CARBON MANAGEMENT IN AGRICULTURAL SOILS

R. LAL

*Carbon Management and Sequestration Center, The Ohio State University, Columbus,
Ohio 43210 USA
(E-mail: LaL.1@osu.edu; Tel: +1-614-2929069; Fax: +1-614-2927432)*

Abstract. World soils have been a major source of enrichment of atmospheric concentration of CO_2 ever since the dawn of settled agriculture, about 10,000 years ago. Historic emission of soil C is estimated at 78 ± 12 Pg out of the total terrestrial emission of 136 ± 55 Pg, and post-industrial fossil fuel emission of 270 ± 30 Pg. Most soils in agricultural ecosystems have lost 50 to 75% of their antecedent soil C pool, with the magnitude of loss ranging from 30 to 60 Mg C/ha. The depletion of soil organic carbon (SOC) pool is exacerbated by soil drainage, plowing, removal of crop residue, biomass burning, subsistence or low-input agriculture, and soil degradation by erosion and other processes. The magnitude of soil C depletion is high in coarse-textured soils (e.g., sandy texture, excessive internal drainage, low activity clays and poor aggregation), prone to soil erosion and other degradative processes. Thus, most agricultural soils contain soil C pool below their ecological potential. Adoption of recommend management practices (e.g., no-till farming with crop residue mulch, incorporation of forages in the rotation cycle, maintaining a positive nutrient balance, use of manure and other biosolids), conversion of agriculturally marginal soils to a perennial land use, and restoration of degraded soils and wetlands can enhance the SOC pool. Cultivation of peatlands and harvesting of peatland moss must be strongly discouraged, and restoration of degraded soils and ecosystems encouraged especially in developing countries. The rate of SOC sequestration is 300 to 500 Kg C/ha/yr under intensive agricultural practices, and 0.8 to 1.0 Mg/ha/yr through restoration of wetlands. In soils with severe depletion of SOC pool, the rate of SOC sequestration with adoption of restorative measures which add a considerable amount of biomass to the soil, and irrigated farming may be 1.0 to 1.5 Mg/ha/yr. Principal mechanisms of soil C sequestration include aggregation, high humification rate of biosolids applied to soil, deep transfer into the sub-soil horizons, formation of secondary carbonates and leaching of bicarbonates into the ground water. The rate of formation of secondary carbonates may be 10 to 15 Kg/ha/yr, and the rate of leaching of bicarbonates with good quality irrigation water may be 0.25 to 1.0 Mg C/ha/yr. The global potential of soil C sequestration is 0.6 to 1.2 Pg C/yr which can off-set about 15% of the fossil fuel emissions.

Keywords: global warming, soil carbon dynamics, soil carbon sequestration, soil quality, soil aggregation, humification, secondary carbonate.

Introduction

The UNFCC (Article 2) states that "Stabilization of greenhouse gas concentrations in the atmosphere must be achieved at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a framework sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic

development to proceed in a sustainable manner" (www.unfcc.de). In this regard, carbon (C) sequestration in agricultural soils is an important option. Soil C pool comprises two components: soil organic carbon (SOC) and soil inorganic carbon (SIC). The SOC pool includes highly active humus and relatively inert charcoal C. Humus is a dark brown or black amorphous material characterized by a large surface area, high charge density, high affinity for water, and ability to form organo-mineral complexes through reaction with the clay fraction. Charcoal is a product of incomplete combustion of plants, and is recalcitrant with relatively long residence time.

The generic term soil organic matter (SOM) refers to the sum of all organic substances in the soil comprising: (i) a mixture of plant and animal residues at various stages of decomposition, (ii) substances synthesized through microbial and chemical reactions, (iii) and biomass of live soil micro-organisms and other fauna along with their metabolic products.

The SIC pool includes elemental C and carbonate minerals (e.g., gypsum, calcite, dolomite, aragonite, and siderite). There are two predominant components of SIC pool: primary or lithogenic carbonates, and secondary or pedogenic carbonates. Primary carbonates are derived through weathering of parent material. In contrast, secondary carbonates are formed through the dissolution of CO_2 in soil air to form carbonic acid and its reprecipitation with Ca^{+2} or Mg^{+2} added into the soil as amendments or from other sources.

The term soil C sequestration implies transfer of atmospheric CO_2 into soil C pool through: (i) humification of crop residue and other biosolids added to the soil, and (ii) formation of secondary carbonates or leaching of bicarbonates into the ground water such that CO_2 thus captured is not immediately re-emitted. The residence time of C thus sequestered ranges from a few weeks to millennia depending on the nature of carbonaceous substances, stability of secondary carbonates formed and depth of leaching. Leaching of bicarbonates and using biofuel to off-set fossil fuel are not strictly soil C sequestration, but they have important impact on the global C cycle.

The global soil C pool is estimated at 1550 Pg of SOC and 950 Pg of SIC to 1-m depth (Batjes 1996). The soil C pool is about 3.3 times the atmospheric pool (760 Pg) and 4.5 times the biotic pool (560 Pg) (Figure 1). Soil C pool can be a source or sink for atmospheric pool depending on land use and management. There is a direct relationship between soil C pool and the atmospheric pool. Increase of soil C pool by 1 Pg is equivalent to reduction in atmospheric CO_2 concentration of 0.47 ppm, and vice versa.

This manuscript describes characteristics of the soil C pool, factors affecting its dynamics, management techniques to enhance its magnitude and increase the retention time, and anthropogenic factors leading to strong interaction of soil C pool with biotic and atmospheric pools. In addition to SOC, this paper also discusses SIC dynamics, restoration of wetlands, and hidden C costs of agricultural practices.
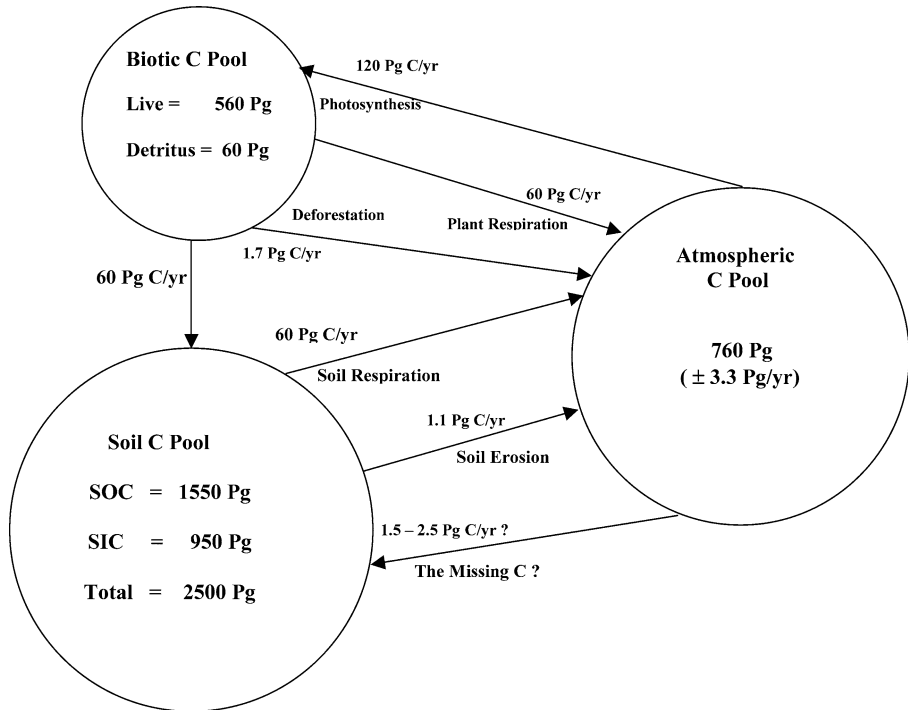
Figure 1. Intersection between soil carbon pool and the biotic and atmospheric C pools has been accentuated by anthropogenic activities including deforestation, biomass burning, soil cultivation, accelerated erosion, and fossil fuel combustion.

