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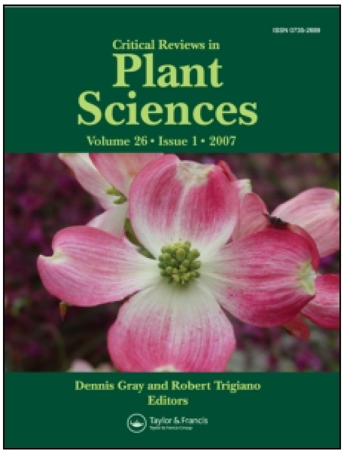

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Global Potential of Soil Carbon Sequestration to Mitigate the Greenhouse Effect

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ABSTRACT: An increase in atmospheric concentration of CO_2 from 280 ppmv in 1750 to 367 ppmv in 1999 is attributed to emissions from fossil fuel combustion estimated at 270 ± 30 Pg C and land use change at 136 ± 55 Pg. Of the emissions from land use change, 78 ± 12 Pg is estimated from depletion of soil organic carbon (SOC) pool. Most agricultural soils have lost 50 to 70% of their original SOC pool, and the depletion is exacerbated by further soil degradation and desertification. The restoration of degraded soils, conversion of agriculturally marginal lands to appropriate land use, and the adoption of recommended management practices on agricultural soils can reverse degradative trends and lead to SOC sequestration. Technological options for SOC sequestration on agricultural soils include adoption of conservation tillage, use of manures, and compost as per integrated nutrient management and precision farming strategies, conversion of monoculture to complex diverse cropping systems, meadow-based rotations and winter cover crops, and establishing perennial vegetation on contours and steep slopes. The global potential of SOC sequestration and restoration of degraded/desertified soils is estimated at 0.6 to 1.2 Pg C/y for about 50 years with a cumulative sink capacity of 30 to 60 Pg. The SOC sequestration is a cost-effective strategy of mitigating the climate change during the first 2 to 3 decades of the 21st century. While improving soil quality, biomass productivity and enhanced environment quality, the strategy of SOC sequestration also buys us time during which the non-carbon fuel alternatives can take effect.

I. INTRODUCTION

The increase in global temperature because of radiative forcing of greenhouse gases (GHGs) in the atmosphere has been estimated at 0.6°C during the 20th century and is projected to be 1.4 to 5.8°C by 2100 relative to 1990 (IPCC, 2001). The magnitude of increase in temperature is likely to vary spatially and temporally, and the continental regions in higher latitudes may warm more than coastal regions and the tropics. Further, nighttime minimum temperatures may increase more than daytime maximum temperature, and winter temperatures more than summer temperatures (Harvell et al., 2002). There may also be change in the amount, distribution, and intensity of rainfall/precipitation, with an overall increase in global humidity and precipitation. The projected climate change may also have a drastic impact on soil quality, growing season duration, and biomass productivity.

The Kyoto Protocol (Oberthür and Ott, 2000) has a provision of assigning credits for carbon (C) sequestration in forestry (article 3.3) and agricultural soils (article 3.4). Thus, enhancement of verifiable C pool in terrestrial (soils and vegetation) and aquatic (wetlands) ecosystems can have both economic and environmental benefits. Similar to other farm produce (e.g., corn, wheat, milk, timber), C grown on farms and forests can also be traded as a marketable commodity. The commodification of C necessitates establishment of the databank for credible and verifiable rates of C sequestration in relation to diverse land uses and soil/vegetation management practices, and identification of technological options that can enhance C sequestration in soil, biota, and wetlands.

Climate is an important and active factor of soil formation (Jenny, 1941, 1980). Consequently, soil properties such as soil organic carbon (SOC) pool are in dynamic equilibrium with climate, particularly with precipitation and temperature

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(Jenny and Raychaudhuri, 1960). Through its effect on precipitation, temperature and vegetation influence the quantity and quality of biomass returned to the soil and hence the SOC pool. All other soil-forming factors remaining the same, the SOC pool is generally more in soils of regions with high precipitation and cool temperatures than those with low precipitation and high temperatures. Further, the quantity and quality of SOC pools are strong determinants of soil quality in terms of biomass productivity and environment moderation capacity (Doran and Parkin, 1994; Bezdicek et al., 1996). Magnitude and dynamics of SOC pool are also indicators of soil degradation because of their influence on numerous physical, chemical, and biological properties and processes that affect soil's ability to perform its functions (Lal, 1997a).

