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Review

Soil carbon sequestration to mitigate climate change

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Abstract

The increase in atmospheric concentration of CO_2 by 31% since 1750 from fossil fuel combustion and land use change necessitates identification of strategies for mitigating the threat of the attendant global warming. Since the industrial revolution, global emissions of carbon (C) are estimated at 270 ± 30 Pg (Pg = petagram = 10^{15} g = 1 billion ton) due to fossil fuel combustion and 136 ± 55 Pg due to land use change and soil cultivation. Emissions due to land use change include those by deforestation, biomass burning, conversion of natural to agricultural ecosystems, drainage of wetlands and soil cultivation. Depletion of soil organic C (SOC) pool have contributed 78 ± 12 Pg of C to the atmosphere. Some cultivated soils have lost one-half to two-thirds of the original SOC pool with a cumulative loss of 30–40 Mg C/ha (Mg = megagram = 10^6 g = 1 ton). The depletion of soil C is accentuated by soil degradation and exacerbated by land misuse and soil mismanagement. Thus, adoption of a restorative land use and recommended management practices (RMPs) on agricultural soils can reduce the rate of enrichment of atmospheric CO_2 while having positive impacts on food security, agro-industries, water quality and the environment. A considerable part of the depleted SOC pool can be restored through conversion of marginal lands into restorative land uses, adoption of conservation tillage with cover crops and crop residue mulch, nutrient cycling including the use of compost and manure, and other systems of sustainable management of soil and water resources. Measured rates of soil C sequestration through adoption of RMPs range from 50 to 1000 kg/ha/year. The global potential of SOC sequestration through these practices is 0.9 ± 0.3 Pg C/year, which may offset one-fourth to one-third of the annual increase in atmospheric CO_2 estimated at 3.3 Pg C/year. The cumulative potential of soil C sequestration over 25–50 years is 30–60 Pg. The soil C sequestration is a truly win–win strategy. It restores degraded soils, enhances biomass production, purifies surface and ground waters, and reduces the rate of enrichment of atmospheric CO_2 by offsetting emissions due to fossil fuel.

Keywords: Greenhouse effect; Soil restoration; Conservation tillage; Mulch farming; Cover cropping; The global C cycle

1. Introduction

There has been a drastic increase in the atmospheric concentration of carbon dioxide (CO_2) and other greenhouse gases (GHGs) since the industrial revolution (Table 1). The atmospheric concentration of CO_2 has increased from 280 ppmv in 1750 to 367 ppmv in 1999 and is currently increasing at the rate of 1.5 ppmv/year or 3.3 Pg C/year (1 Pg = petagram = billion ton) (IPCC, 2001). Atmospheric methane (CH_4) concentration has increased from about 700 to 1745 ppbv over the same period and is increasing at the rate of 7 ppbv/year. Similarly, the atmospheric concentration of

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Table 1
Change in atmospheric concentration of trace gases since the industrial revolution at about 1750 (modified from IPCC, 2001)

Gas	Present concentration	Percent increase since 1750	Present rate of increase (%/year)
Carbon dioxide (CO_2)	379 ppm	31	0.4
Methane (CH_4)	1745 ppb	151	0.4
Nitrous oxide (N_2O)	314 ppb	17	0.25
Chlorofluorocarbons (CFCs)	268 ppt	α	decreasing

ppm = parts per million, ppb = parts per billion, ppt = parts per trillion. Increase in CO_2 concentration in 2003 was 3 ppm.

nitrous oxide (N_2O) has increased from about 270 ppbv in 1750 to 314 ppbv and increasing at the rate of 0.8 ppbv/year (IPCC, 2001). The current radiative forcing of these gases is 1.46 w/m^2 for CO_2, 0.5 w/m^2 for CH_4 and 0.15 w/m^2 for N_2O. This anthropogenic enrichment of GHGs in the atmosphere and the cumulative radiative forcing of all GHGs has led to an increase in the average global surface temperature of 0.6 °C since the late 19th century, with the current warming rate of 0.17 °C/decade (IPCC, 2001). The observed rate of increase of the global mean temperature is in excess of the critical rate of 0.1 °C/decade beyond which the ecosystems cannot adjust. Consequently, land-surface precipitation continues to increase at the rate of 0.5–1%/decade in much of the Northern Hemisphere especially in mid and high latitudes, and decrease in sub-tropical land areas at the rate of 0.3%/decade. These changes may decrease the soil organic carbon (SOC) pool and structural stability, increase soil's susceptibility to water runoff and erosion, and disrupt cycles of water, carbon (C), nitrogen (N), phosphorus (P), sulfur (S) and other elements, and cause adverse impacts on biomass productivity, biodiversity and the environment.

Despite a strong inter-dependence between climate and soil quality (Jenny, 1980), the role of SOC dynamics on historic increase in atmospheric CO_2, and its strategic importance in decreasing the future rate of increase of atmospheric CO_2 are not widely recognized. Therefore, this paper reviews the impact of anthropogenic activities on historic depletion of the SOC pool, assesses the magnitude of the contribution of the SOC pool to atmospheric increase in CO_2, outlines the processes and practices that lead to SOC sequestration with attendant improvements in soil quality and mitigation of climate change, highlights recent developments in the importance of soil erosion on the global C cycle, enumerates debatable issues with regard to SOC sequestration, and indicates the relevance of SOC sequestration to the Kyoto Protocol. This report uses SOC and soil organic matter (SOM) interchangeably with the understanding that SOC is only about 58% of the SOM.

2. Sources of increase in atmospheric concentration of gases

Emissions of CO_2 by fossil fuel combustion have increased drastically during the 20th century (Table 2). The data in Table 3 show the global C budget for the last two decades of the 20th century, lists known sources and sinks, and identifies the magnitude of the so-called missing or fugitive C (Prentice, 2001). The global C budget for the decade of 1980s included 5.4 ± 0.3 Pg C emission by fossil fuel combustion and cement production, and 1.7 ± 0.8 Pg C emission by land use change. The latter consists of deforestation and biomass burning, and conversion of natural to agricultural ecosystems. The annual increase in atmospheric concentration of CO_2 during the 1980s was 3.3 ± 0.2 Pg C/year, absorption by the ocean was 2.0 ± 0.8 Pg C/year, and the unknown residual terrestrial sink was 1.9 ± 1.3 Pg C/year. For the decade of the 1990s, emission by fossil fuel combustion and cement production were 6.3 ± 0.4 Pg C/year, and the emission by land use change was 1.6 ± 0.8 Pg C/year. The increase in atmospheric concentration, however, occurred at the rate of 3.2 ± 0.1 Pg C/year, the ab-

Table 2
Global, U.S. and Indian emissions of CO_2 by fossil fuel combustion (Marland et al., 1999)

Year	Emissions (million tons C/year)		
	Global	India	U.S.
1750	3	–	–
1800	8	–	0.07
1850	54	0.03	5
1900	534	3	180
1950	1630	5	692
1970	4075	14	1152
1980	5297	26	1263
1990	6096	50	1314
1998	6608	79	1487

Table 3
An approximate global carbon budget (modified from IPCC, 2001)

Source/sink	1980s	1990s
	Billion ton	
A. Source		
1. Fossil fuel combustion and cement production	5.0	6.3
2. Land use change	1.7	1.6
Total	6.7	7.9
B. Known sinks		
1. Atmosphere	3.3	3.2
2. Oceans	1.9	1.7
Total	5.2	4.9
C. Missing sinks (the fugitive CO_2) or probable terrestrial sink	1.5	3.0

sorption by the ocean was 2.3 ± 0.8 Pg C/year and the uptake by an unknown terrestrial sink was 2.3 ± 1.3 Pg C/year (Prentice, 2001; Schimel et al., 2001).

These global C budgets are tentative at best, because possible emissions of C by soil erosional and other degradative processes are not accounted for. Nonetheless, the data indicate an important role that land use; soil management and terrestrial ecosystems play in the global C budget. Thus, a complete understanding of the components (pools and fluxes) of the global C budget is required to identify sources and sinks of C and develop strategies for mitigating the risks of climate change.

There are five principal global C pools. The oceanic pool is the largest, followed by the geologic, pedologic (soil), biotic and the atmospheric pool (Fig. 1). All these pools are inter-connected and C circulates among them. The pedologic or soil C pool comprises two components: SOC and the soil inorganic carbon (SIC) pool. The SIC pool is especially important in soils of the dry regions. The SOC concentration ranges from a low in soils of the arid regions to high in soils of the temperate regions, and extremely high in organic or peat soils (Table 4). The SOC pool also varies widely among ecoregions, being higher in cool and moist than warm and dry regions (Table 5). Therefore, the total soil C pool is four times the biotic (trees, etc.) pool and about three times the atmospheric pool.

Table 4
Soil C pool of world soils (adapted from Eswaran et al., 2000)

Soil order	Area (Mha)	Soil organic carbon		Soil inorganic carbon	
		Density (tons/ha)	Pool (billion tons)	Density (tons/ha)	Pool (billion tons)
Alfisols	1262	125	158	34	43
Andisols	91	220	20	0	0
Aridisols	1570	38	59	290	456
Entisols	2114	42	90	124	263
Gelisols	1126	281	316	6	7
Histosols	153	1170	179	0	0
Inceptisols	1286	148	190	26	34
Mollisols	901	134	121	96	116
Oxisols	981	128	126	0	0
Rocky land	1308	17	22	0	0
Shifting sand	532	4	2	9	5
Spodosols	335	191	64	0	0
Ultisols	1105	124	137	0	0
Vertisols	316	133	42	50	21
Total	13,083		1526		945

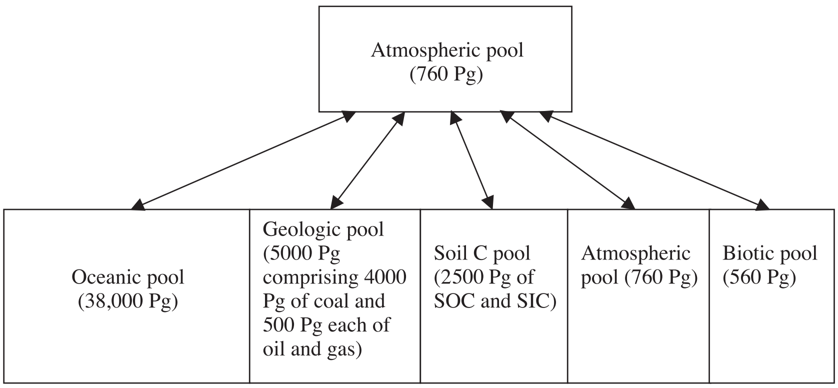

Fig. 1. Principal global carbon pools.