Historic Depletion of Soil Carbon Pool

Soils in their natural state contain a substantial amount of SOC pool. The magnitude and properties of the SOC pool depend on soil properties (e.g., clay content and type, soil water retention, nutrient reserves), profile characteristics (more in young soils with deep effective rooting depth), landscape position (more in foot slopes than summit or shoulder slopes), terrain characteristics (more in north facing and concave slopes than in south facing and convex slopes), temperature (more in cold than warm climates), and rainfall (more in humid than dry regions). The SOC pool ranges from 40 to 400 Mg C/ha under undisturbed natural vegetation cover (Post et al. 1982). The SOC pool is rapidly depleted upon conversion of natural to agricultural ecosystems. The magnitude of depletion may be 50 to 75% following 5 to 20 years after deforestation in soils of the tropics, compared with 25 to 50% over 20 to 50 years in soils of the temperate climates (Lal 2004a). The magnitude of depletion is high when inputs of C in managed ecosystems (through the return of crop residue and roots, along with application of other biosolids) are lower than the outputs. The latter comprise losses of SOC through mineralization, accelerated erosion and leaching.

The magnitude and rate of SOC depletion are high for structurally inert soils comprising low content of low activity clays (e.g., Kaolinite), excessive internal drainage, low available water and nutrient holding capacities, weak and low aggregation and poor soil structure, and overall low agronomic/biomass productivity. Soils of sub-Saharan Africa, West Asia and North Africa, Central Asia and many soils of the tropics and sub-tropics come under this category. Landscape position also has an important effect on SOC pool and its dynamics through moderation of runoff and soil erosion. Landscape positions which exacerbate soil erosion comprise convex slopes, side slopes, long and steep slopes and undulating terrains which accentuate the effects of rainfall and runoff erosivity. Over and above the pedologic and physiographic factors, socioeconomic and political factors also play an important role in the magnitude of SOC depletion upon conversion from natural to agricultural ecosystems. Agricultural systems, in which all outputs are balanced with appropriate inputs, cause lower SOC depletion than subsistence farming systems based on fertility-mining and extractive practices in which output exceeds the input. The SOC depletion is generally higher for plow-based than no-till systems of seedbed preparation, and also higher for those systems which do not return crop residue and other biosolids than systems based on mulch farming and liberal use of organic amendments.

The depletion of SOC pool has a positive (adverse) feedback enhancing atmospheric CO_2 concentration. A severe depletion of the SOC pool leads to decline in soil quality, negative nutrient/elemental balance, negative water balance exacerbated by high losses caused by severe runoff and high soil evaporation, and reduction in soil biodiversity with particularly severe impact on activity and species diversity of soil macrofauna (e.g., earthworms). Decline in soil quality reduces net primary productivity (NPP), decreases the quality and quantity of biomass returned to the soil, and further accentuates the depletion of SOC pool C.

Terrestrial Carbon Sequestration

Carbon sequestration implies transfer of atmospheric CO_2 into a long lived terrestrial pool (biotic, soil) so that CO_2 thus sequestered is not immediately released into the atmosphere. Three predominant components of terrestrial C sequestration include soil, biota and biofuel (Figure 2). Increase in SOC pool must be assessed to 2-m depth, because significant management-induced changes in SOC pool can occur deep in the sub-soil (Lorenz and Lal 2005). Increase in SOC pool, assessed in terms of either fixed depth or on equal soil mass basis, must be done for major land use and soil management systems. Management-induced changes in SOC pool can occur in labile, intermediate or the passive C fractions. Changes in the labile fraction can occur even over a short period, while those in the intermediate and passive fractions occur over a long time horizon.
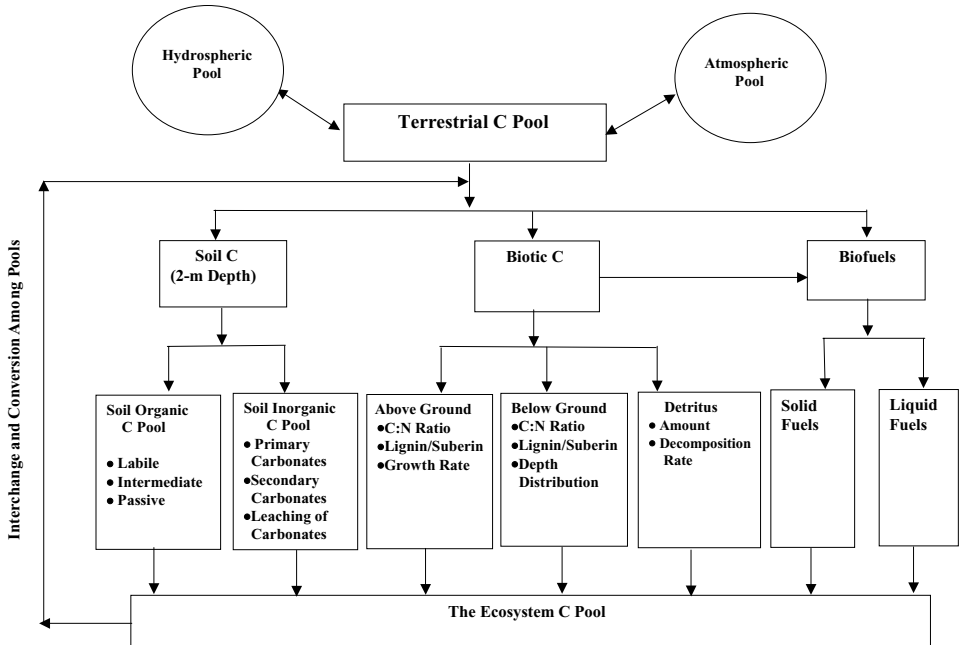
Figure 2. Components of terrestrial carbon sequestration.

There are three mechanisms or processes of soil C sequestration. Improvement of soil structure and formulation of stable micro-aggregates is an important process (Tisdall and Oades 1982; Six et al. 2000; Bossuyt et al. 2002). Humic substances and other persistent compounds (e.g., polymers) have a long lasting effect on micro-aggregate dynamics (Gale et al. 2000a,b), stabilization of macro-aggregates, thereby encapsulating and physically protecting organic matter against microbial activity. Clay content and mineralogy have strong impact on aggregation. Furthermore, total SOC concentration increases with increase in aggregate size (Beare et al. 1994a,b.)

Humification efficiency of biomass C (e.g., crop residues, leaf litter and other detritus material) depends on climate, soil properties, tillage methods, and nutrient availability. The humification efficiency is more in cool and humid climates than warm and dry regions. Furthermore, clayey soils with high surface area have a higher humification efficiency than coarse-textured soils. No-till farming positively impacts the humification efficiency. Puget et al. (2005) reported that the fraction of total C in corn residue converted to SOC in Coshocton, Ohio, was 11.9% for no-till corn and 8.3% for plow till corn. Allmaras et al. (2004) observed that humification efficiency was 26% for no-till compared with 11% for moldboard plow and chisel till. The humification efficiency is also strongly influenced by nutrient availability because C is only one of the building blocks of

humus, the others being N, P, S, Zn, Cu, etc.. Himes (1998) reported that se-
questration of 10 Mg of C in crop residue into 17.241 Mg of humus would re-
quire 28 Mg of C in 62 Mg of oven dry residue. In addition, it would require 833
Kg N, 200 Kg P and 143 Kg S. Thus, humification of residue C can occur only
if essential nutrients (e.g., N, P, S) are available. For a Luvisol in central Ohio,
Jacinthe et al. (2002) reported that residue-C conversion into SOC averaged 14%
and 32% without and with application of fertilizer, respectively. With low mulch
application, SOC stocks were similar (25.6 MgC/ha) with and without fertilizer
application. However, when the mulch rate was high, additional SOC accretion
occurred only in plots receiving additional fertilizer. Campbell et al. (2001) indi-
cated that without adequate fertilization, the adoption of no-till does not necessarily
increase SOC pool. Nitrogen fertilization rate and placement have a significant im-
pact on SOC sequestration rate (Gregorich et al. 1995, 1996; Wanniarachchi et al.
1999). Illuviation and translocation of C into sub-soil horizons is another impor-
tant mechanism. Deep translocation, away from the zone of anthropogenic and
climatic disturbances, can occur due to bioturbation by earthworms (Lavelle and
Pashanasi 1989) and termites, and deep root system development (Lorenz and Lal
2005).

