the environment. While the issues are serious and diverse, the common link among them is the global C cycle as influenced by the terrestrial C pool and its dynamics through interactive effects of human-induced and natural perturbations. Strategies to address these issues involve enhancing the terrestrial C pool for reversing the degradation processes and improving ecosystem functions.

The objective of this paper is to outline and deliberate direct and ancillary benefits of soil organic matter (SOM), identify knowledge gaps and prioritize researchable issues in SOM with special reference to soil quality, climate change and global food security. The focus is more on outlining the basic issues rather than collating and synthesizing a comprehensive literature review.

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Climate change

The Intergovernmental Panel on Climate Change (2007) report indicates that atmospheric concentration of greenhouse gasses (GHGs) increased between the pre-industrial era and 2005 from 280 p.p.m. to 379 p.p.m. for CO_2, 750 p.p.b. to 1750 p.p.b. for CH_4, and 270 p.p.b. to 319 p.p.b. for N_2O. Two of the most important GHGs reached a new maximum concentration in the atmosphere in 2006. The concentration of CO_2 reached 381.2 p.p.m., and that of N_2O 320.1 p.p.m. (WMO, 2006). Consequently, the mean global temperature has increased from 13.6°C to 14.4°C, sea level has risen by 15.2 cm to 22.9 cm during the 20th century, and the average cover of the arctic sea ice has shrunk at the rate of 2.7% per decade. Two predominant sources of GHGs have been the terrestrial and the geological carbon (C) and nitrogen (N) pools. Between 1850 and 2000, the relative contribution of CO_2-C to atmospheric abundance from the geological pool was 270 ± 30 Gt by fossil fuel combustion compared with that from the terrestrial pool estimated at 136 ± 55 Gt by deforestation, biomass burning, land use conversion and soil cultivation. Until the 1940s, more CO_2-C was emitted from terrestrial sources than from fossil fuel combustion. Depletion of the C pool in world soils is estimated at 78 ± 12 Gt (Lal, 1999, 2004).

Soil quality and agronomic production

Numerous and wide ranging benefits of SOM for enhancing soil quality and influencing the underlying pedological processes were quantified by Jenny (Jenny, 1941, 1961; Jenny & Raychaudhary, 1961). Some direct benefits of the SOM pool include improvement in soil structure, retention of water and plant nutrients, increase in soil biodiversity and decrease in risks of soil erosion and the related degradation. Important among numerous ancillary benefits are increases in use efficiency of input because of the reduction in losses of water and nutrients from the root zone, an increase in the soil's (and ecosystem's) resilience, and moderation of climate through sequestration of atmospheric CO_2 into stable SOM components with a long residence time and the ability to oxidize CH_4. In accord with the direct and ancillary benefits of SOM to soil quality, there are several soil properties and processes influenced by its quantity and quality. Soil degradative processes that lead to depletion of the SOM pool include decline in soil structure, depletion of plant nutrients, and change in soil temperature and moisture regimes that enhance mineralization. The rate and magnitude of depletion of the SOM pool are exacerbated by accelerated soil erosion. In contrast, reversal of degradation trends through conversion to restorative land use would enhance the SOM pool. Processes leading to restoration of the SOM pool include increase in aggregation, improvement in elemental cycling, increase in soil biodiversity and reduction in losses by runoff and erosion. There is a strong and positive impact of maintaining/enhancing the SOM pool on soil and environment quality, and the urgent need to increase the SOM pool for restoring the quality of degraded soils, especially those in the developing countries of sub-Saharan Africa (SSA) and South Asia (SA). The relative magnitude of soil degradation in developed and developing countries indicates that the problem of erosion-induced degradation is more serious in developing than developed countries (Table 1). Management of the SOM pool to improve soil quality and agronomic productivity is now related to the urgency to increase food production (Swaminathan, 2000; Sanchez & Swaminathan, 2005) and the need for intensive land management during the 21st century through adoption of land saving technologies (Wild, 2003).

There is an urgency and concern to feed the world population of 6.7 billion (B) in 2008 and expected to be 7.5 B by 2020, 9.4 B by 2050 and *c.* 10 B by 2100. With reference to managing the SOM pool, there are three important features of the projected rapid increase in world population: (i) almost all of the future increase in population will occur in developing countries (Cohen, 2003) where the soil and water resources are already under great stress; (ii) the projected increase of 3–3.5 billion will occur over a short period between 2000 and 2050; and (iii) such an unprecedented increase in developing countries does not provide enough time to make appropriate adjustments to meet the basic demands. There are *c.* 850 million food-insecure people in the world (Sanchez, 2002; Rosegrant & Cline, 2003; Borlaug, 2007), the number may increase by another 100 million by 2015, and the UN Millennium Goals will not be realised. An additional 3.4 billion people suffer from hidden hunger because of the intake of food grown on poor quality soils (UN, 2006). Globally, food production must be doubled by 2050 to meet the increasing demand of the growing population. Management of the SOM pool can play an important role in advancing food security. To meet the future demand in food production, the global average cereal grain yield of 2.64 Mg ha^{-1} and total cereal production of 1267 million Mg in 2000 must be increased to 3.60 Mg ha^{-1} and total cereal production of 1700 million Mg by 2025, and 4.30 Mg ha^{-1} and 1995 million Mg by 2050 (Wild, 2003). The required increase in grain yields (+ 35% by 2025 and + 58% by 2050) will be