Table 5
Estimates of soil organic carbon pool (adapted and recalculated from IPCC, 2000; Prentice, 2001)

Ecosystem	Area (10^9 ha)	SOC pool (billion tons C)	SOC density (tons C/ha)
Forests			
· Tropical	1.76	213–216	121–123
· Temperate	1.04	100–153	96–147
· Boreal	1.37	338–471	247–344
Tropical savannas and grasslands	2.25	247–264	110–117
Temperate grassland and scrub land	1.25	176–295	141–236
Tundra	0.95	115–121	121–127
Desert and semi-desert	4.55	159–191	35–42
Cropland	1.60	128–165	80–103
Wetlands	0.35	225	643

There are some estimates of the historic loss of C from geologic and terrestrial pools and transfer to the atmospheric pool. From 1850 to 1998, 270 ± 30 Pg of C were emitted from fossil fuel burning and cement production (Marland et al., 1999; IPCC, 2000). Of this, 176 ± 10 Pg C were absorbed by the atmosphere (Etheridge et al., 1996; Keeling and Whorf, 1999), and the remainder by the ocean and the terrestrial sinks. During the same period, emissions from land use change are estimated at 136 ± 55 Pg C (Houghton, 1995, 1999).

There are two components of estimated emissions of 136 ± 55 Pg C from land use change: decomposition of vegetation and mineralization/oxidation of humus or SOC. There are no systematic estimates of the historic loss of SOC upon conversion from natural to managed ecosystems. Jenny (1980) observed that "among the causes held responsible for CO_2 enrichment, highest ranks are accorded to the continuing burning of fossil fuels and the cutting of forests. The contributions of soil organic matter appear underestimated." The historic SOC loss has been estimated at 40 Pg by Houghton (1999), 55 Pg by IPCC (1996) and Schimel (1995), 500 Pg by Wallace (1994), 537 Pg by Buringh (1984) and 60–90 Pg by Lal (1999). Until the 1950s, more C was emitted into the atmosphere from the land use change and soil cultivation than from fossil fuel combustion. Whereas the exact magnitude of the historic loss of SOC may be debatable, it is important to realize that the process of SOC depletion can be reversed. Further, improvements in quality and quantity of the SOC pool can increase biomass/agronomic production, enhance water quality, reduce sedimentation of reservoirs and waterways, and mitigate risks of global warming.

3. Factors affecting depletion of soil carbon pool

Depletion of the SOC pool has major adverse economic and ecological consequences, because the SOC pool serves numerous on-site and off-site functions of value to human society and well being. Principal on-site functions of the SOC pool are:

(i) Source and sink of principal plant nutrients (e.g., N, P, S, Zn, Mo);
(ii) Source of charge density and responsible for ion exchange;
(iii) Absorbent of water at low moisture potentials leading to increase in plant available water capacity;
(iv) Promoter of soil aggregation that improves soil tilth;
(v) Cause of high water infiltration capacity and low losses due to surface runoff;
(vi) Substrate for energy for soil biota leading to increase in soil biodiversity;
(vii) Source of strength for soil aggregates leading to reduction in susceptibility to erosion;
(viii) Cause of high nutrient and water use efficiency because of reduction in losses by drainage, evaporation and volatilization;
(ix) Buffer against sudden fluctuations in soil reaction (pH) due to application of agricultural chemicals; and
(x) Moderator of soil temperature through its effect on soil color and albedo.

In addition, there are also off-site functions of SOC pool, which have both economic and environmental significance. Important among these are:

(i) Reduces sediment load in streams and rivers,
(ii) Filters pollutants of agricultural chemicals,
(iii) Reactors for biodegradation of contaminants, and
(iv) Buffers the emissions of GHGs from soil to the atmosphere.

It is because of these multifareous functions that led Albrecht (1938) to observe that "soil organic matter (SOM) is one of our most important national resources; its unwise exploitation has been devastating; and it must be given its proper rank in any conservation policy." Indeed, the unwise exploitation of this precious resource is due to human greed and short-sightedness causing land misuse and soil mismanagement.

Anthropogenic perturbations exacerbate the emission of CO_2 from soil caused by decomposition of SOM or soil respiration (Schlesinger, 2000b). The emissions are accentuated by agricultural activities including tropical deforestation (Fig. 2) and biomass burning (Fig. 3), plowing (Reicosky, 2002), drainage of wetlands and low-input farming or shifting cultivation (Fig. 4; Tiessen et al., 2001). In addition to its impact on decomposition of SOM (Trumbore et al., 1996), macroclimate has a large impact on a fraction of the SOC pool which is active (Franzluebbers et al., 2001a). Conversion of natural to agricultural ecosystems increases maximum soil temperature and decreases soil moisture storage in the root zone, especially in drained agricultural soils (Lal, 1996). Thus, land use history has a strong impact on the SOC pool (Pulleman et al., 2000). Biomass burning is an important management tool, especially in agricultural ecosystems of the tropics. The process emits numerous gases immediately but also leaves charcoal as a residual material. Charcoal, produced by incomplete

Fig. 2. Deforestation of tropical rainforest in southern Nigeria. The rate of tropical deforestation may be 20 million hectares per year.

Fig. 3. Biomass burning, such as that of the cut forest in Brazil, causes large emissions of greenhouse gases and soot or black carbon into the atmosphere.

combustion, is a passive component, and may constitute up to 35% of the total SOC pool in fire-prone ecosystems (Skjemstad et al., 2002). As the SOC pool declines due to cultivation and soil degradation, the more resistant charcoal fraction increases as a portion of the total C pool (Zech and Guggenberger, 1996; Skjemstad et al., 2001).

Similar to deforestation and biomass burning, cultivation of soil, by plowing and other tillage methods, also enhances mineralization of SOC and releases CO_2 into the atmosphere (Reicosky et al., 1999). Tillage increases SOC mineralization by bringing crop residue closer to microbes where soil moisture conditions favor mineralization (Gregorich et al., 1998), physically disrupts aggregates and exposes hitherto encapsulated C to decomposition. Both activities decrease soil moisture, increase maximum soil temperature and exacerbate rate of SOC mineralization.

Thus, a better understanding of tillage effects on SOC dynamics is crucial to developing and identify-

Fig. 4. Soil erosion leads to preferential removal of topsoil rich in soil organic carbon as in the case for this in Alfisol in western Nigeria.

ing sustainable systems of soil management for C sequestration. There is a strong interaction between tillage and drainage. Both activities decrease soil moisture, increase maximum soil temperature and exacerbate rate of SOC mineralization. Nutrient mining, as is the case with low input and subsistence farming practices, is another cause of depletion of SOC pool (Smaling, 1993). Negative elemental balance, a widespread problem in sub-Saharan Africa, is caused by not replacing the essential plant nutrients harvested in crop and livestock products by addition of fertilizer and/or manure. Excessive grazing (Fig. 5) has the same effect as mining of soil fertility by inappropriate cropping. Uncultivated fallowing, plowing for weed control but not growing a crop so that soil moisture in the profile can be recharged for cropping in the next season, is another practice that exacerbates SOC depletion. In the west central Great Plains of the U.S., this system requires a 14-month fallow period between the harvest and continuous cropping in some instances. Fallowing during summer keeps the soil moist and enhances the mineralization rate. Therefore, elimination of summer fallowing is an important strategy of SOC sequestration (Rasmussen et al., 1998). The objective is to maintain a dense vegetal cover on the soil surface so that biomass C can be added/returned to the soil. Consequently, the SOC pool can be maintained or increased in most semi-arid soils if they are cropped every year, crop residues are returned to the soil, and erosion is kept to a minimum.

4. Depletion of soil organic carbon pool by erosion versus mineralization

Depletion of the SOC pool on agricultural soils is exacerbated by and in turn also exacerbates soil degradation. It comprises physical degradation (i.e., reduction in aggregation, decline in soil structure, crusting, compaction, reduction in water infiltration capacity and water/air imbalance leading to anaerobiosis) and erosion, chemical degradation (i.e., nutrient depletion, decline in pH and acidification, build up of salts in the root zone, nutrient/elemental imbalance and disruption in elemental cycles), and biological degradation (i.e., reduction in activity and species diversity of soil fauna, decline in biomass C and depletion of SOC pool). Soil degradation decreases biomass productivity, reduces the quantity (and quality) of biomass returned to the soil, and as a consequence decreases the SOC pool. Among all soil degradative processes, accelerated soil erosion has the most severe impact on the SOC pool. Several experiments have shown on-site depletion of the SOC pool by accelerated erosion (De Jong and Kachanoski, 1988; Fig. 6). However, on-site depletion does not

Fig. 5. No till farming and other conservation tillage practices eliminate drastic soil disturbance, and enhance soil organic matter in the surface layers. Conversion from plow till to no-till with residue mulch is a viable option for SOC sequestration.

Fig. 6. *Mucuna utilis* (velvet bean), a suitable cover crop for the humid tropics of west Africa, and other cover crops enhance SOC pool.

necessarily imply emission of GHGs into the atmosphere. Some of the SOC redistributed over the landscape by erosion and carried into the aquatic ecosystems and depressional sites may be mineralized and released as CO_2 (Lal, 1999), while the other is buried and sequestered (Stallard, 1998; Smith et al., 2001). It is estimated that about 1.14 Pg of C may be annually emitted into the atmosphere through erosion-induced processes (Lal, 2001a), and must be accounted for in the global C budget of the type shown in Table 3. Knowledge of the impact of erosional processes on SOC dynamics, and understanding the fate of C translocated by erosional processes is crucial to assessing the role of erosion on emissions of GHGs into the atmosphere.

Soil erosion is a major factor depleting SOC pool on sloping lands. On relatively flat soils with no erosion risks; however, mineralization predominates over erosion. For example, Rasmussen et al. (1998) observed that in Pendleton, eastern Oregon, biological oxidation of soil organic matter rather than accelerated erosion is the principal cause of SOC depletion. On steep slopes, however, erosional processes may be the principal cause of SOC depletion. Several studies have documented that long-term SOC loss in prairie soils is due to accelerated soil erosion (Gregorich and Anderson, 1985; De Jong and Kachanoski, 1988; Dumanski et al., 1998). Therefore, adoption of conservation-effective farming systems and judicious management of soil erosion are crucial to maintaining and enhancing the SOC pool.