The strong interdependence between climate and soil quality makes it necessary to predict the effects of climate changes on soil properties (e.g., SOC pool, soil aggregation) on climate change and vice versa. This article reviews the importance of land use and management options on C sequestration in soil and estimates the potential of soil C sequestration to mitigate the climate change. It builds on and updates the previous reviews on the topic (Lal and Bruce, 1999; Lal, 1999, 2000, 2001, 2002).

II. CHANGE IN ATMOSPHERIC CONCENTRATION OF GREENHOUSE GASES

The balance between the incoming solar radiation and the outgoing radiation emitted by the Earth has been disturbed by the continued increase in atmospheric concentration of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other GHGs. The concentration of CO_2 has increased from 280 parts per million by volume (ppmv) in 1750 to 367 ppmv in 1999 and currently is increasing at the rate of 1.5 ppmv/yr or 3.3 Pg/yr (1 Pg = petagram = 1 billion metric tons = 1×10^{15} g). The concentration of CH_4 has increased from about 700 ppbv to 1745 ppbv over the same period and is increasing at the rate of 7 ppbv/yr. Similarly, the concentration of N_2O has increased from about 270 ppbv in 1750 to 314 ppbv and is increasing at an average rate of 0.8 ppbv/yr (IPCC, 2001). These gases influence the radiation balance by permitting the short wave radiation to enter the Earth's atmosphere but capturing a fraction of the long wave radiation emitted by the Earth. This imbalance is expressed in terms of "radiative forcing", which is defined as the change in net irradiance (w/m^2) at the tropopause after allowing the stratospheric temperatures to readjust to radiative equilibrium (Ramaswamy, 2001).

The current radiative forcing of these gases is 1.46 W/m^2 for CO_2 (global warming potential or GWP = 1), 0.5 W/m^2 for CH_4 (GWP = 21), and 0.15 W/m^2 for N_2O (GWP = 310) (IPCC, 2001). The 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 (Folland and Karl, 2001). The warming rate since 1976 is 0.17°C/decade (IPCC, 2001), which is in excess of the 0.1°C/decade limit beyond which the ecosystems cannot adjust. Consequently, the land-surface precipitation continues to increase at the rate of 0.5 to 1%/decade in much of the Northern Hemisphere especially in mid and high latitudes, and decrease in subtropical land areas at the rate of 0.3%/decade (IPCC, 2001). With business as usual, the increase in atmospheric temperature is projected to be 1.4 to 5.8°C by 2100. In regions where the precipitation has increased, it is accompanied by an increase in heavy and extreme precipitation events. These changes in temperature and precipitation have strong impacts on soil quality, especially on SOC pool and dynamics, aggregation, erodibility, and cycling of H_2O and other important elements (e.g., C, N, P, S). In general, the SOC pool may decline leading to increase in erodibility or soil's susceptibility to erosion, decrease in infiltration capacity, reduction in plant available water capacity, decrease in soil's buffering capacity to retain plant nutrients and other ions, and increase in risks of overall soil degradation. The depletion of SOC pool will be more in the surface than in the subsoil, and eventually even the passive or recalcitrant fraction will also be depleted.

III. SOURCES OF INCREASE IN ATMOSPHERIC CONCENTRATION OF GASES

The global C budget for the decade of 1980s included 5.4 ± 0.3 Pg C emissions by fossil fuel combustion and cement manufacture and 1.7 ± 0.8 Pg C emissions by land use change (IPCC, 2001). The annual increase in atmospheric concentration of CO_2 was 3.3 ± 0.2 Pg C/yr, absorption by ocean was 2.0 ± 0.8 Pg C/yr, and the unknown residual terrestrial sink was 1.9 ± 1.3 Pg C/yr. For the decade of 1990s, emissions by fossil fuel combustion and cement manufacture were estimated at 6.3 ± 0.4 Pg C/yr, and emission by land use change was 1.6 ± 0.8 Pg C/yr. The increase in atmospheric concentration, however, occurred at the rate of 3.2 ± 0.1 Pg C/yr (Prentice, 2001). The absorption by ocean was 2.3 ± 0.8 Pg C/yr, and the uptake by an unknown terrestrial sink was 2.3 ± 1.3 Pg C/yr. Emissions by soil cultivation and degradative processes, including erosion/deposition cycles, are not accounted for in these estimates. Therefore, a complete understanding of the global C budget and of the impact of anthropogenic activities is essential. In this regard, the importance of knowing the principal C pools, fluxes among these pools, and the impact of anthropogenic perturbations on these pools and fluxes cannot be overemphasized.