Table 1 The relative magnitude of soil degradation in developed and developing countries (modified from Oldeman, 1994)

Degradation process	Total area affected in the world /Mha	% of the World's degraded area	
		In developing countries	In developed countries
Water erosion	1100	77	23
Wind erosion	550	83	17
Loss of nutrients	136	97	3
Salinization	289	94	6
Pollution	21	100	0
Acidification	6	83	17
Compaction	68	47	53
Waterlogging	11	91	9

even larger (+ 62% by 2025 and ± 121% by 2050) if there is a strong shift in the dietary habits of populations in emerging economies. Human nutrition and diet can have a significant impact on SOM dynamics, soil quality and the environment through the degree of agricultural intensification (Iserman & Iserman, 2004). There are implications of diet and nutrient requirements on soil quality (Lampert, 2003), for which judicious management of SOM is crucial. While the data on crop performance in relation to some recommended management practices (RMPs) are known from developing countries, credible information is needed on the rate of C storage for diverse soils and ecosystems. Research data are also needed with regard to the soil-specific functions relating SOM storage to soil quality characteristics (e.g. available water holding capacity, structural stability, erodibility, water and nutrient use efficiency, water transmission properties, aeration and gaseous diffusion, emission of GHGs including CH_4 and N_2O, and agronomic/biomass yields). Lal (2006) estimated that increasing the SOC pool by 1 Mg ha^{-1} $year^{-1}$ might increase food production by 6–12 million Mg $year^{-1}$ in SSA, and 24–40 million Mg $year^{-1}$ in all developing countries. The need for enhancing the SOM pool in soils of the tropics is also underscored by the fact that soils on poor land quality classes (class IV to class IX) predominate in developing countries of the tropics (Table 2). Improving soil quality and increasing SOM along with the inputs required to raise productivity, remains a major challenge.

Present techniques of SOM management

Proven technology of SOM management can be broadly grouped under two categories: (i) those that increase C input into the soil and (ii) those that decrease losses from managed agroecosystems (Figure 1). Input of C into the soil can be moderated either by recycling biosolids or by growing biomass *in situ*. Similarly, losses of SOM can be curtailed by reducing erosion, decreasing leaching and minimizing decomposition. Based on the choice of appropriate strategies, there are numerous management options for enhancing the SOM pool (Figure 2). Processes that lead to C sequestration include humification, aggregation and illuviation (transfer into the sub-soil) for soil organic C (SOC) and formation of secondary carbonates and leaching of biocarbonates for soil inorganic C (SIC) sequestration. The largest potential for SOC sequestration exists in restoring those degraded soils whose SOM reserves have been depleted the most by past land misuse and soil mismanagement. In addition to off-setting fossil fuel emissions and improving the environment, enhancing the SOM pool in cropland soils is also important for increasing agronomic productivity and advancing global food security (Lal, 2006).

Table 2 Land quality in temperate versus tropical climates (Blum & Eswaran, 2004)

Land quality class	Temperate	Tropical	Others
	% of ice-free land surface		
I	2.14	0.25	–
II	2.55	2.43	–
III	0.70	1.51	2.33
IV	1.31	1.83	0.82
V	4.76	9.90	1.85
VI	1.66	8.53	3.13
VII	2.01	2.31	4.70
VIII	–	–	16.70
IX	0.15	0.16	28.45
Total	15.28	26.92	57.98
% > Class III	35.2	80.7	95.9

Soil/site specific management options of enhancing the SOM pool in ecosystems are outlined in Figure 3. The long-term goal is to increase the SOM pool in the root zone to above the critical level (Loveland & Webb, 2003). However, addition of biomass-C without consideration of other components (N, P, S etc.) may decrease the SOC pool in some situations where it may accentuate the rate of mineralization. The critical limit of SOM for agricultural soils may change with possible change in crop yields with the projected global warming (Schimel, 2006). Indeed, the choice of an appropriate strategy depends on the land use and many other factors pertaining to biophysical environment and the human dimensions. While increasing the SOM pool is an important goal for choosing soil and crop management practices, it is difficult if not impossible to bring about a measurable increase in the SOM pool over a short period of 2–5 years. The problem is especially challenging in developing countries of the tropics, where the need to enhance the SOM pool is the greatest because the drastic depletion of the SOM pool is also linked with severe decline in soil quality by accelerated erosion, nutrient depletion, acidification, elemental imbalance, decline in soil structure, salination, etc. (Oldeman, 1994).