Soil degradation affects 1216 Mha by moderate plus severe categories in the world and 130 Mha in South Asia (Table 6). The "moderate" level refers to the degree of soil degradation in which the soil has a reduced productivity but is still suitable for use in local farming systems especially with an increased level of input (Oldeman, 1994). Some global hotspots of soil degradation are sub-Saharan Africa, South Asia, the Himalayan-Tibetan ecoregion, the Andean region, Central America and the Caribbean. Severely eroded soils may have lost one-half to two-thirds of their original carbon pool (Lal, 2000), and the loss is more in soils with larger than smaller pools, and in the tropics than in temperate regions.

Table 6
Estimates of soil degradation in the world and South Asia at moderate + level of severity (calculated from Oldeman, 1994; FAO, 1994)

Process	World	South Asia
	Mha	
Water erosion	751	49
Wind erosion	280	47
Chemical degradation	146	31
Physical degradation	39	3
Total degraded area	1216	130

Most agricultural soils now contain a lower SOC pool than their potential as determined by the specific climatic conditions and soil profile characteristics. The historic loss of SOC pool in some sloping lands may be 30–40 Mg C/ha, or one-half to two-thirds of the original pool. The SOC pool can be enhanced by adopting recommended management practices (RMPs) and restoring degraded soils. Therefore, an important strategic question is "to what extent can SOC sink capacity potentially offset increases in atmospheric CO_2?"

5. Impact of potential climate change on soil organic matter and soil quality

Projected climate change may affect soil moisture and temperature regimes. At the ecosystem level, the soil affects vegetation through its influence on water availability, elemental cycling and soil temperature regime (Cheddadi et al., 2001). Changes in soil moisture and temperature regimes can affect species composition in the ecosystem. These changes may affect the SOC pool and soil physical properties because of the changes in biomass (detritus material, above ground and below ground biomass) returned to the soil. The effect of climate change may be different in tropical, temperate and Boreal regions. Projected increase in temperature and decrease in effective rainfall may decrease the net primary productivity (NPP) in many tropical regions, but increase it in the boreal forest regions (White et al., 1999). There will be a longer growing season in the temperate regions of northern Europe and America leading to introduction of new/more productive cultivars and even new species in the region (Kleemola et al., 1995; Sohlenius and Boström, 1999). In these regions, the NPP may also increase due to the CO_2 fertilization effect (Lemon, 1983; Drake and Leadley, 1991; Bazzaz, 1990; Poorter, 1993; Lawlor and Mitchell, 1991; Hendrey, 1993). Theoretically, an average rise in mean annual temperature of 1 °C is equivalent of an approximate poleward shift of vegetation zones by 200 km (Ozenda and Borel, 1990). However, the projected climate change may be gradual and the initial effects subtle (Hendry and Grime, 1990).

Soil temperature is the primary rate determinant of microbial processes. Therefore, increase in soil temperature will exacerbate the rate of mineralization leading to a decrease in the SOC pool. However, decomposition by-products at higher temperatures may be more recalcitrant than those at lower temperatures (Dalias et al., 2001). Decline in SOC pool will have an adverse effect on soil structure, with a possible increase in erodibility and the attendant increase in susceptibility to crusting, compaction, runoff and erosion. The decline in SOC pool with the projected climate change may be especially severe in Boreal, Tundra and Polar regions compared to mid latitudes. Peat and other organic soils of the cold regions (e.g., cryosols) are presently a net C sink (Lal et al., 2000). These soils may become a net C source with projected increase in temperature.

The impact of projected climate change on soil quality and ecosystem functions have been studied for some ecoregions. Bottner et al. (1995) assessed the impact of projected climate change for the Mediterranean Basin. They predicted that a 3 °C increase in temperature would cause an average altitudinal shift of the vegetation belts of 500 m. An increase in temperature would deplete the SOC pool in the upper layers by 28% in the humid zone, 20% in the subhumid zone and 15% in the arid zone. Cheddadi et al. (2001) assessed the effects of projected climate change on vegetation in the Mediterranean region. They projected that an increase in atmospheric CO_2 to 500 ppmv with an attendant increase in temperature of 2 °C and reduction in precipitation by 30% may drastically alter the present vegetation. In Atlantic Europe, Duckworth et al. (2000) observed that a 2 °C increase in temperature would shift climax vegetation towards that associated with warmer conditions, equivalent to a shift of about 100 km on the ground. For a detailed review on the impact of climate change on biomass and agronomic production in different ecoregions, readers are referred to a comprehensive review by Rosenzweig and Hillel (1998).

6. Soil carbon sequestration: technological options

The term "soil C sequestration" implies removal of atmospheric CO_2 by plants and storage of fixed C as soil organic matter. The strategy is to increase SOC density in the soil, improve depth distribution of SOC and stabilize SOC by encapsulating it within stable micro-aggregates so that C is protected from microbial processes or as recalcitrant C with long turnover time. In this context, managing agroecosystems is an important strategy for SOC/terrestrial sequestration. Agriculture is defined as an anthropogenic manipulation of C through uptake, fixation, emission and transfer of C among different pools. Thus, land use change, along with adoption of RMPs, can be an important instrument of SOC sequestration (Post and Kwon, 2000). Whereas land misuse and soil mismanagement have caused depletion of SOC with an attendant emission of CO_2 and other GHGs into the atmosphere, there is a strong case that enhancing SOC pool could substantially offset fossil fuel emissions (Kauppi et al., 2001). However, the SOC sink capacity depends on the antecedent level of SOM, climate, profile characteristics and management.

The sink capacity of SOM for atmospheric $C0_2$ can be greatly enhanced when degraded soils and ecosystems are restored, marginal agricultural soils are converted to a restorative land use or replanted to perennial vegetation, and RMPs are adopted on agricultural soils (Table 7). Although generic RMPs are similar (e.g., mulch farming, reduced tillage, integrated nutrient management (INM), integrated pest management (IPM), precision farming), site-specific adaptation is extremely important. With adaptation of RMPs outlined in Table 7, SOC can accumulate in soils because tillage-induced soil disturbances are eliminated, erosion losses are minimized, and large quantities of root and above-ground biomass are returned to the soil. These practices conserve soil water, improve soil quality and enhance the SOC pool. Incorporation of SOC into the sub-soil can increase its mean residence time (MRT). Converting agricultural land to a more natural or restorative land use essentially reverses some of the effects responsible for SOC losses that occurred upon conversion of natural to managed ecosystems. Applying ecological concepts to the management of natural resources (e.g., nutrient cycling, energy budget, soil engineering by macroinvertebrates and enhanced soil biodiversity) may be an important factor to improving soil quality and SOC sequestration (Lavelle, 2000). Adoption of RMPs builds up SOC by increasing the input of C through crop residues and biosolids (Paustian et al., 1997). Sequestered SOC with a relatively long turnover time (Swift, 2001), is returned to the recalcitrant soil pool, thus decreasing the rate of accumulation of atmospheric CO_2 concentration. The SOC concentration in the surface layer usually increases with increasing inputs of biosolids (Graham et al., 2002) although the specific empirical relation depends on soil moisture and temperature regimes, nutrient availability (N, P, K, S), texture and climate. In addition to the quantity of input, quality of biomass can also be important in determining the SOC pool.

Table 7
Comparison between traditional and recommended management practices in relation to soil organic carbon sequestration

Traditional methods	Recommended management practices
1. Biomass burning and residue removal	Residue returned as surface mulch
2. Conventional tillage and clean cultivation	Conservation tillage, no till and mulch farming
3. Bare/idle fallow	Growing cover crops during the off-season
4. Continuous monoculture	Crop rotations with high diversity
5. Low input subsistence farming and soil fertility mining	Judicious use of off-farm input
6. Intensive use of chemical fertilizers	Integrated nutrient management with compost, biosolids and nutrient cycling, precision farming
7. Intensive cropping	Integrating tress and livestock with crop production
8. Surface flood irrigation	Drip, furrow or sub-irrigation
9. Indiscriminate use of pesticides	Integrated pest management
10. Cultivating marginal soils	Conservation reserve program, restoration of degraded soils through land use change

Biodiversity is also important to soil C dynamics. It is defined as "the variability among living organisms from all sources, including terrestrial, marine ecosystems and other aquatic ecosystems and ecological complexes of which they are part; this includes diversity within species, between species and for ecosystems. It is possible to distinguish between genetic diversity, organism species diversity, ecological diversity and functional diversity" (UNCBD, 1992). A healthy soil is teeming with life, and comprises highly diverse soil biota. The latter comprises representatives of all groups of micro-organisms and fungi, green algae and cyanobacteria, and of all but a few exclusively marine phyla of animals (Lee, 1991). With reference to SOC pool and its dynamics, important members of soil biota include earthworms, termites, ants, some insect larvae and few others of the large soil animals that comprise "bioturbation" (Lavelle, 1997). Activity of these animals have a strong influence on soil physical and biological qualities especially with regards to soil structure, porosity, aeration, water infiltration, drainage, nutrient/elemental cycling and organic matter pool and fluxes.

Soil biodiversity has a positive impact on the SOC pool. All other factors being equal, ecosystems with high biodiversity sequester more C in soil and biota than those with reduced biodiversity. In managed ecosystems, soil biodiversity is likely to increase with conversion to conservation tillage, replacement of toxic chemicals with viable alternatives, substitution of monoculture with mixed crop rotations and complex/diverse systems, restoration of degraded soils and ecosystems, and conversion of crop or pasture land to a restorative land use (e.g., set aside land or Conservation Reserve Program [CRP]). The data from Yurimaguas, Peru show that application of chemicals in high input systems decrease population density of soil fauna and biomass. In comparison with cropland, biomass C is also more in pastures, fallow and forest ecosystems (Lavelle and Pashanasi, 1989).

Soil biodiversity has a favorable impact on soil structure. Activity of soil biota produces organic polymers, which form and stabilize aggregates. Fungal hyphae and polysaccharides of microbial origin play an important role in soil aggregation. Earthworms and termites also positively impact soil structure, and enhance aggregation (Lal and Akinremi, 1983).