There are five principal global C pools (Figure 1). The oceanic pool is the largest, estimated at 38,000 Pg followed by the geologic pool at 5000 Pg, soil organic carbon (SOC) pool at 1550 Pg to 1–meter depth, the biotic pool at 560 Pg and the atmospheric pool at 760 Pg. In addition to the SOC that varies among soils and regions (Table 1), there also exists soil inorganic carbon (SIC) pool estimated at 695 to 748 Pg to 1–meter depth (Batjes, 1996; Eswaran et al., 1995). There are two types of SIC pool: (1) lithogenic inorganic carbon (LIC), and (2) pedogenic inorganic carbon (PIC). The latter are formed through the dissolution of LIC or from the weathering byproducts of carbonate-bearing minerals and reprecipitation of weathering products. The PIC may also be formed through precipitation of atmospheric CO_2 with Ca^{+2}, Mg^{+2} and other cations. The SIC pool is an important constituent of the soils of the arid and semiarid regions estimated to cover 4.9×10^9 ha. Similar to the SOC, the dynamics of SIC pool is also influenced by soil degradation and anthropogenic perturbations (Lal and Kimble, 2000). Therefore, total soil C pool, estimated at 2300 Pg to 1–meter depth, is 4.1 times the biotic pool and about 3.0 times the atmospheric pool. The atmospheric pool has been increasing steadily (at an average rate of 3.3 Pg C/yr during the 1980s and 3.2 Pg C/yr during the 1990s) at the expense of the geologic, biotic and soil C pools (Figure 1).

There are some estimates of the historic loss of C from geologic and terrestrial pools and transfer of this C into the atmosphere. From 1850 to 1998, 270 ± 30 Pg C were emitted from fossil fuel burning and cement production (Marland et al., 1999). Of this, 176 ± 10 Pg C were absorbed by the atmosphere (Etheridge et al., 1996; Keeling and Whorf, 1999), and the remainder was absorbed by the ocean and the terrestrial sinks. During the same period, emissions from land use change are estimated at 136 ± 55 Pg (Houghton, 1999; Houghton et al., 1999). Emissions from land use change were related to deforestation, biomass burning, conversion of natural to agricultural systems, and the plowing of soil.

There are two components of estimated emissions of 136 ± 55 Pg 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 and SIC on conversion from natural to managed ecosystems. The historic loss of SOC has been estimated at 40 Pg by Houghton (1995), 55 Pg by IPCC (1995) and Schimel (1995), 500 Pg by Wallace (1994), 537 Pg by Buringh (1984), and 66 to 90 Pg (78 ± 12 Pg) by Lal (1999). Regardless of the uncertainties in the available statistics, it is apparent that world soils historically have been a major source of atmospheric enrichment of CO_2. In fact, until the 1950s, more C was emitted into the atmosphere from land use change and soil cultivation than from fossil fuel combustion. Presently, about 20% (1.6 Pg out of 7.9 Pg for the 1990s) of the global emissions come from land use change (IPCC, 2001). However, net flux of C between soil and the atmosphere is not known at national, regional, or global scale.