No-till (NT) farming is assumed to be the oldest tillage method practised since the dawn of settled agriculture. The modern version of NT farming is practised on *c.* 100 Mha of cropland, mostly in Brazil, USA, Canada, Argentina, Chile and Australia (Derpsch, 2007). Yet, its impact on soil properties and processes in relation to SOM dynamics is not widely understood. For example, the effects of NT cropping systems on the concentration and depth distribution of SOM have not been widely documented for a range of soils and eco-regions, including for soils of the tropics. Further, its effects on the chemical composition of SOM and on its chemical recalcitrance against decomposition have not been widely assessed. The need to enhance the residence time of the SOM pool necessitates identification of land use and management practices that increase recalcitrance against microbial decomposition. Study of the recalcitrance of SOM requires characterization of soil from long-term experiments using analytical techniques such as ^{13}CNMR spectroscopy (Kögel-Knabner, 1997; Kiem *et al.*, 2000) and/or gas

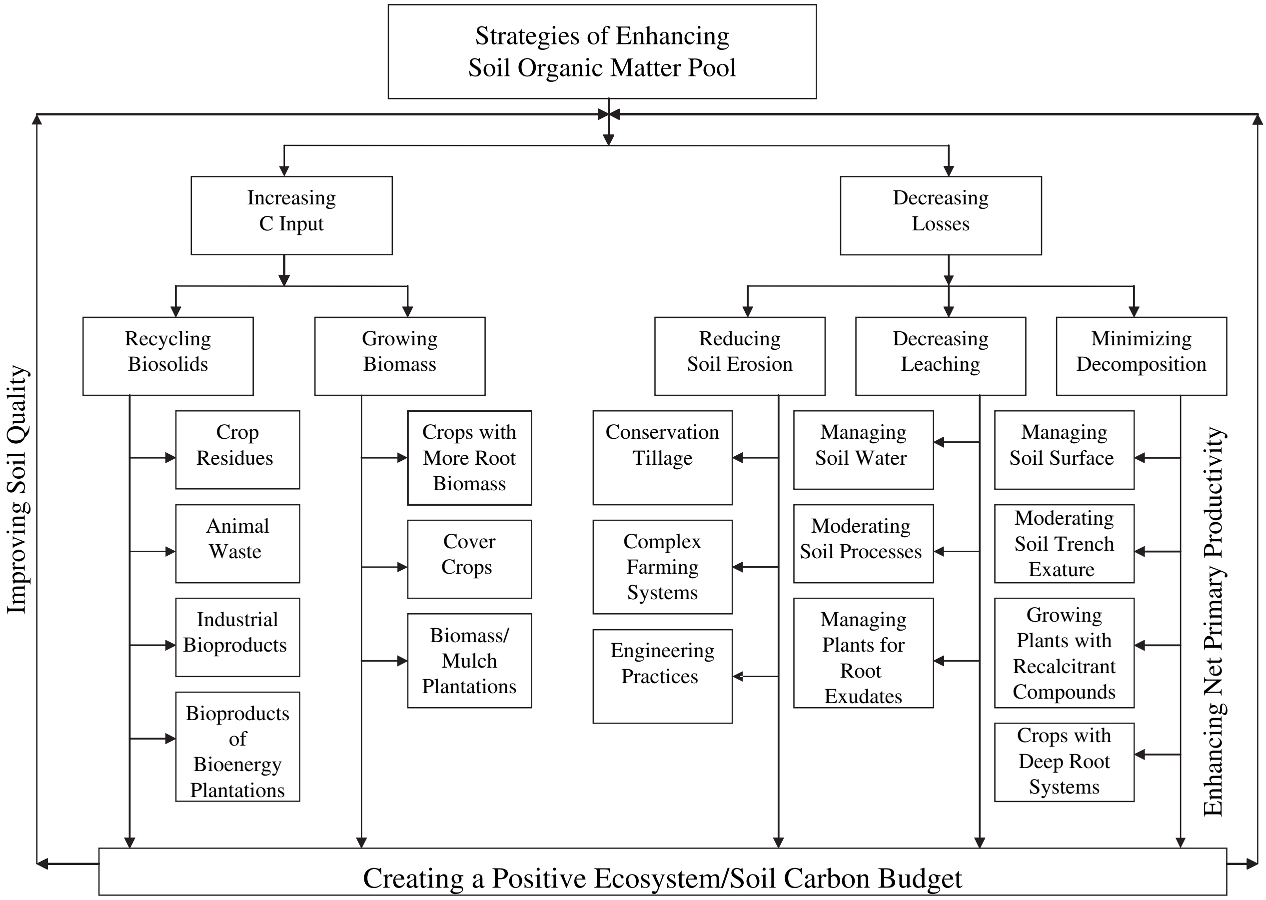

Figure 1 Strategies of enhancing and preserving the soil organic matter pool.

chromatography coupled with isotope ratio mass spectrometry (Dignac *et al*., 2005; Wiesenberg & Schwark, 2006). Guggenberger *et al*. (1995) observed that soil management techniques have little impact on the chemical composition of the SOM despite having large impact on its concentration. Effects are similar to that of cropping systems on the composition of the particulate organic matter (POM) (Golchin *et al*., 1995; Oades *et al*., 1998). Dieckow *et al*. (2005) reported that land use, cropping and N fertilization of a sub-tropical Acrisol had no effect on the composition of SOM in silt- and clay-sized fractions or on the whole soil. However, soil under grassland management had larger alkyl and smaller aromatic C concentrations than that under cropland.

Technological options for soil organic matter management

Several options are being considered for stabilizing atmospheric abundance of GHGs (Bohannon, 2007). Important among these options is C sequestration in world soils through increase in the SOM pool. While the technology to improve the SOM pool is known and has been proven for diverse soils in a wide range of ecosystems, there is a conspicuous lack of adoption of these technologies, especially by the resource-poor small land holders in SSA, SA and elsewhere in the developing countries.