Soil and crop management practices that enhance SOC pool include the following.

6.1. Conservation tillage

Conventional tillage and erosion deplete SOC pools in agricultural soils. Thus, soils can store C upon conversion from plow till to no till (Fig. 7) or conservation tillage, by reducing soil disturbance, decreasing the fallow period and incorporation of cover crops in the rotation cycle. Eliminating summer fallowing in arid and semi-arid regions and adopting no till with residue mulching improves soil structure, lowers bulk density and increases infiltration capacity (Shaver et al., 2002). However, the benefits of no till on SOC sequestration may be soil/site specific, and the improvement in SOC may be inconsistent in fine-textured and poorly drained soils (Wander et al., 1998). Some studies have also shown more N_2O emissions in no till (Mackenzie et al., 1998). Similar to the merits of conservation tillage reported in North America, Brazil and Argentina (Lal, 2000; Sa et al., 2001) several studies have reported the high potential of SOC sequestration in European soils (Smith et al.,

Fig. 7. Growing crops with contour hedgerows of *Leucaena leucocephala* is an example of a wide range of agroforestry systems.

1998, 2000a,b). Smith et al. (1998) estimated that adoption of conservation tillage has the potential to sequester about 23 Tg C/year in the European Union or about 43 Tg C/year in the wider Europe including the former Soviet Union. In addition to enhancing SOC pool, up to 3.2 Tg C/year may also be saved in agricultural fossil fuel emissions. Smith et al. (1998) concluded that 100% conversion to no till agriculture could mitigate all fossil fuel C emission from agriculture in Europe.

6.2. Cover crops

The benefits of adopting conservation tillage for SOC sequestration are greatly enhanced by growing cover crops in the rotation cycle (Fig. 7). Growing leguminous cover crops enhances biodiversity, the quality of residue input and SOC pool (Singh et al., 1998; Fullen and Auerswald, 1998; Uhlen and Tveitnes, 1995). It is well established that ecosystems with high biodiversity absorb and sequester more C than those with low or reduced biodiversity. Drinkwater et al. (1998) observed that legume-based cropping systems reduce C and N losses from soil. In Georgia, USA, Sainju et al. (2002) observed that practicing no till with hairy vetch can improve SOC. Franzluebbers et al. (2001b) also observed in Georgia, USA that improved forage management can enhance the SOC pool. However, the use of cover crops as a short-term green manure may not necessarily enhance the SOC pool. The beneficial effect of growing cover crops on enhancing SOC pool has been reported from Hungary by Berzseny and Gyrffy (1997), U.K. by Fullen and Auerswald (1998) and Johnston (1973), Sweden by Nilsson (1986), Netherlands by Van Dijk (1982) and Europe by Smith et al. (1997).

6.3. Nutrient management

Judicious nutrient management is crucial to SOC sequestration. In general, the use of organic manures and compost enhances the SOC pool more than application of the same amount of nutrients as inorganic fertilizers (Gregorich et al., 2001). The fertilizer effects on SOC pool are related to the amount of biomass C produced/returned to the soil and its humification. Adequate supply of N and other essential nutrients in soil can enhance biomass production under elevated CO_2 concentration (Van Kessel et al., 2000). Long-term manure applications increase the SOC pool and may improve aggregation (Sommerfeldt et al., 1988; Gilley and Risse, 2000), and the effects may persist for a century or longer (Compton and Boone, 2000). The potential of conservation tillage to sequester SOC is greatly enhanced whereby soils are amended with organic manures (Hao et al., 2002). Smith and Powlson (2000) reported that 820 million metric tons of manure are produced each year in Europe, and only 54% is applied to arable land and the remainder to non-arable agricultural land. They observed that applying manure to cropland can enhance its SOC pool more than it does on pasture land. Smith and Powlson estimated that if all manure were incorporated into arable land in the European Union, there would be a net sequestration of 6.8 Tg C/year, which is equivalent to 0.8% of the 1990 CO_2-C emissions for the region. Beneficial impacts of manuring for U.S. cropland were reported by Lal et al. (1998).

6.4. Irrigation

Similar to the addition of fertilizers and manures in a nutrient-depleted soil, judicious application of irrigation water in a drought prone soil can enhance biomass production, increase the amount of aboveground and the root biomass returned to the soil and improve SOC concentration. In addition, enhancing irrigation efficiency can also decrease the hidden C costs (Sauerbeck, 2001). In Texas, Bordovsky et al. (1999) observed that surface SOC concentration in plots growing irrigated grain sorghum and wheat increased with time. Irrigation can also enhance SOC concentrations in grassland (Conant et al., 2001).

6.5. Restoring degraded soils

Restoring degraded soils and ecosystems has a high potential for sequestrating soil C. Most degraded soils have lost a large fraction of the antecedent SOC pool, which can be restored through adopting judicious land use practices. The CRP has been effective in reducing the sediment load and enhancing the SOC pool. The rate of SOC sequestration under CRP may be 600–1000 kg C/ha/year (Follett et al., 2001b). In Shropshire, U.K., Fullen (1998) observed that mean

SOC content increased consistently and significantly on plots set aside under the grass ley system at the rate of 0.78% in 4 years.

6.6. Pasture management

On a global basis, grassland/grazing lands occupy 3460 Mha. Restoring degraded grazing lands and improving forage species is important to sequestering SOC and SIC. Furthermore, converting marginal croplands to pastures (by CRP and other set-aside provisions) can also sequester C. Similar to cropland, management options for improving pastures include judicious use of fertilizers, controlled grazing, sowing legumes and grasses or other species adapted to the environment, improvement of soil fauna and irrigation (Follett et al., 2001a). Conant et al. (2001) reported rates of SOC sequestration through pasture improvement ranging from 0.11 to 3.04 Mg C/ha/year with a mean of 0.54 Mg C/ha/year.

6.7. Forest soils

Converting degraded soils under agriculture and other land uses into forests and perennial land use can enhance the SOC pool. The magnitude and rate of SOC sequestration with afforestation depends on climate, soil type, species and nutrient management (Lal, 2001c). Despite its significance, a few studies have assessed the C sink capacity of forest soils (Lal, 2001d; Kimble et al., 2002). In east central Minnesota, an experiment by Johnston et al. (1996) showed an average SOC sequestration rate of 0.8–1.0 Mg/ha/year. Afforestation, however, may not always enhance the SOC pool. In New Zealand, Groenendijk et al. (2002) reported that afforestation of pastures with radiata pine (*Pinus radiata*) decreased the SOC concentration by 15% to a depth of 12–18 cm. These researchers concluded that afforestation of hill country pasture soils resulted in net mineralization of the SOC pool. In the Cerrado region of Central Brazil, Neufeldt et al. (2002) also observed that reforestation of pasture with pine led to a clear reduction of SOC compared to pasture and eucalyptus plantation. In such cases, agroforestry may be another option of conserving soil and improving the SOC pool. On a Vertisol in Ethiopia, Lulu and Insam (2000) observed positive effects of alley cropping (i.e., agroforestry) with *Sesbania* on the SOC pool. In Europe, Nabuurs et al. (1997) reported that total SOC pool of soils supporting European forests is 12.0 Pg, but did not provide an estimate of the rate of SOC sequestration in forest soils.

Afforestation of marginal agricultural soils or degraded soils has a large potential of SOC sequestration. Bouma et al. (1998) observed that in Europe a major change in land use may occur because of technological, socio-economic and political developments. For example, adoption of RMPs or technical advances in modern agriculture may produce the same yield on 30–50% of the current agricultural land. That being the case, there is a potential for converting spare agricultural land to forestry. With conversion to a permanent land cover, there is a large potential of SOC sequestration through agricultural intensification.

6.8. Urban soils

Urban forestry is an important land use in North America, Europe and elsewhere in developed countries. Transforming landscapes from non-urban to urban land use has the potential to drastically alter the SOC pool and fluxes. Analyzing soils from an urban rural land use gradient, Pouyat et al. (2002) observed higher SOC densities in urban than in sub-urban and rural lands. Preserving SOC at the watershed level may also involve a judicious use of urban organic wastes (Binder and Patzel, 2001).

Conversion to an appropriate land use and adopting RMPs lead to SOC sequestration through the following processes:

(i) Aggregation: increase in stable micro-aggregates through formation of organo-mineral complexes encapsulates C and protects it against microbial activities.
(ii) Humification: an increase in chemically recalcitrant humic compounds enhances the relative proportion of passive fraction of SOC. A high clay content and relatively higher proportion of high activity clays (HACs) enhances the retention of recalcitrant SOC fraction.
(iii) Translocation into the sub-soil: translocation of SOC into the sub-soil can move it away from the zone of disturbance by plowing and other

Table 8
Global land use (FAO, 2001)

Land use	Area (Mha)
Total area	13,414
Land area	13,083
Arable land	1369
Permanent crops	132
Permanent pasture	3460
Agricultural soils	4961
Forest and woodland	4172
Others	11,549

agronomic operations, and minimize the risks removed by erosional processes.

(iv) Formation of secondary carbonates: land use and management systems in arid and semi-arid regions that enhance formation of secondary carbonates also lead to SIC sequestration (Monger and Gallegos, 2000). Leaching of carbonates into the groundwater is another mechanism of SIC sequestration, especially in irrigated soils (Nordt et al., 2000).

While assessing the net SOC sequestration by land use change and adoption of soil/crop management practices, it is important to consider the hidden C costs of input (e.g., fertilizer, herbicides, tillage, irrigation) (West and Marland, 2002). Herbicides, used intensively for weed control especially in no till systems, are extremely C intensive. Change in land use and adoption of RMPs may involve change in input of herbicides/pesticides, fertilizers, manures, irrigation and tillage operations. Thus, the hidden C costs of these inputs must be accounted for (Schlesinger, 2000b) (Table 8).