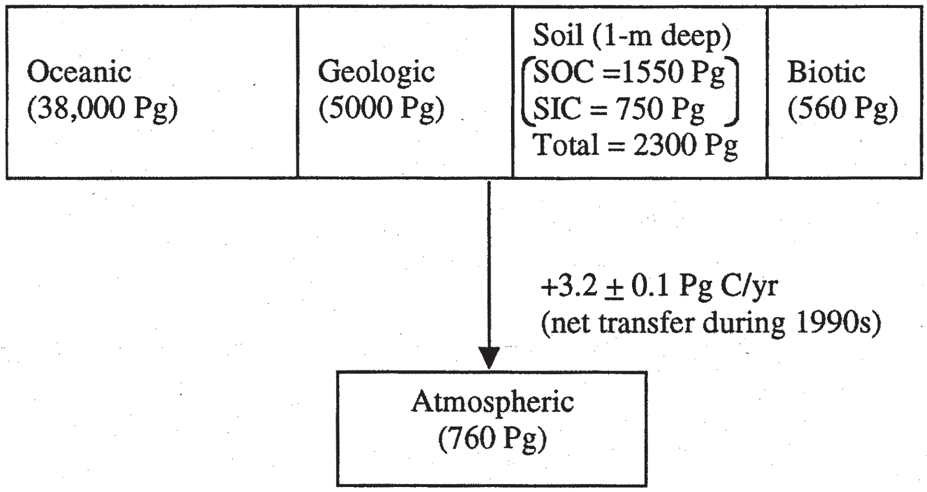

FIGURE 1. The atmospheric C pool of 760 Pg is increasing at the rate of 3.2 ± 0.1 Pg C/yr at the expense of the geologic, soil, and biotic pools. Figures in parenthesis indicate the magnitude of each pool.

TABLE 1
Estimates of Soil Organic Carbon Pool (IPCC, 2000; Prentice, 2001)

Ecosystem	Area (10^9 ha)	SOC pool (Pg C)
Forests		
• Tropical	1.76	213-216
• Temperate	1.04	100-153
• Boreal	1.37	338-471
Tropical savannas and grasslands	2.25	247-264
Temperate grassland and scrub land	1.25	176-295
Tundra	0.95	115-121
Desert and semi-desert	4.55	159-191
Cropland	1.60	128-165
Wetlands	0.35	225

In addition to CO_2, world soils can also be a source of CH_4, N_2O, and emission of other GHGs into the atmosphere. Of the total CH_4 emission of 500 to 600 Tg/yr, principal agricultural sources of CH_4 include emissions from rice paddies estimated at 40 Tg/yr (Neue and Sass, 1998; Sass et al., 1999), ruminant animals at 80 to 115 Tg CH_4/yr (Prather and Ehhalt, 2001), and biomass burning at 23 to 55 Tg CH_4/yr. Other important sources of CH_4 emissions include wetlands, landfills, energy production, and waste treatment. Of the total N_2O emissions of 17.7 Tg N/yr with a range of 6.7 to 36.6 (Mosier et al., 1998), agricultural sources include emissions from soils estimated at 4.2 Tg N/yr, biomass burning 0.5 Tg N/yr, and cattle and feedlots at 2.1 Tg N/yr (Prather and Ehhalt, 2001). The application of fertilizers and manures constitutes a principal source of N_2O from soils to the atmosphere (Follett, 2001).

IV. FACTORS AFFECTING GASEOUS EMISSIONS FROM SOILS

The emission of CO_2 from soil is caused by decomposition of organic matter or soil respiration (Schlesinger, 2000), which is accelerated by agricultural activities, including biomass, burning, plowing, drainage, and low-input farming (Figure 2). The rate of decomposition of organic matter primarily depends on soil temperature and moisture regimes (Jenny, 1980), and soil texture. In fact, macroclimate has a large impact on the portion of the soil organic matter that is potentially active (Franzluebbers et al., 2001). Consequently, mean annual temperature has a strong impact on SOC pool and its turnover (Trumbore et al., 1996). Conversion of natural to agricultural ecosystems increases the maximum soil temperature and decreases the soil moisture storage in the root zone, especially in drained agricultural soils. Thus, land use history strongly impacts the SOC pool (Pulleman et al., 2000). Northeast of Para'state in the eastern Amazon of Brazil, Sommer et al. (2000) reported significant changes in SOC pool to 6–m depth because of deforestation and land use change over 100 years of settlement. The SOC pool in soils was 196 Mg C/ha under a primary forest, 185 Mg C/ha under slash-and-burn agriculture, and only 146 to 167 Mg C/ha under (semi-) permanent annual cropping culture. Thus, conversion to agricultural ecosystem depleted SOC pool by 30 to 50 Mg C/ha over 100 years.