No-till farming

The SOM pool can be maintained or enhanced by adoption of NT farming and conservation tillage (CT) with the liberal use of crop residue mulch, manure, compost and incorporation of cover crops (forages) in the rotation cycle. Some animal-based (e.g. pastoral, agro-pastoral and agrisilvipastoral) and forestry-based (e.g. agro-forestry, short-rotation, woody perennials agroforestry) farming systems can sequester C, especially when marginal/degraded croplands are converted to these restorative systems. While market forces and the economic benefits are strong determinants that govern the decision about technology adoption in commercial/industrialized farming, the situation of the resource-poor farmers who practise subsistence or extractive farming in SSA and SA (Figure 4) prohibits their adoption of RMPs. Small land holders, faced by the perpetual food insecurity leading to hunger and malnutrition along with

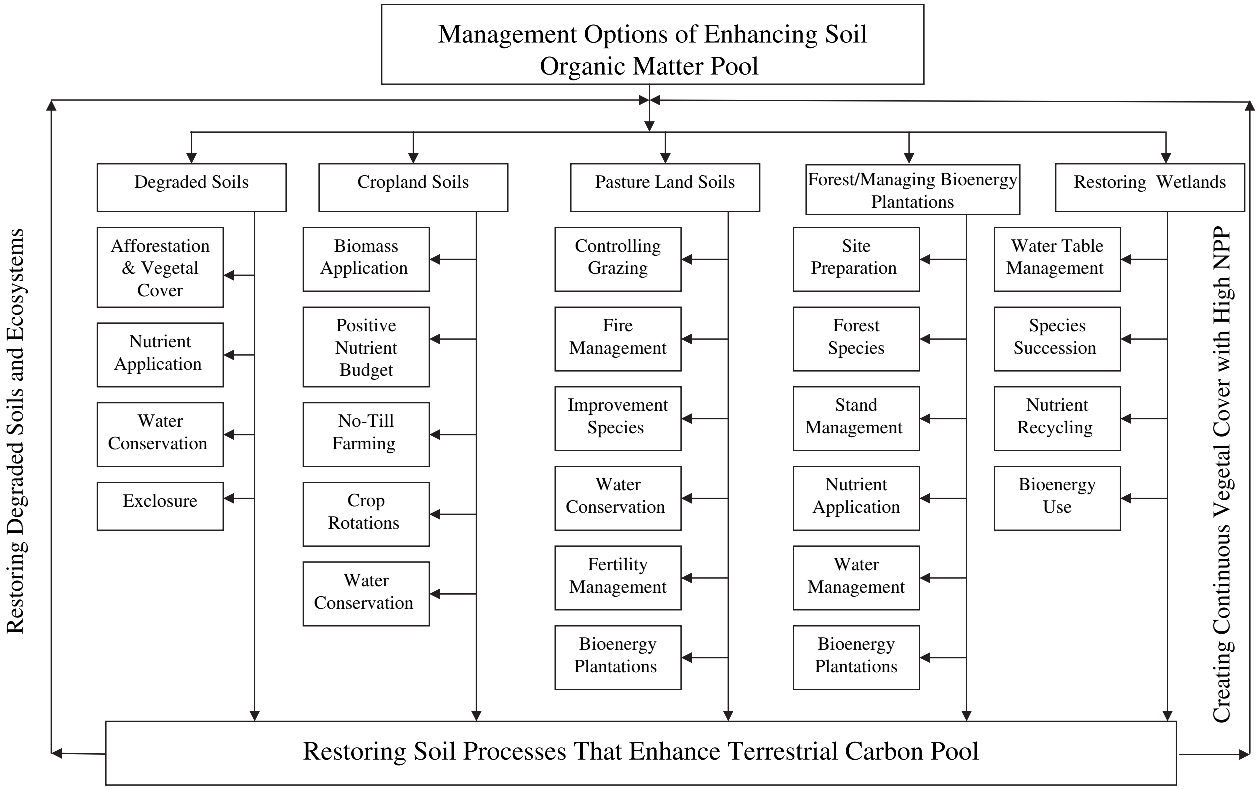

Figure 2 Technological options for enhancing organic carbon pool in soils of managed ecosystems.

sub-standard living, naturally give importance to immediate needs over those of future generations. The stewardship of soil resources cannot be considered practically by people facing starvation. There are also no incentives for the small-size land holders. Further, social and political unrest, exacerbated by poverty and hunger, also hinders the adoption of RMPs.

There are numerous constraints to widespread adoption of NT farming in developing countries. Important among these are the competing uses of crop residues (e.g. fodder, fuel and construction materials), use of animal dung for household fuel rather than as soil amendment, lack of availability of herbicides and appropriate seed drill, lack of or no incorporation of cover crops in the rotation cycle, among others, and an uncertain land tenure system. Identifying clean/modern biofuels and alternate sources of household energy is crucial to improving the SOM pool and enhancing soil quality.