There are several factors which enhance SOC pool upon conversion to a restora-
tive land use and adoption of recommended management practices (RMPs). In
general, structurally-active soils have a higher SOC capacity than structurally
inert soils (e.g., Kaolinitic clay, low surface area, low aggregation, etc.). Soils
developed on terrains that are not prone to erosion and which create favor-
able soil moisture and temperature regimes sequester more SOC than those
highly susceptible to erosion. Land use is an important factor. In general, a
perennial land use which causes less soil disturbance and adds higher biomass
amount enhances SOC pool more than seasonal crops. Ecosystems with high
NPP, continuous ground cover and less disturbance have high SOC pool, and vice
versa.

Sequestration of Soil Inorganic Carbon

The SIC pool is important in soils of arid and semi-arid climates (Schlesinger 1982,
1997), and mostly comprises of carbonates, including calcite, dolomite, aragonite
and siderite. Formation of secondary or pedogenic carbonates is an important mech-
anism of soil C sequestration. Monger (2002) describes four mechanisms of for-
mation of secondary carbonates: (i) dissolution of existing carbonates in the upper
layers, translocation onto the sub-soil, and reprecipitation with cations added from
outside the ecosystem (Marion et al. 1985), (ii) rise of Ca^{+2} from shallow water
table by capillarity and subsequent precipitation in the surface layer through reac-
tion with carbonic acid formed through dissolution of CO_2 in soil air (Sobecki and
Wilding 1983), (iii) carbonate dissolution and reprecipitation *in situ* with addition

of cations from elsewhere (Rabenhorst and Wilding 1986), and (iv) carbonate formation through activity of soil organisms (e.g., termites and micro-organisms) (Boquet et al. 1973; Monger et al. 1991; Zavarzin 2002). The depth of formation of secondary carbonates increases with increase in mean annual precipitation, being shallow in arid and deep in semi-arid and sub-humid climates. The depth of leaching may depend on soil pH, amount of infiltrating water and the concentration of carbonates in the soil horizons. The deposition of secondary carbonates may occur near subtle textural break in the lower solum (Schaetzl et al. 1996). The boundary zone may have unique pedologic characteristics (Allen and Hole 1968). In some soils, the depth of formation may be 1 m or even deeper, especially if active organic matter is deposited in the sub-soil layers by plants characterized by a deep root system. The dissolution of CO_2 into carbonic acid increases with increase in easily decomposable biomass in the sub-soil either from decaying roots (e.g., grasses) or addition of biosolids (e.g., crop residues, compost, etc.). In all four processes outlined above, the cations (Ca^{+2}, Mg^{+2}) must come from outside the system either through weathering of bed rock, fertilizer use, irrigation, water runon, dust deposition or applications of biosolids, etc. Increase in activity of soil micro-organisms and termites is also important. Indeed, visible accumulations of secondary carbonates are common where carbonate films, threads, concretions and pendants occur below peds and especially around roots (Gillam 1937; Sherman and Ikawa 1958; Wilding et al. 1990; Schaetzl et al. 1996).

Lundi et al. (2003) measured the rate of formation of secondary carbonates in the Boreal grassland and Boreal forest regions of Saskatchewan, Canada. The rate of carbonate-C accumulation was 10 to 15 Kg/ha/yr. They also observed that prairie soils sequestered 1.4 times more C in the form of pedogenic carbonates than as organic matter. In northern China, Qi et al. (2001) also reported that the SIC pool was 1.8 time the SOC pool in soils prone to desertification.

Leaching of carbonates into the ground water is another mechanism of SIC sequestration. The rate of leaching may be as high as 0.25 to 1.0 Mg C/ha/yr (Wilding, 1999). This mechanism is especially important when waters unsaturated with Ca $(HCO_3)_2$ are used for irrigation. This mechanism is extremely relevant to 275 Mha of irrigated cropland in arid and semi-arid regions of the world. Adoption of RMPs which enhance crop yields and reclaim salinized soils (e.g., use of gypsum, application of compost and other biosolids) accentuate leaching of biocarbonates, especially if irrigation water is not saturated with carbonates.

Application of lime on acidic soils is another important factor which needs to be addressed with regards to SIC dynamics in agricultural soils. USEPA (2003) estimated that 2.4 TgC is emitted annually from U.S. cropland through application of lime primarily due to dissolution of lime under acidic soil conditions. In addition, production and transport and spread of lime requires 38 Kg C/ha/yr (West and Marland 2002). However, a significant proportion of dissolved lime on agricultural soils may be leached out, eventually transported into the ocean and resequestered. West and McBride (2005) used IPCC (2000) data and reported that net emissions

from application of lime on agricultural soils is 0.12 and 0.13 Mg C per Mg of limestone and dolomite, respectively.

The role of SIC sequestration on soil C dynamics in relation to the climate change is less understood than that of SOC sequestration. There is a strong need to assess the formation of secondary carbonates, the magnitude of leaching and the impact of land use and management on overall SIC dynamics.

Carbon Sequestration in Wetlands and Peat Soils

Wetlands cover only 4 to 5% of the land area of the earth (Mathews and Fung 1987). Yet, global wetlands comprise the largest pool of stored SOC (Eswaran et al. 1993) and contain 400 to 500 Pg of C or about 20% of the total soil C pool of 2500 Pg (Gorham 1991; Maltby and Immirzi 1993). Therefore, SOC dynamics in wetlands can strongly impact the global C cycle. Presently, wetlands are a small sink for atmospheric CO_2 (Gorham 1991), but a major source of CH_4 (Fung et al. 1991). Conversion of wetlands into agricultural ecosystems have drastically disturbed the biogeochemical cycles. North America contained 20 Mha of wetlands prior to European settlement. However, 50% of the wetlands in the Prairie Pothole Region of the U.S. and 71% of that in Canada may have been drained for agriculture (Mitsch and Gosselink 2000). Chimner et al. (2002) reported that simulated drying predicted an average C loss of 70 g $C/m^2/yr$. Consequently, restoration of wetlands can enhance SOC pool. Being a highly productive ecosystem, restored wetlands can be a large sink for atmospheric CO_2. However, the rate of SOC sequestration in restored wetlands may be more in continuously flooded than seasonally inundated wetlands. Similar to uplands, the rate of SOC sequestration in wetlands also depends on availability of nutrients, especially N, and can be as much as 0.8 Mg C/ha/yr (Gleason 2001). Restored wetlands are not an exact replacement of natural wetlands in terms of biogeochemical processes such as denitrification potential (Hunter and Faulkner 2001; D'Angelo et al. 2005). Denitrification rates increase in response to increased inorganic N loading of agricultural run on (Poe et al. 2003). Restored wetlands may also be a less important source of CH_4 and N_2O, both of which are extremely potent greenhouse gases with global warming potential of 21 and 310, respectively. The diminished emission of CH_4 and N_2O may be due to low runon of N and P, especially if the watershed area surrounding the wetlands is not cultivated. Therefore, restoration of drained wetlands creates an important sink for sequestration of atmospheric CO_2, and must be given a high priority in any strategic land use planning. Cultivation of peatlands in the U.S. is practically negating all the benefits of SOC sequestration through no-till farming. Peat moss extraction exposes deep peat and accentuates mineralization (Glatzel et al. 2004). Cultivation of peatlands and moss harvesting must be strongly discouraged. Peatland management is also being linked to the Kyoto Protocol (Roulet 2000).
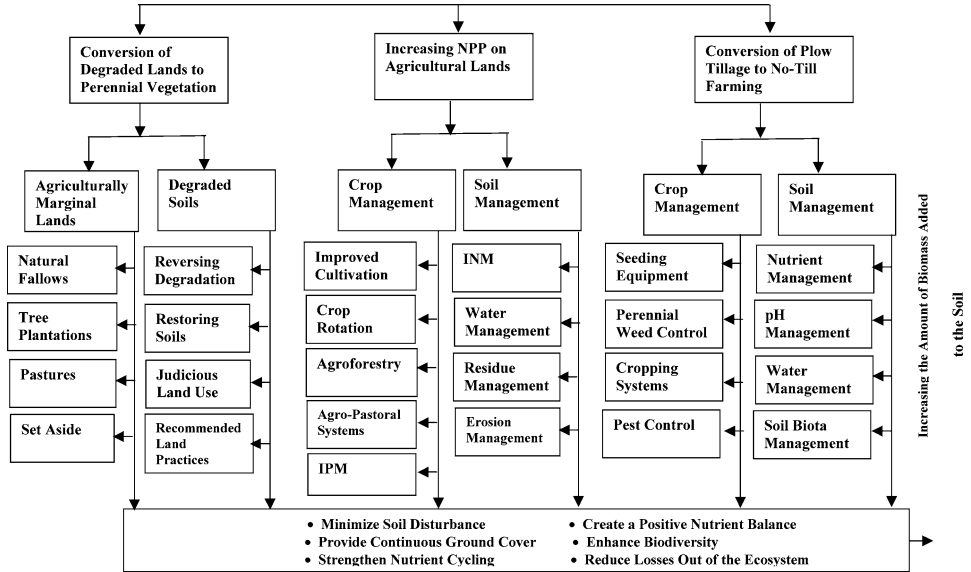
Figure 3. Strategies for soil carbon sequestration (IPM = Integrated pest management, INM = Integrated nutrient management).