Biomass burning, an important management tool in several natural and agroecosystems, emits numerous gases immediately but also leaves charcoal as a residual material resistant to further decomposition. Charcoal is an important form of C produced by incomplete combustion. Being a passive component, charcoal does not contribute to SOC pool or soil biological activity. As SOC pool declines due to cultivation, the more resistant charcoal fraction increases as a portion of the total C pool (Zech and Guggenberger, 1996; Skjemstad et al., 2001, 2002) and may constitute up to 35% of the total SOC pool in fire-prone ecosystems (Skjemstad et al., 2002). Therefore, biomass burning has important negative and positive impacts on C dynamics. Carbon dating of charcoal has shown some to have been around for over 1500 years, is fairly stable, and a permanent form of C sequestration.

Deforestation and biomass burning are obvious factors leading to the release of CO_2, CH_4, N_2O, and NO_x into the atmosphere (Houghton et al., 2001). Cultivation of soil, by plowing and other tillage methods, enhances mineralization of SOC pool (Reicosky et al., 1999), and is not an obvious source of CO_2. The data in Table 2 show that tillage exacerbates losses of SOC pool, regardless of the soil type and climate. Tillage-induced soil disturbance may increase SOC mineralization by bringing crop residue closer to microbes, more soil-residue contact, and within the plow layer where soil moisture conditions favor higher mineralization rates (Gregorich et al., 1998). Tillage also physically disrupts/breaks aggregates and exposes hitherto encapsulated (protected) C to microbial processes (Kay, 1998). The rate of depletion of SOC pool by tillage is especially high in soils of the tropics (Lal, 2002). For a Brazilian Oxisol, Novotny et al. (1999) observed that increase of tillage intensity resulted in a general decrease in humic substances because of preferential degradation of large molecular size humic substances.

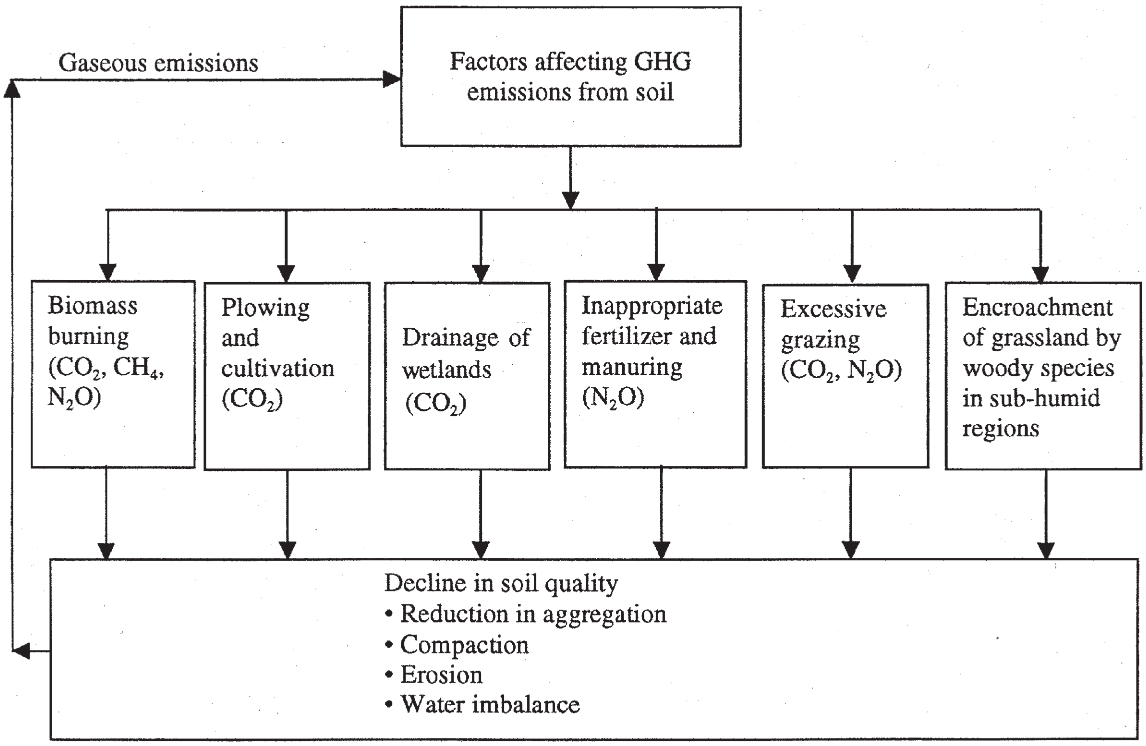

FIGURE 2. Agricultural practices affecting emissions of greenhouse gases into the atmosphere.