Modern biofuels and SOM

Development of clean sources of household fuel is also an essential pre-requisite to using animal dung (Venkatraman *et al.*, 2005) and crop residues as amendments for improving soil quality. Animal dung and other agricultural/urban biosolids could be used in a biodigester to generate electricity and the by-products synthesized into fortified compost for use as soil amendments. Such power generators must be developed at village/community level. In addition, biofuel plantations must 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.

There are five pathways of C fixation. These are: (i) the Calvin cycle, (ii) the reductive citric acid cycle, (iii) the reductive acetyl-CoA pathway, (iv) the 3-hydroxypropionate/malyl-CoA cycle, and (v) the 3-hydroxypropionate/4-hydroxybutyrate cycle (Thauer, 2007). The fifth pathway involves growing cyanobacteria as a source of producing biomass. Rather than using woody perennials (e.g. poplar, willow, eucalyptus and mesquite) and warm season grasses (e.g. switchgrass and miscanthus), it may be prudent to produce biomass by growing algae and cyanobacteria, which represent other pathways of C fixation. In addition to C, these organisms also play an important role in the Earth's nitrogen (N) and sulphur cycles and can be grown in bioreactors that do not compete with land, water and other scarce and non-renewable resources.

Crop residues are being widely considered as a source of lignocellulosic biomass for conversion into ethanol (Somerville, 2006; Kennedy, 2007). However, there are few systematic and long-term studies designed to assess the impact of residue harvest on SOM concentration, and rate of C sequestration and soil quality (Wilhelm *et al.*, 2004). Serious concerns are being raised as to whether bioenergy produced from crop residues is

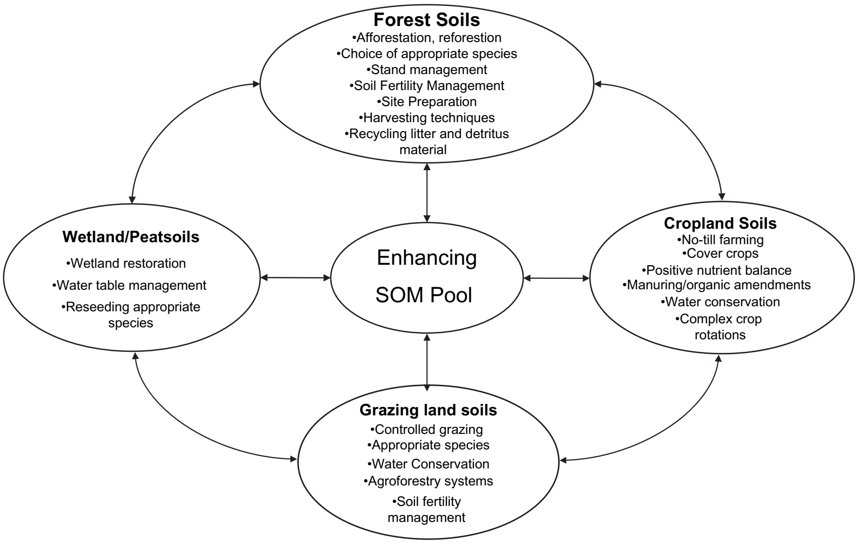

Figure 3 Techniques of enhancing the SOM pool.

effective in improving the C balance (Baker & Craig, 2007; Cassman & Liska, 2007; Doorbosch & Steinblik, 2007). The serious question that needs to be answered critically and objectively regards the amount of energy that can be produced without harming the environment (European Environment Agency, 2006). In Ohio, Blanco-Canqui & Lal (2007a, b, c) reported that even 25% removal of maize stover from a long-term NT experiment resulted in a significant adverse impact on the SOM pool and soil quality. In addition to losses of nutrients contained in the residues (Singh *et al*., 2005), information on SOM dynamics under different scenarios of residue harvest is needed through long-term experiments conducted on a wide range of soils and environments.

The impact of N application on the mineralization and humification of large input of carbonaceous crop residues (e.g. corn, wheat, barley and rice rather than legumes such as soya beans, cowpeas, pigeon peas and alfalfa) is a debatable issue. Khan *et al*. (2007) indicated the importance of the judicious management of N if crop (maize) residues are to be harvested for bioenergy production. The feasibility of using NT residues as