7. The potential of world soils to sequester carbon

The potential of SOC sequestration is high in the world's degraded soils and ecosystems estimated at 1216 Mha (Table 6), and agricultural soils estimated at 4961 Mha (Table 7). These soils have lost a significant part of their original SOC pool, and have the capacity to sequester C by converting to a restorative land use and adopting recommended management practices. All other factors remaining the same, the potential of SOC sequestration is in the following order: degraded soils and desertified ecosystems>cropland>grazing lands>forest lands and permanent crops. Most croplands (1369 Mha worldwide, see Table 6) have lost 30–40 Mg C/ha and most degraded soils (1216 Mha) may have lost 40–60 Mg C/ha (Lal, 2000). A significant part of the historic C loss (estimated at 66–90 Pg) can be sequestered over 25–50 years. The rates of SOC sequestration on cropland range from 0.02 to 0.76 Mg C/ha/year for adopting improved systems of crop management, 0.1 to 1.3 Mg C/ha/year by converting from plow till to no till, and 0.25 to 0.5 Mg C/ha/year for rice land management (Lal, 2000, 2001b; IPCC, 2000). On rangeland, rates of SOC sequestration range from 0.02 to 1.3 Mg C/ha/year on restoring degraded grasslands, 0.16 to 0.50 Mg C/ha/year by systems that may improve grassland productivity, and 0.5 to 1.4 Mg C/ha/year by systems involving fire management (Follett et al., 2001a,b; IPCC, 2000). The rates of SOC gain in forest lands, especially for reforestation, are generally low (Lal, 2000; Kimble et al., 2002).

There are several national and global estimates of soil C sequestration (Table 9; Dumanski et al., 1998; Lal, 1999). Smith et al. (2000a) estimated that a realistic potential for C mitigation on U.K. agricultural soils is 10.4 Tg C/year, which is about 6.6% of 1990 U.K. CO_2-C emissions. Extending the methodology to Europe, Smith et al. (2000b) assessed a range of options for C mitigation in European agricultural soils, and estimated the SOC sequestration potential of 56 Tg C/year. Lal (2000) estimated the potential of world cropland soils to sequester C at the rate of 0.4–

Table 9
Estimates of global soil carbon sequestration potential

Land use	Soil C sequestration potential (Pg C/year)	Reference
World cropland	0.43–0.57	Lal and Bruce (1999)
Desertification control	1.0	Squires et al. (1995)
Desertification control	0.2–0.4	Lal (2001b)
Soils of the tropics	0.28–0.54	Lal (2002)
World soils	0.4–0.8	IPCC (1996)
Permanent pasture	1.87	Conant et al. (2001)

0.6 Pg C/year (excluding erosion and biofuel offset). In addition, desertification control has a potential to sequester 0.2–0.6 Pg C/year (without considering erosion control and biofuel offset). Therefore, the total potential of soil C sequestration may be 0.6–1.2 Pg C/year. There is also a large potential of grassland management (Conant et al., 2001), most of which has been included in desertification control. Based on these potentials, the global C budget thus can be computed. Soil C sequestration would increase the oceanic/land uptake by an additional 0.9 ± 0.3 Pg C/year for about 50 years with accumulative sink capacity of 30–60 Pg. These assessments contradict those by (Schlesinger and Andrews, 2000) who argue that large increases in the soil C pool seem unlikely.

In addition to decreasing the rate of enrichment of atmospheric concentration of CO_2, enhancing the SOC pool would improve soil quality and agronomic/biomass productivity. Increasing SOC pool in agricultural/degraded soils could offset emissions of CO_2 from fossil fuel combustion. However, in the context of the Kyoto Protocol, the hidden C costs of input must also be considered (Schlesinger, 2000a; Robertson et al., 2000). With increasing population from 6 billion in 2000 to 8 billion by 2020, the necessity of food production will be more than ever before. The techniques of SOC sequestration outlined herein (e.g., conservation tillage, mulch farming, cover crops, manuring and fertilizer use, irrigation and restoration of degraded soils) are needed to meet the food demands of the growing population, with an ancillary benefit of SOC sequestration. Further, adopting RMPs would lead to a 10–40% reduction of present agricultural energy requirements (Sauerbeck, 2001). Loss of SOC, decline in soil structure and overall degradation of the soil resources are standard features of non-sustainable land use (Carter, 2002), and these features are reversed through adoption of practices which lead to SOC sequestration. Thus, soil C sequestration is a win–win strategy.

8. Debatable issues on soil carbon sequestration

There are numerous debatable issues about SOC sequestration that need to be addressed. An important one is about the efficacy of SOC sequestration especially in view of the hidden C costs of the input involved (Schlesinger, 1999, 2000a,b; Robertson et al., 2000). Nitrogenous fertilizers have hidden C costs of 0.86 kg C/kg N (IPCC, 1996), and pesticides are at least 5 times more C intensive. It is widely recognized that judicious use of fertilizers with a high use efficiency through precision farming (Matson et al., 2000) and other improved management options, and nutrient cycling through manuring (Jenkinson et al., 1987; Smith and Powlson, 2000) are efficient means of SOC sequestration. Similarly, lifting irrigation water is also C-intensive, but irrigation increases biomass production by two to three times compared with the rainfed systems and leads to SOC sequestration (Coneth et al., 1998; Dormaar and Carefoot, 1998). Judicious use of irrigation can also lead to SIC sequestration through leaching of bicarbonates into the groundwater (Nordt et al., 2000).

There is also a concern about the lack of response of conservation tillage to SOC sequestration (Wander et al., 1998), and the permanence of C sequestered in the soil. The question of "whether SOC sequestered in soil is readily lost by subsequent misuse and mismanagement" needs to be addressed by two different approaches. Effectiveness of conversion to conservation tillage on SOC sequestration depends on soil and climatic factors. Light-textured and well-drained soils in moist and cool climates sequester more SOC than clayey and poorly drained, or soils of low-activity clays in arid and warm climates. The first approach is the assessment of the MRT (pool divided by flux) of C in soil versus other ecosystems, which is about 5 years in the atmosphere, 10 years in vegetation and 35 years in soil. Thus, MRT of C in soil is three to four times that in the vegetation. The second approach is to assess the impact of plowing a no till farm on the C sequestered. If the plowing is undertaken as a remedial measure to alleviate another soil-related constraint (e.g., compaction, weed infestation), its adverse impact on SOC may be minimal. Further, there are numerous options of a prescriptive soil disturbance including the use of non-inversion tools (e.g., chisel plow, paraplow).

Monitoring and verification of the rate of SOC sequestration in a transparent, cost-effective and credible manner is also cited as an impediment to developing a user-friendly trading system. There is a wide range of laboratory methods available for determining SOC pool, and new ones are being developed. Soil scientists have assessed changes in SOC pool in relation to fertility and plant nutrition since the beginning of the 20th century. Admittedly, there is a strong need to standardize these methods, so that results are comparable among laboratories. There is also a need to develop scaling procedures so that data can be extrapolated from point source to ecosystem or regional scale. However, these issues are not unique to the SOC pool and are also encountered in assessing other terrestrial C pools (e.g., forests, wetlands). The important consideration is to recognize and overcome these problems by standardizing sampling and analytical procedures and scaling techniques.

It is also argued that SOC sequestration is a major challenge in soils of the tropics and sub-tropics, where climate is harsh and resource-poor farmers cannot afford the off-farm input. Yes, SOC sequestration requires input of crop residue/biosolids and of fertilizers/manures to enhance biomass production. Further, the rate of mineralization is high in the tropics and the humification efficiency is low. The potential of SOC sequestration in degraded soils and ecosystems of the tropics is high, and realization of this potential is challenging. Yet, the need to restore degraded soils and ecosystems in the tropics and sub-tropics is also urgent and of a high priority. This challenge has to be and can be met.

Then there is a question of the relatively finite sink capacity of the SOC pool vis-à-vis infinite or at least large capacity of the geologic or oceanic pool. The global potential of SOC sequestration is merely 30–60 Pg C at the rate of about 0.9 ± 0.3 Pg C/year over the next 50 years. Despite the finite capacity, SOC sequestration is the most cost-effective strategy during the first half of the 21st century (Battelle, 2000) with numerous ancillary benefits. In addition to the high costs of geologic and oceanic sequestration, there are also concerns about the adverse effects on aquatic ecosystems and risks of leakage.

9. Relevance to the Kyoto Protocol

The U.N. Framework Convention on Climate Change proposed a treaty in December 1997 in Kyoto, Japan, to make it mandatory for industrialized nations to reduce their fossil fuel emission by 5% below the 1990 level. As per this treaty, called the Kyoto Protocol, the U.S. was required to reduce its emissions to 93% of those in 1990. In fact, the U.S. emissions of CO_2-C have actually increased by about 18% since 1990, and making the 7% reduction target unachievable. Subsequent to U.S. withdrawal from signing the treaty, the Kyoto Protocol was revised in Bonn in July 2001. The revised Protocol comprises two new clauses relevant to SOC sequestration:

1. Countries are allowed to subtract from their industrial C emissions certain increases in C sequestered in "sinks" such as forests and soils; and
2. Countries are allowed to trade emission allowances that can reduce abatement costs. The UNFCCC/Kyoto Protocol recognizes soil C sinks provided that the rate of SOC sequestration and the cumulative magnitude can be verified by standard procedures.

Subsequently, President Bush announced "clean skies and global change" initiatives, and made two significant announcements as voluntary alternatives to the Kyoto Protocol:

1. "We look for ways to increase the amount of carbon stored by American farms and forests through a strong conservation title in the Farm Bill" (President Bush, 14 February 2002).
2. There exists an opportunity for "sequestration of greenhouse gases in agricultural and forestry sinks" (Economic report to the U.S. Congress, 2002).

The SOC sequestration is a viable strategy both for countries that have signed the Kyoto Protocol and those that have sought voluntary alternatives. Where land use/land use changes and soil management are a net sink for C, it is important to identify and implement policy instruments that facilitate realization of this sink. The SOC sequestration may also be credited under the Clean Development Mechanism (CDM, Article 12), emission trading (Article 17) or joint implementation activities (Article 6) of the Kyoto Protocol.

From a global policy perspective, it is equally important to recognize that restoration of degraded soils and ecosystems, and increasing the SOC pool represent an enormous opportunity that cannot be ignored. A coordinated SOC sequestration program implemented at a global scale could at the same time increase agricultural productivity especially in developing countries, and mitigate climate change. It is thus important that international organizations (e.g., FAO, UNDP, World Bank), developing countries concerned with food security (e.g., sub-Saharan Africa, South Asia), and industrialized countries concerned with climate change and environment pollution (e.g., U.S., Canada, Europe, Japan, Australia) join forces and implement comprehensive programs to restore degraded soils to sequester C and enhance productivity.