Thus, a better understanding of the SOC dynamics in relation to land use and management is crucial to developing/identifying sustainable systems of management of natural resources for C sequestration. There is a strong interaction between tillage and drainage. Both activities decrease soil moisture regime, increase the maximum soil temperature (Fausey and Lal, 1989), and exacerbate the rate of mineralization of SOC (Sullivan et al., 1998). Nutrient mining, as is the case with low input and subsistence farming practiced by small land holders of the tropics and subtropics, is another cause of depletion of SOC pool. Negative elemental balance (nutrient mining), a widespread problem in sub-Saharan Africa (Smaling, 1993), is caused by not replacing the essential plant nutrients harvested in crop and livestock products with the addition of fertilizer and/or manure. Excessive grazing has the same effect as mining of soil fertility by inappropriate cropping (Follett et al., 2001). 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 western central Great Plains of the U.S., this system requires a 14–month fallow period between the harvest and continuous cropping in some instances. Tillage fallowing during summer keeps the subsoil moist but dries out the surface soil and enhances the mineralization rate. Therefore, the elimination of the 7 to 9 rod weeder “tillage events” of summer fallowing is an important strategy of SOC sequestration (Rasmussen et al., 1998). The objective is to maintain a dense vegetal cover for photosynthesis on the soil surface so that biomass C can be added/returned to the soil. These strategies depend on rainfall and its distribution. Care is needed to control water use by the vegetal cover so as not to deplete soil water for the following agronomic crop. The timing of subsequent rain events play a large role in the performance of the following crop. Consequently, the SOC pool can be maintained or increased in most semiarid soils if they are cropped every year, crop residues are returned to soil without tillage, and erosion is kept to a minimum. Up to 25 mm of water can be lost with tillage to a depth of 15 cm. In essence, the depletion of SOC pool is caused by land misuse and soil rain mismanagement.

TABLE 2
Tillage and Cultivation Effects on SOC Dynamics

Country	Location	Soil	Rotation	SOC depletion by tillage	Reference
Argentina	Pampa	Typic Argiudoll	Corn-wheat-soybean	--	Alvarez et al. (1998)
Brazil	Passofundo, RGS	Rhodic Ferralsol	Wheat/soybean-vetch/maize	60%	Frexio et al. (2002)
Brazil	Minas Gerais	Typic Haplustox	Maize-soybean	3 to 28%	Neufeldt et al. (2002)
Canada	Alberta	Irrigated soil	Wheat-beat-wheat-legume Wheat-wheat-legume-beat	0.45 Mg C/ha/yr	Hao et al. (2001)
Canada	Ontario	--	Maize monoculture and legume-based rotation	30-40% over 35 yrs	Gregorich et al. (2001)
Canada	Ontario	Typic Haploboroll	Wheat based rotation	20 to 25% more emissions with plowing	Curtin et al. (2000)
Canada	Saskatchewan	Praire	Wheat, wheat-fallow	360-460 kg/ha/yr	Curtin et al. (2000)
Indonesia	Sumatra	Oxisols	Cassava-based	7 Mg C/ha/yr	Hairiah et al. (2000)
South Africa	Highveld	Plinthustaffs	Cultivated	55-65% over 98 yrs	Lobe et al. (2001)
Tanzania	Northern	Savanna woodland soils	Agricultural feeding	SOC concentration declined over 3 to 15 yrs	Glaser et al. (2001)
USA	Arlington, WI	--	Maize	745 to 863 kg C/ha/yr for 50 yrs	Kucharik et al. (2001)
USA	Wyoming	Sandy loam	Wheat-fallow	18-26% after 60 yrs	Reeder et al. (1998)
USA	Colorado	Seimi-arid grassland	Cultivated		Burke et al. (1995)
USA	North Dakota	Typic Haplustoll	Conversion of CRP to hay	1.2 Mg C/ha over 3 years	Wienhold & Tanaka (2001)
USA	SE coastal plains	Typic Kandiudults	Corn-soybean-clover	CO_2 fluxes 3 times in plow till	Reicosky et al. (1999)