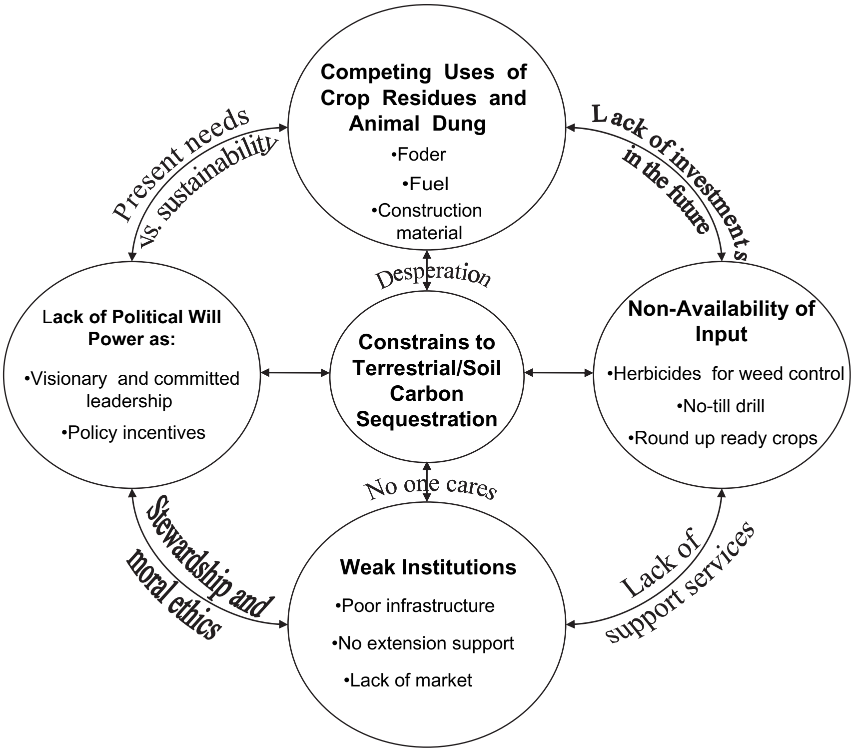

Figure 4 Constraints to carbon sequestration in developing countries.

a feedstock for production of cellulosic ethanol (Graham *et al.*, 2007) needs careful and objective analyses. In addition to using cellulosic biomass as feedstock for producing ethanol, biomass is also 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) reported that a 300 – Mg day^{-1} biofine plant is operational at Caserta, Italy. Other feedstock chemicals being derived from biomass include fermentable levoglucosan derived from cellulose and furfural from the pentoses in hemicelluloses. Some argue that the bio-economy, based on those alternative uses of crop residues, may revolutionize agriculture (Hayes, 2006), and assume that agro-based industries can boost the economy by producing ethanol and chemicals while also generating biochar as a byproduct of the biorefinery. Those who oppose the removal of crop residues are concerned with the decline in agronomic productivity, the increase in use of fertilizers and herbicides to compensate for the loss of nutrients and increase in infestation of weeds by the residue-free soil and increases in risks of soil erosion and non-point source pollution.

Assessment of soil carbon storage

Soil C storage (SCS) is considered a viable option to mitigate climate change (Lal *et al.*, 2003; Lal, 2004; Pacala & Socolow, 2004). The SCS in a specific ecosystem is assessed in comparison with a reference ecosystem over a given period of time and designated space (Bernoux *et al.*, 2005, Figure 5). The question of establishing a baseline in assessing the SCS is critical and needs an objective consideration. Using the analyses of SOC pool data from the long-term Morrow plots in Illinois, Khan *et al.* (2007) reported a decline in the SOC pool over 51 years in plots receiving fertilizer. However, comparative analyses made between unfertilized and fertilized plots for either 1995 or 2005 data would lead to a different interpretation that fertilizer use enhanced SCS. Thus, choice of baseline is critical.

Net SCS must be assessed in relation to the hidden C costs (of all inputs including fertilizers, pesticides, irrigation and energy), and fluxes of all GHGs (e.g. CO_2, CH_4 and N_2O) (Robertson *et al.*, 2000; Flessa *et al.*, 2002). Some management systems (e.g. NT farming) may enhance the SOM concentration either in the surface soil or the whole profile, but may also alter the fluxes of CH_4 and N_2O. Thus, estimation of the net rate of SCS must be based on due consideration of all hidden C costs and fluxes of all GHGs (Schlesinger, 1999). Integrated evaluation of GHG emissions is essential for determining the net rate of C sequestration. The relevant aspect of SCS that needs additional research is the gross versus the net C gains, and the residence time of C sequestration in soil under a managed ecosystem.

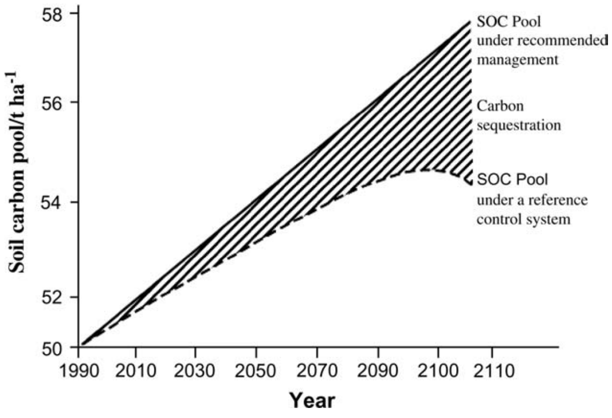

Figure 5 Schematic of assessing the rate and magnitude of soil carbon sequestration with reference to the baseline.

Most studies on SOM dynamics have been made for the plough layer (0–20 cm depth). There is a strong need to assess the land use and management impacts on depth-distribution because of the depth-dependent response of some practices to temporal changes in the SOM pool. For example, the schematics in Figure 6 show that conversion of plough tillage to NT may enhance the SOM concentration in the surface soil but decrease that in the sub-soil (Puget & Lal, 2004; Baker *et al.*, 2007). Some argue that seemingly larger SOC concentrations in NT systems may merely be due to shallow depth of sampling (Baker *et al.*, 2007; Blanco-Canqui & Lal, 2008). Therefore, measurement of management-induced changes in SOM concentration to at least 1-m (preferably 2-m) depth is important. Assessment of the SOM pool to 2-m depth may be especially important in