10. Research and development priorities

An important issue at hand is the "commodification" or "moneytization" of soil C. In fact, soil C is a new farm commodity that can be bought and sold like any other farm commodity (e.g., corn, soybean, meat, dairy or poultry). For soil C to be traded, bought and sold as any other farm commodity, there is a need for creation of a market, comprising buyers and sellers who trade C. Creation of an effective C market implies the following: (i) imposing a cap on industrial CO_2 emissions with a quota system; (ii) assessing the societal value of soil C based on intrinsic properties (e.g., market value of N, P, K, S and water contained in soil humus) and ancillary benefits (e.g., improvement in water quality, reduction in sedimentation/siltation of waterways and reservoirs, biodegradation of pollutants); and (iii) imposing penalties on land managers who convert to soil degradative land uses. In addition to biophysical issues, creating an effective C market also implies addressing the human-dimensions issues. It is important to identify and implement policies that lead to adoption of the RMPs.

There are several biophysical issues that need to be addressed. Important among these are the following:

(a) Which terrestrial and aquatic ecosystems have large potential soil C sinks (or bright spots), and what are the criteria to identify them and assess their C sink capacity.
(b) What are the recommended land use and management practices for soil C sequestration, and what are the corresponding rates under "on-farm" conditions.
(c) What are the relevant processes of soil C sequestration (e.g., aggregation, humification, formation of secondary carbonates), and what is the residence time of C thus sequestered.
(d) What are the cost-effective, credible, transparent and simple methods of measuring the rate of soil C sequestration, and what is their accuracy and precision.
(e) What is the cost of soil C sequestration under different land uses and soil/vegetation/water management practices.
(f) What is the impact of change in management (conversion from a long-term no till to occasional plowing) on soil C pool.
(g) What are the links between soil and atmospheric processes especially with regard to exchange of GHGs.
(h) How is the quality and quantity of SOC pool related to soil quality (e.g., structure, plant available water capacity, nutrient reserves), water quality (e.g., transport of agricultural chemicals) and air quality.
(i) How can assessment of soil C pool be included into the regional and national databank on soil properties assessed under routine soil surveys.
(j) How can we encourage soil scientists to interact with their counterparts in other basic sciences (e.g., geology, hydrology, climatology, plant biology, chemistry) and applied sciences (e.g., economics, sociology, public policy).

Addressing these questions, at regional/national and international scales, implies developing effective inter-disciplinary research program(s) specifically designed to replace myths by facts. Some important facts urgently needed are the following:

(a) The historic loss of soil C pool upon conversion from natural to managed ecosystems for major soils in principal ecoregions.
(b) The fate of eroded soil C, especially with regard to mineralization of C redistributed over the landscape, transported by water and wind, and deposited in depressional sites and aquatic ecosystems.

(c) The impact of low input or subsistence farming practices on emission of GHGs from soil into the atmosphere.
(d) The soil and ecological factors under which conversion from plow till to no till improves productivity and sequesters C in soil.
(e) The importance of secondary carbonates in soil C sequestration especially in irrigated agriculture.
(f) Land use and management techniques that enhance SOC/SIC pool in soils of the tropics and sub-tropics.
(g) The impact or urban land uses (e.g., golf courses, lawns, roads, buildings) on soil C pool and fluxes.
(h) The microbial/chemical/physical processes that control the dynamics of C, N, P and S.
(i) The link between the cycles of C and H_2O as mediated by energy balance.
(j) The link between soil aggregation and C dynamics, especially with regards to the clay content and mineralogy.

Realization of this strategic option of soil C sequestration to reduce the rate of enrichment of atmospheric CO_2 necessitates addressing these issues objectively through an inter-disciplinary research and development program. Such an endeavor requires a paradigm shift in our thinking of soil and its management.

In view of the issues facing the 21st century, sustainable management of soil must:

(i) Maximize long-term productivity per unit input of the non-renewable/limiting resources (e.g., nutrients, energy);
(ii) Minimize environment pollution with regard to emission of GHGs and non-point source pollution of water;
(iii) Moderate/buffer sudden changes in air and water qualities; and
(iv) Proxy for interpretation of past global/climate changes through interpretation of the soil profile data.

While food security has been an issue since the dawn of civilization, and it has been the cause of regional wars and population migration due to interaction among humans, future threats to global peace may also arise from the relationship/interaction between human and nature rather than human to human. The global C cycle is an important determinant of the "human to nature" interaction.

11. Conclusions

The potential of SOC sequestration is finite in magnitude and duration. It is only a short-term strategy to mitigating anthropogenic enrichment of atmospheric CO_2. The annual SOC sequestration potential is only 0.9 ± 0.3 Pg C/year. The atmospheric concentration of CO_2 at the observed rate of 1990 (3.2 Pg C/year) will continue to increase at the rate of 2.0–2.6 Pg C/year even with soil C sequestration. Thus, a long-term solution lies in developing alternatives to fossil fuel. Yet, SOC sequestration buys us time during which alternatives to fossil fuel are developed and implemented. It is a bridge to the future. It also leads to improvement in soil quality. Soil C sequestration is something that we cannot afford to ignore.

References

Albrecht, W.A., 1938. Loss of soil organic matter and its restoration. Soils and Men. USDA Yearbook of Agriculture. USDA, Washington, DC, pp. 347–360.

Battelle, 2000. Global Energy Technology Strategy: Addressing Climate Change. Initial Findings from an International Public–Private Collaboration. Battelle, Washington, DC.

Bazzaz, F.A., 1990. The response of natural ecosystems to the rising global CO_2 levels. Annual Review of Ecology and Systematics 21, 167–196.

Berzseny, Z., Gyrffy, B., 1997. Effect of crop rotation and fertilization on maize and wheat yield stability in long-term experiments. Agrok ma s Talajtan 46, 377–398.

Binder, C., Patzel, N., 2001. Preserving tropical soil organic matter at watershed level. A possible contribution of urban organic wastes. Nutrient Cycling in Agroecology 61, 171–181.

Bordovsky, D.G., Choudhar, M., Gerard, C.J., 1999. Effect of tillage, cropping and residue management on soil properties in the Texas Rolling Plains. Soil Science 164, 331–340.

Bottner, P., Coûteaux, M.M., Vallejo, V.R., 1995. Soil organic matter in Mediterranean-type ecosystems and global climate changes: a case study—the soils of the Mediterranean Basin. In: Moreno, J.M., Oechel, W.C. (Eds.), Global Change and Mediterranean Type Ecosystems. Springer-Verlag, New York, pp. 306–325.

Bouma, J., Varallyay, G., Batjes, N.H., 1998. Principal land use changes anticipated in Europe. Agriculture, Ecosystems and Environment 67, 103–119.

Buringh, P., 1984. Organic carbon in soils of the world. In: Woodwell, G.M. (Ed.), The Role of Terrestrial Vegetation in the Global Carbon Cycle. SCOPE 23. Wiley, Chichester, pp. 41–109.
Carter, M.R., 2002. Soil quality for sustainable land management: organic matter and aggregation interactions that maintain soil functions. Agronomy Journal 94, 38–47.
Cheddadi, R., Guiot, J., Jolly, D., 2001. The Mediterranean vegetation: what if the atmospheric CO_2 increased? Landscape Ecology 16, 667–675.
Compton, J.E., Boone, R.D., 2000. Long-term impacts of agriculture on soil carbon and nitrogen in New England forests. Ecology 81, 2314–2330.
Conant, R.T., Paustian, K., Elliott, E.T., 2001. Grassland management and conversion into grassland: effects on soil carbon. Applied Ecology 11, 343–355.
Coneth, A.J., Blair, G.J., Rochester, I.J., 1998. Soil organic carbon fraction in a Vertisol under irrigated cotton production as affected by burning and incorporating cotton stubble. Australian Journal of Soil Research 36, 655–667.
Dalias, P., Anderson, J.M., Bottner, P., Coûteaux, M.-M., 2001. Long-term effects of temperature on carbon mineralization processes. Soil Biology & Biochemistry 33, 1049–1057.
De Jong, E., Kachanoski, R.G., 1988. The importance of erosion in the carbon balance of prairie soils. Canadian Journal of Soil Science 68, 111–119.
Dormaar, J.F., Carefoot, J.M., 1998. Effect of straw management and nitrogen fertilizer on selected soil properties as potential soil quality indicators of an irrigated dark brown Chernozemic soil. Canadian Journal of Soil Science 78, 511–517.
Drake, B.G., Leadley, P.W., 1991. Canopy photosynthesis of crops and native plant communities exposed to long-term elevated CO_2. Plant, Cell and Environment 14, 853–860.
Drinkwater, L.E., Wagoner, P., Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature (London) 396, 262–265.
Duckworth, J.C., Bunce, R.G.H., Malloch, A.J.C., 2000. Modelling the potential effects of climate change on calcareous grasslands in Atlantic. European Journal of Biogeology 27, 347–358.
Dumanski, J., Desjardins, R.L., Tarnocai, C., Montreal, C., Gregorich, E.G., Kirkwood, V., Campbell, C.A., 1998. Possibilities for future carbon sequestration in Canadian agriculture in relation to land use changes. Climatic Change 40, 81–103.
Eswaran, H., Reich, F.P., Kimble, J.M., Beinroth, F.H., Padamnabhan, E., Moncharoen, P., 2000. Global carbon stocks. In: Lal, R., Kimble, J.M., Eswaran, H., Stewart, B.A. (Eds.), Global Climate Change and Pedogenic Carbonates. CRC/Lewis, Boca Raton, FL.
Etheridge, D.M., Steele, L.P., Langenfelds, R.L., Francey, R.J., Barnola, J.M., Morgan, V.I., 1996. Natural and anthropogenic changes in atmospheric CO_2 over the last 1000 years from air in Antarctic ice and fern. Journal of Geophysical Research 101, 4115–4128.
FAO, 1994. Land degradation in South Asia: its severity, causes and effects upon the people. World Soil Resources Reports, vol. 78. FAO, Rome, Italy.
FAO, 2001. Production Yearbook. Food & Agric. Organization, Rome, Italy.
Follett, R.F., Kimble, J.M., Lal, R., 2001a. The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. CRC/Lewis, Boca Raton, FL. 442 pp.
Follett, R.F., Pruessner, E.G., Samson-Liebig, S.E., Kimble, J.M., Waltman, S.W., 2001b. Carbon sequestration under the Conservation Reserve Program in the historic grasslands of the United States of America. In: Lal, R. (Ed.), Soil Carbon Sequestration and the Greenhouse Effect. Soil Science Society of America Special Publication, vol. 57. American Society of Agronomy, Madison, WI.
Franzluebbers, A.J., Haney, R.L., Honeycutt, C.W., Arshad, M.A., Schomberg, H.H., Hons, F.M., 2001a. Climatic influences on active fractions of soil organic matter. Soil Biology & Biochemistry 33, 1103–1111.
Franzluebbers, A.J., Stuedemann, J.A., Wilkinson, S.R., 2001b. Bermuda grass management in the southern piedmont USA: I. Soil and surface residue carbon and sulfur. Soil Science Society of America Journal 65, 834–841.
Fullen, M.A., 1998. Effects of grass ley set-aside on runoff, erosion and organic matter levels in sandy soils in east Shropshire, UK. Soil and Tillage Research 46, 41–49.
Fullen, M.A., Auerswald, K., 1998. Effect of grass ley set-aside on runoff, erosion and organic matter levels in sandy soil in east Shropshire, UK. Soil and Tillage Research 46, 41–49.
Gilley, J.E., Risse, L.M., 2000. Runoff and soil loss as affected by the application of manure. Transactions of the ASAE 43, 1583–1588.
Graham, M.H., Haynes, R.F., Meyer, J.H., 2002. Soil organic matter content and quality: effects of fertilizer applications, burning and trash retention on a long-term sugarcane experiment in South Africa. Soil Biology & Biochemistry 34, 93–102.
Gregorich, E.G., Anderson, D.W., 1985. Effects of cultivation and erosion on soils of four toposequences in the Canadian Prairie. Geoderma 36, 343–345.
Gregorich, E.G., Greer, K.J., Anderson, D.W., Liang, B.C., 1998. Carbon distribution and losses: erosion and deposition effects. Soil and Tillage Research 47, 291–302.
Gregorich, E.G., Drury, C.F., Baldock, J.A., 2001. Changes in soil carbon under long-term maize in monoculture and legume-based rotation. Canadian Journal of Soil Science 81, 21–31.
Groenendijk, F.M., Condron, L.M., Rijkse, W.C., 2002. Effects of afforestation on organic carbon, nitrogen and sulfur concentrations in New Zealand hill country soils. Geoderma 108, 91–100.
Hao, Y., Lal, R., Owens, L.B., Izaurralde, R.C., Post, M., Hothem, D., 2002. Effect of cropland management and slope position on soil organic carbon pools in the North Appalachian Experimental Watersheds. Soil & Till. Res. 68, 133–142.
Hendrey, G.R., 1993. Free-Air CO_2 Enrichment for Plant Research in the Field C.K. Smoley, Boca Raton, FL. 308 pp.
Hendry, G.A.F., Grime, J.P., 1990. Natural vegetation. In: Cannell, M.G.R., Hooper, M.D. (Eds.), The Greenhouse Effect and the Terrestrial Ecosystems in the UK. HMSO, London, pp. 27–31.
Houghton, R.A., 1995. Changes in the storage of terrestrial carbon since 1850. In: Lal, R., Kimble, J.M., Levine, E., Stewart, B.A. (Eds.), Soils and Global Change. CRC/Lewis, Boca Raton, FL, pp. 45–65.
Houghton, R.A., 1999. The annual net flux of carbon to the atmo-