Management of Soil Carbon

The strategy of soil C management is to increase the amount of crop residues and biosolids to the soil surface through: (i) minimizing soil disturbance, (ii) providing continuous ground cover, (iii) strengthening nutrient recycling mechanisms, (iv) creating a positive nutrient balance, (v) enhancing biodiversity, and (vi) reducing losses of water and nutrients out of the ecosystem. There are three principal options to achieve these: (i) converting degraded lands to perennial vegetation, (ii) increasing net primary productivity (NPP) of agricultural ecosystems, and (iii) converting plow tillage to no-till farming (Figure 3).

Degraded lands may involve either agriculturally marginal lands (e.g., too shallow, too steep, too wet, too dry, too rocky, or physically inaccessible) or soils which have been degraded by a multitude of factors leading to decline in soil's physical, chemical or biological quality. Principal degradation processes include soil erosion by water and wind, decline in soil structure leading to crusting and compaction, salinization, nutrient/elemental imbalance, water imbalance (inundation, drought) or invasion by obnoxious species. The objective is to establish a perennial land use, increase productivity of agricultural ecosystems (e.g., crops, pastures) through adoption of RMPs, and conversion of plow tillage to no-till farming. The rate of soil C sequestration is 300–350 Kg/ha/yr through conversion to a perennial land use (Post and Kwon 2000). Soil disturbance, such as plowing, reduces the SOC pool (Angers et al. 1995, 1997; Reeves et al. 1997; Dao 1998; Needleman et al.

1999; Clapp et al. 2000). Conversion of plow tillage to no-till increases SOC pool, especially in the surface layer (Allmaras et al. 2004; Puget and Lal 2005). There are several factors which affect SOC sequestration in a no-till system. The global mean rate of SOC sequestration for conversion from plow tillage to no-till is 400–600 Kg/ha/yr (West and Post 2002), and 100–200 Kg/ha/yr for intensification of agricultural ecosystems (Lal et al. 1998). Conversion of plow tillage to no-till is more effective in C sequestration in soils of lighter than heavier texture (Puget and Lal 2005; Wander et al. 1998; Ellert and Bettany 1995). Other factors which influence SOC sequestration include the quality and quantity of biomass returned to the soil surface as mulch (Huggins et al. 1998; Duiker and Lal 1999), and the antecedent SOC pool (Campbell et al. 1991). In addition to texture, the rate of SOC sequestration upon conversion to no-till farming also depends on landscape position and slope gradient (Hao et al. 2002). The SOC sequestration is more on gentler than steeper slopes, and on middle and lower slopes than summit positions.

Conversion to no-till farming is an important strategy for off-setting anthropogenic emissions by 2050 (Pacala and Socolow 2004). However, its effectiveness depends on the quality of crop residue mulch returned to the soil (Sa et al. 2001). In no-till systems where the biomass input is less than the output (by decomposition, leaching, residue removal), the SOC sequestration rate may be negative. The rates of the SOC sequeatration for no-till farming in diverse ecosystems vary widely among ecosystems and range from 0 to 1000 Kg/ha/yr (Lal 2003a; Lal et al. 1998; Sa et al. 2001; Post and Kwon 2000; West and Post 2002; West and Marland 2002). Forage-based crop rotations and complex cropping systems play an important role in tillage-induced changes in soil carbon sequestration (Jarecki and Lal 2003). There is a strong synergism between crop residue management and no-till farming. Effectiveness of no-till farming in erosion control, moisture conservation and SOC sequestration depend on the use of crop residue as mulch. However, crop residues are also being considered as potential feedstock for ethanol production. Removal of crop residues from agricultural soils can impact soil C budget. Readers are referred to detail discussion on the energy balance of removing residues for ethanol production by Weiss (2004), Kim and Dale (2004), Shapouri et al. (1995, 2002), Pimentel (2003), Pimentel et al. (2004), Sheehan et al. (2004), Wilhelm et al. (1986, 2004), Lal (2004b), Lemur and Lal (2005); Liebig et al. (2005) and Kim and Dale (2004).

Soil Erosion and Carbon Dynamics

Accelerated erosion plays an important, but less recognized, role in the global C budget. The direction and magnitude of the impact, however, can be determined by understanding the basic processes involved and their effects on SOC dynamics. Soil erosion is a four stage process. The SOC pool is affected through alterations in ecological conditions at each of these stages. The net effect of the accelerated

erosion is to decrease the ecosystem C budget (ECB). Net decrease in the ECB is attributed to: (i) decline in soil quality on site with an attendant reduction in NPP, (ii) decline in SOC pool on site, (iii) breakdown of soil aggregates due to rainfall and runoff impact and exposure of the soil organic matter hitherto encapsulated and physically protected to microbial attack, and (iv) prevalence of methanogenesis and nitrification/denitrification processes at the depositional site leading to emissions of CH_4 and N_2O. However, clay and SOC transported into the aquatic ecosystems and depressional sites may be re-aggregated through formation of organo-mineral complexes. The rate of decomposition in aquatic ecosystems is also low either due to the inundation or deep burial. However, deposition is only one of the four stages of erosion. The overall effect of all four stages of erosional process is a net reduction in ECB with attendant emission of CO_2, CH_4 and N_2O into the atmosphere. Lal (2003) estimated the erosion-induced emission of CO_2 into the atmosphere at 0.8–1.2 Pg C/yr compared with burial of 0.4–0.6 Pg C/yr into the ocean. Therefore, adoption of conservation-effective measures at global scale may avoid emission of CO_2 into the atmosphere, while reducing the severity and magnitude of anoxia in the coastal ecosystems (e.g., Gulf of Mexico) (Snyder et al. 2001; Ferber 2001). However, some researchers (especially sedimentologists) argue that oil erosion represents a net sink (Stallard 1998; Smith et al. 2001; Van Oost et al. 2005). The hypothesis that soil erosion is a C sink is based on the assumption that the burial of SOC on depositional areas reduces the decomposition rate, and the SOC removed at the eroded sites is replaced by newly produced SOC through photosynthesis and biomass return. The replacement of SOC on eroded sites, however, is a slow process and the time lag between removal and replacement must be considered. Nonetheless, these two contradictory views need to be objectively addressed and resolved through innovative experimentation.