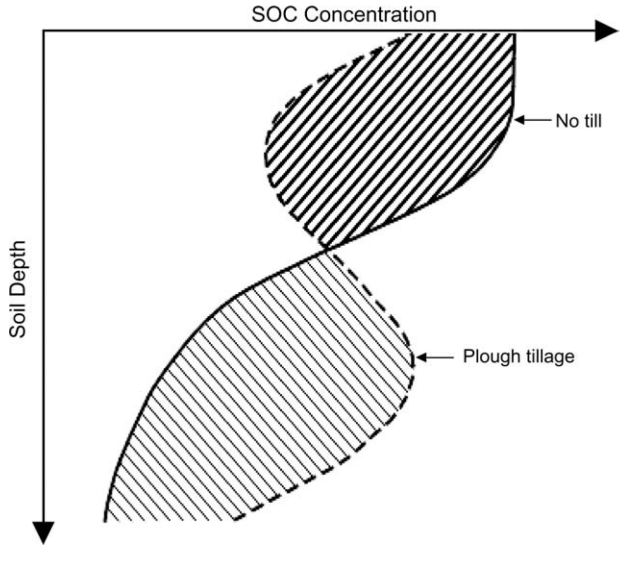

Figure 6 A possible schematic of the soil organic carbon profile in no-till and plough tillage systems.

forest ecosystems where deep tap roots may transfer biomass C to deeper layers and enhance its residence time in the soil (Lorenz & Lal, 2005).

Fate of carbon in soil organic matter transported by erosional processes

Whether soil erosion is a source (Lal, 2003) or sink (Stallard, 1998; Smith *et al*., 2001; Van Oost *et al*., 2007) of atmospheric CO_2 must be determined by assessing the fate of C in SOM transported by the erosional processes. Such an assessment requires a detailed evaluation of the C budget at each of the four stages of the erosion process (e.g. detachment, transport/splash, redistribution over the landscape and transfer to depression/deposition sites and aquatic ecosystems). Merely assessing the gain in C pool at depression sites and aquatic ecosystems or evaluating the loss of C in the soils subject to erosion can lead to erroneous conclusions and misleading interpretations.

Modern innovations for enhancing soil carbon storage

The importance of applying crop residues as an amendment to enhance SCS has long been recognized (Melsted, 1954; Tisdale & 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 & 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 SCS in fertilized sub-plots despite increase in input of the biomass-C. On the contrary, a noticeable decline in C pool occurred with 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 through biological N fixation. This important issue of the elemental requirements for SCS needs to be resolved for soil type, crop rotations and the tillage method. Is it possible that the conclusions from Morrow (Khan *et al*., 2007) plots may have been different if these experiments had been managed with a NT system of seedbed preparation? Soil-specific and demand-specific (yield of grains and biomass, and desired rates of SCS) rates of N application are required to minimize losses, reduce environmental pollution (leaching of nitrates and emission of N_2O) and maximize energy efficiency.

Significant advances in SOM research can be made by using modern innovations in nanotechnology, biotechnology and information technology. Combination of nano-technology and biotechnology can provide useful tools to restore degraded soils and ecosystems and enhance the SOM pool. Some possible innovations include nano-enhanced products (e.g. nanofertilizers and nanopesticides) with a nano-based 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 environments. 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 and minimize the adverse effects of drought stress. Similarly, nanoporous membranes are available to minimize loss of water from soil. Nanomaterials are efficient sorbents of pollutants and can reduce eutrophication of natural waters, and nanofilters are available to remove agricultural and natural chemicals from water. Nanocrystals of magnetite (< 12 nm) can bind up to 100 times as much as larger Fe particles. Nanosensors can be used to improve predictability of edaphic environments by remote sensing, using nanoscale mass spectrometers, atomic force microscopes and other modern devices. With remote sensing of edaphic conditions, automatic release of targeted input (nanoscale precision farming) can effectively and efficiently alleviate soil-related constraints. However, the C input into deep sub-soil may lead to priming of old or passive C (Fontaine *et al*., 2007), an important topic that needs additional research.

In a similar way to nanotechnology, biotechnology also has numerous applications for understanding and managing pedospheric properties and processes. Relevant examples of such applications include: (i) enhancing SCS in terrestrial ecosystems (soils, trees and wetlands) by using GM plants characterized by a favourable root:shoot ratio and the harvest index with a large biomass production, and a deep root system containing recalcitrant compounds (e.g. phenolics); (ii) expanding the land base by bringing new land under production, which was hitherto not cultivable, by growing specifically improved crops/cultivars, and restoring degraded ecosystems through bioremediation of contaminated soils; (iii) growing efficient plants with high N-fixation capacity and built-in resistance to drought (aerobic rice), anaerobiosis, nutrient/elemental imbalance, unfavourable soil pH/reaction, etc.; and (iv) 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.