sphere from changes in land use 1850 to 1990. Tellus 50B, 298–313.

Intergovernmental Panel on Climate Change, 1996. Climate Change 1995: Impact, Adaptations and Mitigation of Climate Change: Scientific Technical Analyses. Working Group 1. Cambridge Univ. Press, Cambridge, UK.

Intergovernmental Panel on Climate Change, 2000. Land Use, Land Use Change and Forestry. Special Report. Cambridge Univ. Press, Cambridge, U.K.

Intergovernmental Panel on Climate Change, 2001. Climate Change: The Scientific Basis. Cambridge Univ. Press, Cambridge, UK.

Jenkinson, D.S., Hart, P.B.S., Rayner, J.H., Parry, L.C., 1987. Modelling the turnover of organic matter in long-term experiments at Rothamstedt, UK. INTECOL Bulletin 15, 1–8.

Jenny, H., 1980. The Soil Resource: Origin and Behavior. Springer, New York. 377 pp.

Johnston, A.E., 1973. The effects of ley and arable cropping systems on the amount of organic matter in the Rothamstead and Woburn Ley-Arable Experiments. Rothamstead Report for 1972, Part 2, 131–159.

Johnston, M.H., Homann, P.S., Engstrom, J.K., Grigal, D.F., 1996. Changes in ecosystem carbon storage over 40 years on an old field/forest landscape in east–central Minnesota. Forest Ecology and Management 83, 17–26.

Kauppi, P., Sedjo, R., Apps, M., Cerri, C., Fujimoro, T., Janzen, H., Krankina, O., Makundi, W., Marland, G., Masera, O., Nabuurs, G.-J., Razali, W., Ravindranath, N.H., 2001. Technological and economic potential of options to enhance, maintain and manage biological carbon reservoirs and geo-engineering. In: Metz, B., Davidson, O., Swart, R., Pan, J. (Eds.), Climate Change 2001-Mitigation. Cambridge Univ. Press, UK, pp. 301–343.

Keeling, C.D., Whorf, T.P., 1999. Atmospheric CO_2 records from sites in S10 air sampling network. Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center. Oakridge National Laboratory, Oakridge, TN, USA.

Kimble, J.M., Heath, L.S., Birdsey, R.A., Lal, R., 2002. The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect. CRC/Lewis, Boca Raton, FL. 429 pp.

Kleemola, J., Pehu, E., Peltonen-Sainio, P., Karvonen, T., 1995. Modeling the impact of climate change on growth of spring barley in Finland. Journal of Biogeography 22, 581–590.

Lal, R., 1996. Deforestation and land use effects on soil degradation and rehabilitation in western Nigeria. II: soil chemical properties. Land Degradation and Development 7, 87–98.

Lal, R., 1999. Soil management and restoration for C sequestration to mitigate the accelerated greenhouse effect. Progress in Environmental Science 1, 307–326.

Lal, R., 2000. World cropland soils as a source or sink for atmospheric carbon. Advances in Agronomy 71, 145–191.

Lal, R., 2001a. Fate of eroded soil carbon: emission or sequestration. In: Lal, R. (Ed.), Soil Carbon Sequestration and the Greenhouse Effect. Soil Science Society of America Special Publication, vol. 57. Madison, WI, pp. 173–181.

Lal, R., 2001b. Potential of desertification control to sequester carbon and mitigate the greenhouse effect. Climate Change 15, 35–72.

Lal, R., 2001c. The potential of soil carbon sequestration in forest ecosystem to mitigate the greenhouse effect. In: Lal, R. (Ed.), Soil Carbon Sequestration and the Greenhouse Effect. Soil Science Society of America Special Publication, vol. 57. Madison, WI.

Lal, R., 2001d. Potential of soil carbon sequestration in forest ecosystem. In: Lal, R. (Ed.), Soil Carbon Sequestration and the Greenhouse Effect. Soil Science Society of America Special Publication, vol. 57. Madison, WI, 137–154.

Lal, R., 2002. The potential of soils of the tropics to sequester carbon and mitigate the greenhouse effect. Advances in Agronomy 74, 155–192.

Lal, R., Akinremi, O.O., 1983. Physical properties of earthworm casts and surface soil as influenced by management. Soil Science 135, 116–122.

Lal, R., Bruce, J.P., 1999. The potential of world cropland soils to sequester C and mitigate the greenhouse effect. Environmental Science and Policy 2, 177–185.

Lal, R., Kimble, J.M., Follett, R.F., Cole, C.V., 1998. The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Ann Arbor Sci. Publ., Chelsea, MI. 128 pp.

Lal, R., Kimble, J.M., Stewart, B.A., 2000. Global Climate Change and Cold Regions Ecosystems. CRC/Lewis, Boca Raton, FL. 265 pp.

Lavelle, P., 1997. Faunal activities and soil processes: adaptive strategies that determine ecosystem function. Advances in Ecology Research 27, 93–132.

Lavelle, P., 2000. Ecological challenges for soil science. Soil Science 165, 73–86.

Lavelle, P., Pashanasi, B., 1989. Soil macrofauna and land management in Peruvian Amazonia. Pedobiologia 33, 283–291.

Lawlor, D.W., Mitchell, R.A.C., 1991. The effects of increasing CO_2 on crop photosynthesis and productivity: a review of field studies. Plant, Cell and Environment 14, 807–818.

Lee, K.E., 1991. The diversity of soil organisms. In: Hawksworth, D.L. (Ed.), The Biodiversity of Microorganisms and Invertebrates: Its Role in Sustainable Agriculture. CAB International, Wallingford, UK, pp. 73–87.

Lemon, E.R., 1983. CO_2 and Plants: The Response of Plants to Rising Levels of Atmospheric Carbon Dioxide. Westview Press, Boulder, CO. 280 pp.

Lulu, B., Insam, H., 2000. Effects of cropping systems and manuring on soil microbial and C status of a Vertisol in Ethiopia. Bodenkultur 51, 107–114.

Mackenzie, A.F., Fan, M.X., Cardin, F., 1998. Nitrous oxide emission in three years as affected by tillage, corn–soybeans–alfalfa rotations, and nitrogen fertilization. Journal of Environmental Quality 27, 698–703.

Marland, G., Andres, R.G., Boden, T.A., Johnson, C., Brenkert, A., 1999. Global, regional and national CO_2 emission estimates from fossil fuel burning, cement production and gas flaring, 1751–1996. Report NDP-030. Carbon Dioxide Information Analysis Center, Oakridge National Laboratory, Oakridge, TN, USA.

Matson, P.A., Naylor, R., Ortiz-Monasterio, I., 2000. Integration of environmental, agronomic and economic aspects of fertilizer management. Science 280, 112–115.

Monger, H.C., Gallegos, R.A., 2000. Biotic and abiotic processes and rates of pedogenic carbonate accumulation in the southwestern United States—relationship to atmospheric CO_2 sequestration. In: Lal, R., Kimble, J.M., Eswaran, H., Stewart, B.A. (Eds.), Global Climate Change and Pedogenic Carbonates. CRC/Lewis, Boca Raton, FL, pp. 273–289.