Agricultural Practices and Anthropogenic Emissions

Agriculture is the largest terrestrial biome occupying as much as 35% of the earth's land area (Ramankutty and Foley 1999; Asner et al. 2004). Land use, land use change and forestry contribute 25% of the CO_2, 50% of the CH_4 and 70% of the N_2O emitted into the atmosphere annually (IPCC 2001). Further, the SOC pool of most soils is below their potential level because of the severe depletion caused by historic land use based on extractive soil management practices. Two important factors responsible for emission of CO_2 and depletion of SOC pool are plowing and soil erosion. Thus, conversion of plow tillage to no-till farming, involving a frequent use of cover crops in the rotation cycle along with adoption of integrated nutrient management (INM) and integrated pest management (IPM) strategies are practices which restore the SOC pool. Emission of N_2O is primarily related to use of nitrogenous fertilizers and biomass burning. Through adoption of a judicious land use and RMPs, however, agricultural lands can be a major sink for CO_2 and

CH_4 and also a reduced source of N_2O. The global potential of SOC sequestration is 0.6 to 1.2 Pg C/yr (Lal 2004a), which is equivalent to off-setting about 15% of the global CO_2 emissions. Controlling soil erosion and restoring degraded soils and ecosystems is an important strategy of maintaining/enhancing its SOC pool.

Residence Time or Permanence of Sequestered Carbon

The leakage of C sequestered in soil is often discussed in terms similar to sequestration of CO_2 injected in geological strata. The SOC sequestration is a natural process and is subject to leakage if the recommended land use and soil management practices are discontinued. Long-term maintenance of restorative practices is essential to the permanence of SOC sequestered. The residence time of SOC can be enhanced through: (i) returning of the crop residues and other biosolids at a rate in excess of the rate of decomposition, (ii) minimizing soil disturbance by plowing or other human activities, (iii) incorporating SOC in sub-soil occurs through deep root system development and bioturbation, (iv) meeting nutrient requirements (for N, P, S), and (v) creating soil conditions (e.g., clay content, landscape position) conducive to maintaining the inherent C sink capacity. It is also suggested by some that periodic soil inversion following 10 to 20 years of continuous no-till, may be useful in burying the soil enriched with SOC and bringing to the surface sub-soil containing lower SOC pool and having a potential sink capacity. This concept needs to be validated for identifying specific ecosystem niches where it may be applicable.

Hidden Carbon Costs of Agricultural Practices

There are large hidden C costs of RMPs (Lal 2004c), especially fertilizers, irrigation and pesticides. Several researchers argue that these costs must be deducted from the SOC sequestered to assess the net sequestration rate (Schlesinger 1999; Robertson et al. 2000). However, it is a question of choosing a baseline. For example, hidden C cost in no-till vs. plow tillage may be the same because of similar rates of input in both systems. Furthermore, adoption of RMPs is intended for enhancing the production of food, fiber, forage and fuel from agricultural soils than for SOC sequestration per se. Land managers are not using input for SOC sequestration but to enhance productivity and the profit margin (Lal et al. 2003). This strategy is termed a win-win option because SOC sequestration is a by-product of the necessity of agricultural intensification for meeting demands of the increasing world population.

Geological Versus Terrestrial Carbon Sequestration

There are two principal strategies of CO_2 sequestration: (i) biotic and (ii) abiotic. Biotic sequestration involves capture of atmospheric CO_2 by chlorophyll bearing plants through the natural process of photosynthesis. Annually, about 120 Pg of atmospheric CO_2-C is photosynthesized into carbohydrates and other organic compounds. The photosynthetic plants may be terrestrial or aquatic. The photosynthetic process can be managed through choice of plant species, nutrient application, and alleviation of other soil and environmental constraints so that the NPP can be increased and the total ecosystem carbon pool enhanced. Nutrient management of terrestrial plants was responsible for bringing about a quantum jump in global agricultural production during the second half of the 20th century. The impact of oceanic fertilization on sequestration of atmospheric CO_2 in aquatic biota, however, has been a debatable issue and an inconclusive option (Chisholm et al. 2001; Johnson and Karl 2000).

In addition to advancing global food security, the terrestrial C sink plays a major role in the global C cycle. It is strongly believed that the so-called missing C is absorbed in some terrestrial sinks (Fung 2000, Pacala et al. 2001; Scholes and Noble 2001). The implementation of the Kyoto Protocol in 2004 has enhanced the interest in the terrestrial C sink, of which soil C sequestration is an important component.

The knowledge of the global C cycle of individual components of the Earth's system (ocean and the terrestrial ecosystems) indicate that natural processes cannot absorb enough of the anthropogenic emissions of CO_2 to effectively mitigate the projected global warming (Falkowski et al. 2000). Therefore, geochemists and engineers argue that chemical and engineering techniques may be necessary to stabilize the atmospheric CO_2 concentration at a desired level. Achieving carbon-neutral energy by 2050- must rely on chemical and engineering techniques of CO_2 sequestration (Lackner 2003). The abiotic or engineering sequestration involves injecting CO_2 into reservoirs in which it may displace or mobilize oil or gas. However, oil and gas wells have a limited capacity, and this is not a true sequestration because the source of CO_2 is the underground oil wells rather than the atmosphere. Injecting CO_2, collected from the stack of fossil fuel power plants (Halman and Steinberg 1999), into saline aquifer and deep geologic strata is another option.

Oceanic injection, similar to that of geologic strata, involves deep injection to ensure that CO_2 remains in liquid form. With natural ocean turnover times of centuries (Lackner 2003), the residence time is long. Also sequestration in environmentally-active part of the ocean (top 1000 m) may have numerous adverse effects. Even the deep injection in ocean can have severe adverse impacts on deep-sea biota (Rivkin and Legendre 2001; Seibel and Walsh 2001).

Merits and demerits of soil vs. geologic sequestration are outlined in Table II. It is apparent that soil (and terrestrial) C sequestration may be economically and environmentally most viable option between 2005 and

TABLE I

Ecologic and economic benefits of soil organic carbon

On-site benefits	Off-site benefits
1. Improvement in soil quality.	1. Reduction in erosion
• Increase in available water capacity	• Decrease in sedimentation
• Increase in aggregation	• Reduction in non-point source pollution
• Increase in nutrient use efficiency	• Improvement in water quality
2. Improvements in soil tilth	• Benefits to agriculture
3. Decrease in cost of seedbed preparation	• Decrease in economic losses caused by flooding
4. Increase in crop yields	2. Soil carbon sequestration
5. Sustainable use of soil and water	• Decline in net CO_2 emission
	• Improvement in air quality

TABLE II

Terrestrial versus geologic sequestration

Parameter	Terrestrial sequestration	Geologic sequestration
1. The process	Natural through photosynthesis	Engineering through capture, compression and injection
2. Sink capacity	Finite (50–100 Pg)	Large
3. Time horizon	Immediate, for next 25 to 50 years	Work in progress, may be applicable in 10 to 20 years by 2015 to 2020.
4. Cost	Negative or low	Very high (each well is $ 5 million).
5. Risks		
• Crop yield	Improvement	–
• Human health	None or minor	High
• Environmental	Positive, it is a win-win-win situation	High
• Leakage risk	None	High
6. Monitoring and verification	Simple and economical methods available	Complex and expensive techniques
7. Regulatory measures	Trading soil C credits, providing farm subsidies	Complex legislative and policy issues

2025 or up to 2050. The geological/oceanic injection techniques may become viable options by 2015 or 2020. In the immediate future, 2005 to 2025, soil/terrestrial C sequestration through natural processes is an important strategy.