Need for new tools to measure SOM dynamics

Most measurements on the impact of geogenic and anthropogenic factors on SOM pool and fluxes are made at a point scale or pedon level. The impacts of SCS on ecosystem services must, however, be assessed at farm, landscape or watershed scales. Therefore, assessment of the components of ecosystem C budget (e.g., life cycle analysis) 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 input (tillage, fertilizers, crop drying and irrigation) and the fate of C transported by leaching, runoff and sediments and mineralization. A holistic approach to ecosystem C budgets would involve full life cycle analysis of RMPs versus the traditional systems over a period of time. In addition to research on the biophysical processes, economic assessment of SOM-enhancing techniques is also needed. Landers (2001) assessed one hidden C cost of converting plough tillage to NT farming in Goinia State of Brazil for a farm of 2270 ha over a 6-year period from 1992-1993 to 1997-1998. By assessing the input at the farm scale, Landers reported that the total number of tractor hours decreased from 10 630 to 5135, leading to 50% reduction in fuel consumption. Similarly, the number of machine operators was reduced by half. It is only in a study at this scale that the ecosystem C budget can be assessed by conducting detailed life cycle analysis. Standardized and cost-effective methodology is needed for assessment of the net C flux from all managed ecosystems (West & Marland, 2004).

Credible measurement of the SOM pool and fluxes at a range of spatial and temporal scales remains a challenge. Soil scientists have monitored management-induced changes in SOM concentrations in the plough layer since *c*. 1850 (see Manlay *et al*., 2007). However, assessing changes in the SOC pool and fluxes in the context of SCS for off-setting anthropogenic emissions requires a different protocol, precision and units of assessment (Mg C ha^{-1} vs. g kg^{-1}) to those needed for soil fertility evaluation on cropland soils. While recent developments in methods of measuring 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 to be answered (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 systems with a soil science perspective (Janzen, 2004).

As with measurements of SOM concentrations, models of SOM pools and their dynamics have been constructed for *c*. two centuries (see 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 & Greenland, 1960; Jenkinson & Rayner, 1977; Parton *et al*., 1987) and more recently development of EPIC, ROTH-C, CENTURY, CQUESTER models, etc., there remains a strong need to predict changes in soil structure and tilth characteristics, along with attendant changes in determinants of soil physical quality, with changes in SOM pools and fluxes. The goal of modelling is to develop a 'sense-making framework' or a decision support system as a tool to manage SOM pool and flux for multifarious uses. Models are needed to: (i) understand processes and identify missing links; (ii) identify what is needed and determine what is possible or achievable in SCS; (iii) develop a framework of diverse management scenarios to optimize net SCS per unit input and area; and (iv) identify multi-functional land use/soil management systems in which SCS is one of the numerous objectives.

In addition to the management-induced changes in SOM pools and fluxes, it is equally important to model the SOM pool and flux in the context of climate change. There are several questions that remain to be addressed with respect to 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 of eco-regions/biomes towards the Earth's poles increase NPP and have a negative/mitigative 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 gained importance since the identification of the so-called *terra preta* by the late Wim Sombroek in the Amazon (Morris, 2006; Mann, 2008). The *terra preta do indio* are anthrocenes 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 (Morris, 2006; Mann, 2008). Some of these dark and fertile patches, presumed to be 7000 years old, contain three times as much N and P as the surrounding soil and 18 times as much SOC (9.0% vs. 0.5%). Since then, many researchers have argued that use of charcoal, with or without reinforcement with compost and fertilizers, is a viable option for SCS and improving soil quality. Indeed, some industry involvement is also occurring to manufacture charcoal-based amendments (Woods *et al*., 2006). Rumpel *et al*. (2006a, b) 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 also preferentially translated to depositional sites by the erosional processes (Rumpel *et al*., 2006). 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. Charcoal-amended soil lost only 4 to 8% of the SOC pool compared with the loss of 25 to 27% for the compost-amended plots. Thus application of charred biomass as a soil amendment/conditioner is an option being widely considered (Glaser *et al*., 2001; Baldock & Smernik, 2002; Lehman *et al*., 2002, 2003; Steiner *et al*., 2004; Topoliantz *et al*., 2005).

Conclusions

The importance of maintaining/enhancing SOM in the root zone for improving soil quality and agronomic productivity has been recognized ever since the dawn of settled agriculture. Measurement and prediction of management-induced changes in SOM concentration (g/kg) in the root zone have been made at a point/pedon scale since the beginning of the 19th century. However, there is a need to measure and monitor management-induced changes in the soil C pool at landscape, farm scale or watershed scale in order to relate the changes in the SOC pool (Mg C ha^{-1} $year^{-1}$) to offset fossil fuel emissions. Assessment of the net rate of SCS in agricultural and managed ecosystems necessitates complete life cycle analysis or computation of the ecosystem C budget. It is also relevant that emission of all GHGs (CO_2, CH_4, N_2O) is assessed in order to compute C equivalence of all fluxes. Relating the SOC pool and flux to emerging global issues requires careful evaluation of the following: (i) measurement of SCS rate with reference to a baseline; (ii) assessment of the SOC pool to 1-m if not 2-m depth; (iii) linkage of the cycling of C with N, P, S water and energy use; (iv) relationship of SOC pools with soil quality properties and agronomic/biomass yield; (v) evaluation of the residue (biomass) requirements for achieving the desired SCS rate; (vi) determination of the impact of harvesting crop residues on soil quality, erosion and non-point source pollution; and (vii) a methodology for trading of C credits, etc. Soil scientists need to be pro-active in assessing the direct and ancillary benefits of SCS in agricultural and other managed ecosystems.

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