Nabuurs, G.J., Päivinen, R., Sikkema, R., Mohren, G.M.J., 1997. The role of European forests in the global carbon cycle—a review. Biomass Bioenergy 13, 345–358.

Neufeldt, H., Resck, D.V.S., Ayarza, M.A., 2002. Texture and land use effects on soil organic matter in Cerrado Oxisols, central Brazil. Geoderma 107, 151–164.

Nilsson, L.G., 1986. Data of yield and soil analysis in the long-term soil fertility experiments. Journal Royal Swedish Academy Agriculture and Forest Supply 18, 32–70.

Nordt, L.C., Wilding, L.P., Drees, L.R., 2000. Pedogenic carbonate transformations in leaching soil systems; implications for the global carbon cycle. In: Lal, R., et al. (Ed.), Global Climate Change and Pedogenic Carbonates. CRC/Lewis, Boca Raton, FL, pp. 43–64.

Oldeman, L.R., 1994. The global extent of soil degradation. In: Greenland, D.J., Szabolcs, I. (Eds.), Soil Resilience and Sustainable Land Use. CAB International, Wallingford, UK, pp. 99–118.

Ozenda, P., Borel, J.-L., 1990. The possible responses of vegetation to a global climate change. Scenario for Western Europe with special reference to the Alps. In: Boer, M., de Groot, R.S. (Eds.), Landscape-Ecological Impact of Climate Change. Proc. European Conf., Lunteren, The Netherlands. IOS Press, Washington, Amsterdam, pp. 221–249.

Paustian, K., Andren, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M., Woomer, P.L., 1997. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use and Management 13, 230–244.

Poorter, H., 1993. Interspecific variation in the growth response of plants to an elevated ambient CO_2 concentration. Vegetatio 104/105, 77–97.

Post, W.M., Kwon, K.C., 2000. Soil carbon sequestration and land-use change: processes and potential. Global Change Biology 6, 317–327.

Pouyat, R., Groffman, P., Yesilonis, I., Hernandez, L., 2002. Soil carbon pools and fluxes in urban ecosystems. Environmental Pollution 116, S107–S118.

Prentice, I.C., 2001. The carbon cycle and the atmospheric carbon dioxide. Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change. Cambridge Univ. Press, UK, pp. 183–237.

Pulleman, M.M., Bouma, J., van Essen, E.A., Meijles, E.W., 2000. Soil organic matter content as a function of different land use history. Soil Science Society of America Journal 64, 689–693.

Rasmussen, P.E., Goulding, K.W.T., Brown, J.R., Grace, P.R., Janzen, H.H., Körschens, M., 1998. Long-term agroecosystems experiments: assessing agricultural sustainability and global change. Science 282, 893–896.

Reicosky, D.C., 2002. Long-term effect of moldboard plowing on tillage-induced CO_2 loss. In: Kimble, J.M., Lal, R., Follett, R.F. (Eds.), Agricultural Practices and Policies for Carbon Sequestration in Soil. CRC/Lewis, Boca Raton, FL, pp. 87–97.

Reicosky, D.C., Reeves, D.W., Prior, S.A., Runion, G.B., Rogers, H.H., Raper, R.L., 1999. Effects of residue management and controlled traffic on carbon dioxide and water loss. Soil and Tillage Research 52, 153–165.

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

Rosenzweig, C., Hillel, D., 1998. Climate Change and the Global Harvest: Potential Impacts of the Greenhouse Effect on Agriculture. Oxford Univ. Press, New York. 324 pp.

Sa, J.C.D., Cerri, C.C., Dick, W.A., Lal, R., Venske, S.P., Piccolo, M.C., Feigl, B.E., 2001. Organic matter dynamics and carbon sequestration rates for a tillage chronosequence in a Brazilian Oxisol. Soil Science Society of America Journal 65, 1486–1499.

Sainju, U.M., Singh, B.P., Yaffa, S., 2002. Soil organic matter and tomato yield following tillage, cover cropping and nitrogen fertilization. Agriculture Journal 94, 594–602.

Sauerbeck, D.R., 2001. CO_2 emissions and C sequestration by agriculture—perspectives and limitations. Nutrient Cycling in Agroecosystems 60, 253–266.

Schimel, D.S., 1995. Terrestrial ecosystems and the carbon cycle. Global Change Biology 1, 77–91.

Schimel, D.S., House, J.I., Hibbard, K.A., Bousquest, P., et al., 2001. Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. Nature 414, 169–172.

Schlesinger, W.H., 1999. Carbon sequestration in soils. Science 286, 2095.

Schlesinger, W.H., 2000a. Soil respiration and the global carbon cycle. Biogeochemistry 48, 7–20.

Schlesinger, W.H., 2000b. Carbon sequestration in soil: some cautions amidst optimism. Agricultural Ecosystems and Environment 82, 121–127.

Schlesinger, W.H., Andrews, J.A., 2000. Soil respiration and the global carbon cycle. Biogeochemistry 48, 7–20.

Shaver, T.M., Peterson, G.A., Ahuja, L.R., Westfall, D.G., Sherrod, L.A., Dunn, G., 2002. Surface soil physical properties after twelve years of dryland no till management. Soil Science Society of America Journal 66, 1296–1303.

Singh, B.R., Borresen, T., Uhlen, G., Ekeberg, E., 1998. Long-term effects of crop rotation, cultivation practices and fertilizers on carbon sequestration in soils in Norway. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Management of Carbon Sequestration in Soil. CRC Press, Boca Raton, pp. 195–208.

Skjemstad, J.O., Dalal, R.C., Janik, L.J., McGowan, J.A., 2001. Changes in chemical nature of soil organic carbon in Vertisols under wheat in southeastern Queensland. Australian Journal of Soil Research 39, 343–359.

Skjemstad, J.O., Reicosky, D.C., Wilts, A.R., McGowan, J.A., 2002. Charcoal carbon in U.S. agricultural soils. Soil Science Society of America Journal 66, 1255–1949.

Smaling, E.M.A., 1993. Soil nutrient depletion in sub-Saharan Africa. In: Van Reuler, H., Prins, W.H. (Eds.), The Role of Plant Nutrients for Sustainable Food Crop Production in Sub-Saharan Africa. Vereniging Van Kunstmest-Producenten, Leidschendam, The Netherlands, pp. 53–67.

Smith, P., Powlson, D.S., 2000. Considering manure and carbon sequestration. Science 287, 428–429.

Smith, P., Powlson, D.S., Glendining, M.J., Smith, J.U., 1997. Potential for carbon sequestration in European soils: preliminary estimates for five scenarios using results from long-term experiments. Global Change Biology 3, 67–79.

Smith, P., Powlson, D.S., Glendining, M.J., Smith, J.U., 1998. Preliminary estimates of the potential for carbon mitigation in European soils through no-till farming. Global Change Biology 4, 679–685.

Smith, P., Powlson, D.S., Smith, J.U., Falloon, P., Coleman, K., 2000a. Meeting the U.K.'s climate change commitments: options for carbon mitigation on agricultural land. Soil Use and Management 16, 1–11.

Smith, P., Powlson, D.S., Smith, J.U., Falloon, P., Coleman, K., 2000b. Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. Global Change Biology 6, 525–539.

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

Sohlenius, B., Boström, S., 1999. Effects of climate change on soil factors and metazoan microfauna (nematodes, tardigrades and rotifers) in a Swedish tundra soil—a soil transplantation experiment. Applied Soil Ecology 12, 113–128.

Sommerfeldt, T.G., Chang, C., Entz, T., 1988. Long-term annual manure applications increase soil organic matter and nitrogen and decrease carbon to nitrogen ratio. Soil Science Society of America Journal 52, 1668–1672.

Squires, V., Glenn, E.P., Ayoub, A.T., 1995. Combating global climate change by combating land degradation. Proceeding of Workshop in Nairobi, 4–8 Sept. 1995. UNEP, Nairobi, Kenya. 348 pp.

Stallard, R.F., 1998. Terrestrial sedimentation and the carbon cycle: coupling weathering and erosion to carbon burial. Global Biogeochemistry Cycles 12, 231–257.

Swift, R.S., 2001. Sequestration of carbon by soil. Soil Science 166, 858–871.

Tiessen, H., Sampaio, E.V.S.B., Salcedo, I.H., 2001. Organic matter turnover and management in low input agriculture of NE Brazil. Nutrient Cycling in Agroecosystems 61, 99–103.

Trumbore, S.E., Chadwick, O.A., Amundson, R., 1996. Rapid exchange of soil C and atmospheric CO_2 driven by temperature change. Science 272, 393–396.

Uhlen, G., Tveitnes, S., 1995. Effects of long-term crop rotation, fertilizers, farm manure and straw on soil productivity. Norwegian Journal of Agricultural Science 9, 143–161.

UNCBD, 1992. United Nations Convention on Biological Diversity. UNCBD, Bonn, Germany.

Van Dijk, H., 1982. Survey of Dutch soil organic research with regard to humification and degradation rates in arable land. In: Boels, D.D., Davis, B., Johnston, A.E. (Eds.), Land Use Seminar on Land Degradation. Balkema, Rotterdam, pp. 133–143.

Van Kessel, C., Horwath, W.R., Hartwig, U., Harris, D., Luscher, A., 2000. Net soil carbon input under ambient and elevated CO_2 concentrations: isotopic evidence after 4 years. Global Change Biology 6, 435–444.

Wallace, A., 1994. Soil organic matter must be restored to near original levels. Communications in Soil Science and Plant Analysis 25, 29–35.

Wander, M.M., Bidar, M.G., Aref, S., 1998. Tillage impacts on depth distribution of total and particulate organic matter in three Illinois soils. Soil Science Society of America Journal 62, 1704–1711.

West, T.O., Marland, G., 2002. Net carbon flux from agriculture: methodology for full carbon cycle analyses. Environmental Pollution 116, 439–444.

White, A., Cannell, M.G.R., Friend, A.D., 1999. Climate change impacts on ecosystems and the terrestrial carbon sink: a new assessment. Global Environmental Change 9, S21–S30.

Zech, W., Guggenberger, G., 1996. Organic matter dynamics in forest soils of temperate and tropical ecosystems. In: Piccolo, A. (Ed.), Humic Substances in Terrestrial Ecosystems. Elsevier, Amsterdam, The Netherlands.