Conclusion

Soil C sequestration is an important strategy of enhancing soil quality, increasing agronomic productivity, reducing risks of soil erosion and sedimentation, decreasing eutrophication and contamination of water, reducing net CO_2 emission by off-setting those due to fossil fuel combustion, and mitigating the climate change. Principal strategies of soil C sequestration are conversion of degraded soils and agriculturally marginal lands to perennial land use including tree plantations, conversion of plow-tillage to no-till farming, and restoration of wetlands. The rate of soil organic carbon sequestration is 300 to 500 Kg C/ha/yr in uplands and 800 to 1000 Kg/ha/yr in restored wetlands. In addition, there is also a potential of sequestration of soil inorganic carbon as secondary carbonates. The rate of formation of secondary carbonates is 10 to 15 Kg C/ha/yr. The leaching of bicarbonates in soils irrigated with good quality water has a potential to remove 0.25 to 1.0 Mg C/ha/yr from about 275 Mha of global irrigated land area. The soil C once sequestered remains in the solum as long as the recommended practices are continued and soil is not disturbed. Removing crop residue can have adverse impact on soil quality, water quality, agronomic production and also cause depletion of soil carbon pool. Soil C sequestration is a bridge to the future until non-carbon fuel options take effect. While soil C sequestration is not a panacea for all environmental issues, it is certainly a step in the right direction to restore degraded soils, increase agronomic yields, improve water quality, reduce erosion along with suspended and dissolved loads, reduce anoxia in coastal ecosystems, and mitigate climate change through reduction in net anthropogenic emission of CO_2 into the atmosphere.

References

Allen, R.J. and Hole, F.D.: 1968, 'Clay accumulation in some Hapludalfs as related to calcareous till and incorporated loess on drumlins in Wisconsin', *Soil Sci. Soc. Am. Proc.* **32**, 403–408.

Allmaras, R.R., Linden, D.R. and Clapp, C.E.: 2004, 'Corn-residue transformations into root and soil carbon as related to nitrogen, tillage and stover management', *Soil Sci. Soc. Am. J.* **68**, 1366–1375.

Angers, D.A., Bolinder, M.A., Carter, M.R., Gregorich, E.G., Voroney, R.P., Drury, C.F., Liang, B.C., Simard, R.R., Donald, R.G., Bearyert, R. and Martel, J.: 1997, 'Impact of tillage practices on organic carbon and nitrogen storage in cool humid soils of eastern Canada', *Soil & Tillage Res.* **41**, 191–201.

Angers, D.A., Voroney, R.P. and Cote, D.: 1995, 'Dynamics of soil organic matter and corn residues affected by tillage practices', *Soil Sci. Soc. Am. J.* **59**, 1311–1315.

Asner, G.P., Elmore, A.J., Olander, L.P., Martin, R.E. and Harris, T.: 2004, 'Grazing systems, ecosystem responses and global change', *Annu. Rev. Environ. Resour.* **29**, 261–299.

Batjes, N.H.: 1996, 'Total carbon and nitrogen in soils of the world', *European J. Soil Sci.* **47**, 151–163.

Beare, M.H., Hendrix, P.F. and Coleman, D.C.: 1994a, 'Water stable aggregates and organic matter fractions in conventional and no-tillage soils', *Soil Sci. Soc. Am. J.* **58**, 777–786.

Beare, M.H., Hendrix, P.F. and Coleman, D.C. 1994b, 'Aggregate protected and unprotected organic matter pools in conventional and no-tillage soils', *Soil Sci. Soc. Am. J.* **58**, 787–795.

Boquet, E., Bononat, A. and Ramos-Cormenzana, A.: 1973, 'A production of calcite crystals (calcium carbonate) by soil bacteria is a general phenomena', *Nature* **246**, 527–528.

Bossuyt, H., Six, J. and Hendrix, P.F.: 2002, 'Aggregate-protected carbon in no-tillage and conventional tillage agroecosystems using carbon in labeled plant residue', *Soil Sci. Soc. Am. J.* **66**, 1965–1973.

Campbell, C.A., Sellers, F., Lafond, G.F. and Zentner, R.P.: 2001, 'Adopting zero tillage management: Impact on soil C and N under long-term crop rotations in a thin black Chernogen', *Can. J. Soil Sci.* **81**, 129–148.

Campbell, C.A., Bowren, K.E., Schnitzer, M., Zentner, R.P. and Townley-Smith, L.: 1991, 'Effect of crop rotations and fertilization on soil organic matter and some biochemical properties of a thick black Chernogen', *Can. J. Soil Sci.* **7**, 377–387.

Chimner, R.A.: 2004, 'Soil respiration rates of tropical peatlands in Micronesia and Hawaii', *Wetlands* **24**, 51–56.

Chimner, R.A., Cooper, D.J. and Parton, W.J.: 2002, 'Modeling carbon accumulation in Rocky Mountain fens', *Wetlands* **22**, 100–110.

Chisholm, S.W., Falkowski, P.G. and Cullen, J.J.: 2001, 'Dis-crediting ocean fertilization', *Science* **294**, 309–310.

Clapp, C.E., Allmaras, R.R., Layese, M.F., Linden, D.R. and Dowdy, R.H.: 2000, 'Soil organic carbon and ^{13}C abundance as related to tillage, crop residue and N fertilizer under continuous corn management in Minnesota', *Soil Tillage Res.* **55**, 127–142.

Costanza, R.R. d'arge, de Groots, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, T., Raskin, R.G., Sutton, P. and Vandenbelt, M.: 1997, 'The value of the World's ecosystem services and natural capital', *Nature* **387**, 253–266.

D'Angelo, E.M., Karathanasis, A.D., Sparks, E.J., Ritchey, S.A. and Wehr-McChesney, S.A.: 2005, 'Soil carbon and microbial communities at mitigated and late successional bottomland forest wetlands', *Wetlands* **25**, 162–175.

Dao, T.H.: 1998, 'Tillage and crop residue effects on carbon dioxide evolution and carbon storage in a Paleustoll', *Soil Sci. Soc. Am. J.* **62**, 250–256.

Duiker, S.J. and Lal, R.: 1999, 'Crop residue and tillage effects on C sequestration in a Luvisol in Central Ohio', *Soil & Tillage Res.* **52**, 73–81.

Ellert, B.H. and Bettany, J.R.: 1995, 'Calculation of organic matter and nutrients stored in soil under contrasting management regime', *Can. Soil Sci.* **75**, 529–538.

Eswaran, H., Van der Berg, E. and Reich, P.: 1993, 'Organic carbon in soils of the world', *Soil Sci. Soc. Am. J.* **57**, 192–194.

Falkowski, P., Scholes, r. J., Boyle, E., Candell, J., Esler, J., et al.: 2000, 'The global carbon cycle: A test of our knowledge of earth as a system', *Science* **290**, 291–296.

Ferber, D.: 2001, 'The deadzone's fiercest crusaders', *Science* **291**, 970–971.

Fung, I.: 2000, 'Variable carbon sinks', *Science* **290**, 1313–1314.

Fung, I.Y., Lerner, J.J., Matthews, E., Prather, M., Steele, L.P. and Fraser, P.J.: 1991, 'Three dimensional model synthesis of global methane cycle', *J. Geophys. Res.* **96**, 13033–13065.

Gale, W.J., Cambardella, C.A. and Bailey, T.B.: 2000a, 'Surface residue and root-derived carbon in stable and unstable aggregates', *Soil Sci. Soc. Am. J.* **64**, 196–201.

Gale, W.J., Cambardella, C.A. and Bailey, T.B.: 2000b, 'Root-derived carbon and the foundation and stabilization of aggregates', *Soil Sci. Soc. Am. J.* **66**, 201–207.

Gillam, W.S.: 1937, 'The formation of lime concretions in the Moody and Croften series', *Soil Sci. Am. Proc.* **2**, 471–477.

Glatzel, S., Basiliko, N. and Moore, T.: 2004, 'Carbon dioxide and methane production potentials of peats from natural, harvested and restored sites, eastern Quebec, Canada', *Wetlands* **24**, 261–267.

Gleason, R.A.: 2001, 'Invertebrate egg and plant seedbanks in natural, restored and drained wetlands in Prairie Pothole Region (USA) and potential effects of sedimentation on recolonization of hydrophytes and aquatic invertebrates'.

Gorham, E.: 1991, 'Northern Peatlands: Role in the carbon budget and the probable responses to global warming', *Ecological Applications* **1**, 182–195. In G.M. Woodwell and F.T. Mackenzie (Eds.), *Biotic Feedbacks in the Global Climate System: Will the Warming Feed the Warming?* New York, Oxford University Press, pp. 169–187.

Gregorich, E.G., Ellert, B.H. and Monreal, C.M.: 1995, 'Turnover of organic matter and storage of corn residue estimated from material ^{13}C abundance', *Can. J. Soil Sci.* **75**, 161–167.

Gregorich, E.G., Ellert, B.H., Durry, C.F. and Liang, B.C.: 1996, 'Fertilization affects on soil organic matter turnover and corn residue C storage', *Soil Sci. Soc. Am. J.* **60**, 472–476.

Halman, M.M. and Steinberg, M.: 1999, *Greenhouse Gas Carbon Dioxide Mitigation: Science and Technology*, Boca Raton, FL, Lewis Publishers, 568 pp.

Hao, Y., Lal, R., Owens, L.B., Izaurralde, R.C., Post, W.M. and Hothem, D.L.: 2002, 'Effect of cropland management and slope position on soil organic carbon pool at the North Appalachian Experimental Watersheds', *Soil & Tillage Res.* **68**, 122–142.

Himes, F.L.: 1998, 'Nitrogen, sulfur and phosphorus and sequestering of carbon', in R. Lal, J.M. Kimble, R.F. Follett and B.A. Stewart (eds.), *Soil Processes and the Carbon Cycle*, Boca Raton, FL, CRC Press, pp. 315–320.

Huggins, D.R., Clapp, C.E., Allmaras, r.R., Lamb, J.A. and Layse, F.F.: 1998, 'Carbon dynamics in corn-soybean sequences as estimated from natural carbon-13 abundance', *Soil Sci. Soc. Am. J.* **62**, 195–203.

Hunter, R.G. and Fulkner, S.G.: 2001, 'Denitrification potentials in restored and natural bottomland hardwood wetlands', *Soil Sci. Soc. Am. J.* **65**, 1865–1872.

IPCC: 2000, *Land Use, Land Use Change and Forestry*, Cambridge, UK, Cambridge University Press, 377 pp.

IPCC: 2001, *Climate Change 2001, The Scientific Basis*, Cambridge, UK, Cambridge University Press.

Jacinthe, P.A., Lal, R. and Kimble, J.M.: 2002, 'Effects of wheat residue fertilization on accumulation and biochemical attributes of organic carbon in a Central Ohio Luvisol', *Soil Sci.* **167**, 750–758.

Jarecki, M. and Lal, R.: 2003, 'Crop management for soil carbon sequestration', *Crit. Rev. Plant Sci.* **22**, 471–502.

Johnson, E. and Heinen, R.: 2004, 'Carbon trading: Time for industry involvement', *Env. Int.* **30**, 279–288.

Johnson, K.S. and Karl, d.M.: 2002, 'Is ocean fertilization credible or creditable?', *Science* **196**, 467–468.

Kim, S. and Dale, B.E.: 2004, 'Global potential bioethanol production from wasted crops and crop residue', *Biomass and Bioenergy* **26**, 361–375.

Lackner, C.: 2003, 'A guide to CO_2 sequestration', *Science* **300**, 1677–1678.

Lal, R.: 2003a, 'Carbon sequestration in dryland ecosystems', *Env. Manage.* **33**, 528–544.

Lal, R.: 2003b, 'Soil erosion and the global carbon budget', *Env. Intl.* **29**, 437–450.

Lal, R.: 2004a, 'Soil carbon sequestration impacts on global climate change and food security', *Science* **305**, 1623–1627.

Lal, R.: 2004b, 'Is crop residue a waste?', *J. Soil Water Cons.* **59**, 136–139.

Lal, R.: 2004c, 'Carbon emission from farm operations', *Env. Intl.* **30**, 981–990.

Lal, R., Kimble, J.M., Follett, R.F. and Cole, C.V.: 1998, *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect*, Chelsea, MI, Ann Arbor Press, 108 pp.

Lal, R., Follett, R.F. and Kimble, J.M.: 2003, 'Achieving soil carbon sequestration in the United States: A challenge to the policy makers', *Soil Sci.* **168**, 827–845.

Lavelle, P. and Pashanasi, B.: 1989, 'Soil and macrofauna and land management in Peruvian Amazonia', *Pedobiolgia* **33**, 283–291.

Lemus, R. and Lal, R.: 2005, 'Bioenergy crops and carbon sequestration', *Crit. Rev. Plant Sci.* (in press).

Liebig, M.A., Johnson, H.A., Hanson, J.D. and Frank, A.B.: 2005, 'Soil carbon under switch grass stands and cultivated cropland', *Biomass and Bioenergy* **28**, 347–354.

Lorenz, K. and Lal, R.: 2005, 'The depth disturbance of soil organic carbon in relation to land use and management and the potential of carbon sequestration in sub-soil horizons', *Adv. Agron.* (in press).

Lundi, A., Mermut, A.R. and Anderson, D.W.: 2003, 'Origin and rate of pedogenic carbonate accumulation in Saskatchewan soils, Canada', *Geoderma* **117**, 143–156.

Maltby, E. and Immirzi, P.: 1993, 'Carbon dynamics in peatlands and other wetland soils: Regional and global perspectives', *Chemosphere* **27**, 999–1023.

Marion, G.M., Schlesinger, W.H. and Fonteyn, P.J.: 1985, 'CALDEP: A regional model for soil $CaCO_3$ (caliche) deposition in south western deserts', *Soil Sci.* **139**, 468–481.

Matthews, E. and Fung, I.Y.: 1987, 'Methane emission from natural wetlands: Global distribution, area, and environmental characteristics of sources', *Global Biogeochemical Cycles* **1**, 61–68.

Mitsch, W.J. and Gosselink, J.G.: 2000, *Wetlands*, Third Edition, New York, Wileys.

Monger, H.C.: 2002, Pedogenic carbonates: Links between biotic and abiotic $CaCO_3$. 17th World Congress of Soil Sci., 14–21 August 2002, Thailand, Symposium #20, oral paper #891.

Monger, H.C., Daugherty, L.A., Lindemann, W.C. and Liddel, C.M.: 1991, 'Microbial precipitation of pedogenic calcite', *Geology* **19**, 997–1000.

Needleman, B.A., Wander, M.M., Bollero, G.A., Boast, C.W., Sims, G.K. and Bullock, D.G.: 1999, 'Interaction of tillage and soil texture: Biologically active soil organic matter in Illinois', *Soil Sci. Soc. Am. J.* **63**, 1326–1334.

Pacala, S.W., Hurtt, G.C., Baker, D., Peylin, P., Houghton, R.A., Birdsey, R.A., Heath, L., et al.: 2001, 'Consistent land and atmosphere-based U.S. carbon sink estimates', *Science* **292**, 2316–2320.

Pacala, S. and Socolow, R.: 2004, 'Stabilization wedges: Solving the climate problem for the next 50 years with current technologies', *Science* **305**, 968–972.

Pimental, D.: 2003, 'Ethanol fuels: Energy balance, economics, and environmental impacts are negative', *Natural Resource Res.* **12**, 127–134.

Pimental, D., Pleasant, A., Barron, J., Gaudioso, J., Pollock, N., Chae, E., Kim, Y., Lassiter, A., Schiavoni, C., Jackson, A., Lee, M. and Eaton, A.: 2004, 'U.S. energy conservation and efficiency: Benefits and costs', *Env. Dev. & Sust.* **6**, 279–305.

Poe, A.C., Piehler, M.F., Thompson, S.P. and Paerl, H.W.: 2003, 'Denitrification in a constructed wetland receiving agricultural runoff', *Wetlands* **23**, 817–826.

Post, W.M. and Kwon, K.C.: 2000, 'Soil carbon sequestration and land-use change: Processes and potential', *Glob. Change Biol.* **6**, 317–327.

Post, W.M., Emanuel, W.R., Zinke, P.J. and Stangenberger, A.G.: 1982, 'Soil carbon pool and world life zones', *Nature* **298**, 156–159.

Puget, P. and Lal, R.: 2005, 'Soil organic carbon and nitrogen in a Mollisol in central Ohio as affected by tillage and land use', *Soil & Tillage Res.* **80**, 201–213.

Puget, P., Lal, R., Izaurralde, C., Post, M. and Owens, L.: 2005, 'Stock and distribution of total and corn-derived soil organic carbon in aggregate and primary particle fractions for different land use and soil management practices', *Soil Sci.* 170 (in press).

Qi, F., Guodong, C. and Kunihiko, E.: 2001, 'Carbon storage in desertified lands', *GeoJournal* **51**, 181–189.

Rabenhorst, M.C. and Wilding, L.P.: 1986, 'Pedogenesis on the Edwards Plateau, Texas. III. A new model for the formation of petrocalcic horizons', *Soil Sci. Soc. Am. J.* **50**, 693–699.

Ramankutty, N. and Foley, J.A.: 1999, 'Estimating historical changes in global land cover: Croplands from 1700 to 1992', *Global Biogeochem. Cycles* **13**, 997–1027.

Reeves, M., Lal, R., Logan, T.J. and Sigaran, J.: 1997, 'Soil nitrogen and carbon response to maize cropping system, nitrogen source, and tillage', *Soil Sci. Soc. Am. J.* **61**, 1387–1392.

Rivkin, R.B. and Legendre, L.: 2001, 'Biogenic carbon cycling in the upper ocean: Effects of microbial respiration', *Science* **291**, 2398–2400.

Robertson, G.P., Paul, E.A. and Harwood, R.R.: 2000, 'Greenhouse gases in intensive agriculture: Contribution of individual gases to radiative forcing of the atmosphere', *Science* **289**, 1922–1925.

Roulet, N.T.: 2000, 'Peatlands, carbon storage, greenhouse gases, and the Kyoto Protocol: Prospects and significance for Canada', *Wetlands* **20**, 605–615.

Sa, J.C. de M., Cerri, C.C., Dick, W.A., Lal, R., Solisman, P., Filho, V., Piccolo, M.C. and Feigh, B.E.: 2001, 'Organic matter dynamics and carbon sequestration rates for a tillage chronosequence in a Brazilian Oxisol', *Soil Sci. Soc. Am. J.* **65**, 1486–1499.

Schaetzl, R.J., Frederick, W.E. and Tornes, L.: 1996, 'Secondary carbonates in three fine and fine loamy Alfisols in Michigan', *Soil Sci. Am. J.* **60**, 1862–1870.

Schlesinger, W.H.: 1982, 'Carbon storage in the caliche of arid soils: A case Study from Arizona', *Soil Sci.* **133**, 247–255.

Schlesinger, W.H.: 1997, *Biochemistry: An analysis of Global Change*, Second Edition, San Diego, Academic Press.

Schlesinger, W.H.: 1999, 'Carbon sequestration in soils', *Science* **284**, 2095.

Scholes, R.J. and Noble, I.R.: 2001, 'Storing carbon on land', *Science* **294**, 1012–1013.

Seibel, B.A. and Walsh, P.J.: 2001, 'Potential impacts of CO_2 injection on deep-sea biota', *Science* **294**, 319–320.

Shapouri, H., Duffield, J.A. and Graboski, M.S.: 1995, 'Estimating the net energy balance of corn ethanol', *Agric. Econ.* Report 721, USDA, Washington, DC.

Shapouri, H., Duffield, J.A. and Wang, M.: 2002, 'The energy balance of corn ethanol: An update', *Agric. Econ.* Report 813, USDA, Washington, DC.

Sheehan, J., Aden, A., Paustian, K., Killian, K., Brenner, J., Walsh, M. and Nelson, R.: 2004, 'Energy and environmental aspects of using corn stoves for fuel ethanol', *J. Ind. Ecol.* **7**, 117–146.

Sherman, G.D. and Ikawa, H.: 1958, 'Calcareous concretions and sheets in soils near South Point, Hawaii', *Pac. Sci.* 255–257.

Six, J., Paustian, K., Elliott, E.T. and Combrink, C.: 2000, 'Soil structure and organic matter. I. Distribution of aggregate size classes and aggregate-associated carbon', *Soil Sci. Soc. Am. J.* **64**, 681–689.

Smith, S.V., Renwick, W.H., Buddemeier, R.W. and Crossland, C.J.: 2001, 'Budgets of soil erosion and deposition for sediments and sedimentary organic carbon across the conterminous United States', *Global Biogeochem Cycles* **15**, 697–707.

Snyder, C.F., Howarth, R.W. and Winstanley, D.: 2001, 'Hypoxia, fertilizer and the Gulf of Mexico', *Science* **292**, 1485–1486.

Sobecki, T.M. and Wilding, L.P.: 1983, 'Formation of calcic and argillic horizons in selected soils of the Texas coast Prairie', *Soil Sci. Am J.* **47**, 707–715.

Stallard, R.F.: 1998, 'Terrestrial sedimentation and carbon cycle: Coupling weathering and erosion to carbon burial', *Global Biogeochem Cycles* **12**, 231–257.

Tisdall, J.M. and Oades, J.M.: 1982, 'Organic matter and water stable aggregates in soils', *J. Soil Sci.* **33**, 141–163.

US EPA: 2003, Agricultural Resources and Environmental Indicators, Agric. Handbook #AH722, USDA-ERS. Natural Resources and Env. Div., Washington, D.C. (http://www.ers.usda.gov/publications/arei/arei2001).

Van Oost, K., Govers, G., Quine, T.A., Heckrath, G., Olsen, J.E., DeGryze, S. and Merck, R.: 2005, 'Landscape scale modeling of carbon cycling under the impact of soil redistribution: The role of tillage erosion', *Global Biogeochem. Cycles* **19**, 1029–1037.

Wander, M.M., Bidart, M.G. and Aref, S.: 1998, 'Tillage impact on depth distribution of total and particulate organic matter in three Illinois soils', *Soil Sci. Soc. Am. J.* **62**, 1704–1710.

Wanniarachchi, S.D., Voroney, R.P., Vyn, T.J., Beyaert, R.P. and MacKenzie, A.F.: 1999, 'Tillage effects on the dynamics of total and corn-residue-derived soil organic matter in two southern Ontario soils', *Can. J. Soil Sci.* **79**, 473–480.

Weisz, P.B.: 2004, 'Basic choices and constraints on long-term energy supplies', *Physics Today* July 2004, pp. 47–55.

West, T.O. and McBride, A.C.: 2005, 'The contribution of agricultural lime to carbon dioxide emissions in the United States: Dissolution, transport and net emissions', *Agric. Ecosys. & Environ.* (in press).

West, T.O. and Post, W.M.: 2002, 'Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis', *Soil Sci. Soc. Am. J.* **66**, 1930–1946.

West, T.O. and Marland, G.: 2002, 'A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the US', *Agric. Ecosys. & Environ.* **91**, 217–232.

Wilding, L.P.: 1999, 'Comments on paper by Lal, et al.', in N.J. Rosenberg, R.C. Izaurralde and E.L. Malone (eds.), *Carbon Sequestration in Soils: Science, Monitoring and Beyond*, Columbus, OH, Battelle Press, pp. 146–149.

Wilding, L.P., West, L.T. and Drees, L.R.: 1990, 'Field and laboratory identification of calcic and petrocalcic horizons', in J.M. Kimble and W.D. Nettleton (eds.), *Proceedings of the International Soil Correlation Meeting, ISCOM-IV: Characterization, Classification and Utilization of Aridisols*, 3–17 October 1987, Lincoln, NE, USDA-SCS.

Wilhelm, W.W., Doran, J.W. and Power, J.F.: 1986, 'Corn and soybean yield response to crop residue management under no-tillage production systems', *Agron. J.* **78**, 184–189.

Wilhelm, W.W., Johnson, J.M.F., Hatfield, J.L., Vorhees, W.B. and Linden, D.R.: 2004, 'Crop and soil productivity response to corn residue removal: A literature review', *Agron. J.* **96**, 1–17.

Zavarzin, G.A.: 2002, 'Microbial geochemical calcium cycle', *Microbiology* **71**, 5–22.