V. DEPLETION OF SOIL ORGANIC CARBON POOL BY EROSION AND OTHER SOIL DEGRADATIVE PROCESSES

The depletion of SOC pool on agricultural soils is exacerbated by soil degradation or the decline in soil quality caused by land misuse and soil mismanagement. Soil degradation 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 water, wind, and tillage 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 carbon and depletion of SOC pool (Lal et al., 1989). Soil degradation decreases biomass productivity, reduces the amount of plant residue returned to the soil, and decreases the SOC pool. Among all soil-degradative processes, accelerated soil erosion has the most severe impact on SOC pool. Several experiments from around the world have shown on-site depletion of SOC pool by accelerated erosion (Table 3). However, on-site depletion of SOC does not necessarily imply emission of translocated SOC into the atmosphere. Therefore, knowledge of the impact of all 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 4–step process comprising detachment, breakdown, transport and deposition of soil particles. These four processes have interacting and often counter effects on soil C (Figure 3). Basically, soil erosional processes affect SOC pool in two ways: (1) the preferential removal of C and its transport with runoff and sediments leads to redistribution of SOC over the landscape or watershed, and (2) the erosion and depositional processes drastically alter the factors affecting mineralization of C. While erosion results in redistribution of C, the mineralization leads to loss of C from soil into the atmosphere. Gregorich et al. (1998) observed that mineralization may be the dominant mechanism of SOC loss during the initial years following the conversion of natural to agricultural ecosystems and that erosion becomes a major factor in the later years.

Tillage erosion or tillage-induced translocation, the net movement of soil downslope through action of mechanical implements and gravity acting on loosened soil, has been observed for many years. The moldboard plow was identified as the primary cause, but all tillage implements contribute to this problem (Govers et al., 1994; Lobb and Kachanoski, 1999). Tillage erosion has become an important factor in soil management considerations and is often confused with water erosion.

Soil translocation from moldboard plow tillage operations has been identified as a cause of soil movement from specific landscape positions that can be greater than currently accepted soil loss tolerance levels (Lindstrom et al., 1992; Govers et al., 1994; Lobb et al., 1995; Poesen et al., 1997). Soil is not directly lost from the fields by tillage translocation, rather it is moved away from the convex slopes and deposited on concave slope positions. Lindstrom, Nelson, and Schumacher (1992) showed that soil movement on a convex slope in southwestern Minnesota could result in a sustained soil loss level of approximately 30 t ha^{-1} yr^{-1} from annual moldboard plowing. Lobb, Kachanoski, and Miller (1995) estimated soil loss in southwestern Ontario from a shoulder position to be 54 t ha^{-1} yr^{-1} from a tillage sequence of moldboard plowing, tandem disk, and a C-tine cultivator. In this case, tillage erosion, as estimated through resident $^{137}C_s$, accounted for at least 70% of the total soil loss. Tillage speed increases nonlinearly the rate of tillage erosion.

The relationship between soil productivity and erosion is complex. Soils are not the sole factors controlling crop yields. The degree to which crop yield losses are related to soils is a function of several interacting factors, including soil physical, chemical and biological properties, landscape position, crop grown, management practices, and weather conditions before and during the growing season. Schumacher et al. (1999) used modeling procedures to show that tillage erosion caused soil loss from the shoulder position, while soil

TABLE 3
Depletion of SOC by erosion

Country	Location	Soil	Rotation	SOC depletion by tillage	Reference
Africa (Francophone)	West Africa	Ferrallidic and Ferruginous	Maize	10-100 Kg C/ha/yr	Roose and Barthes (2001)
Canada	Saskatchewan	Chernozemic and Luvisolic	Wheat monoculture and cereal-hay	Erosion 12.8 Mg/ha/yr depletes SOC	Monreal et al. (1997)
Canada	Country	All	Agricultural soil	954 to 1675 kg C/ha	Gregorich et al. (1998)
Slovakia	Nitra	--	Forest and cultivated land	Decline in carbon pool index by erosion	Zaujec (2001)
South Africa	Highveld	Plinthustalf	Cultivation	55-65% by wind erosion over 100 yrs	Lobe et al. (2001)
USA	Pendleton, OR	--	Summer fallow	Most C released is lost to oxidation	Smith et al. (2001) Rasmussen et al. (1998)
USA	Pendleton, OR	Semi-arid	Summer fallow	Biological oxidation of eroded C causes emission	Ritchie and Rasmussen (2000)
Vietnam	--	Sloping land	Cultivated	50-70%	Dang and Klinnert (2001)

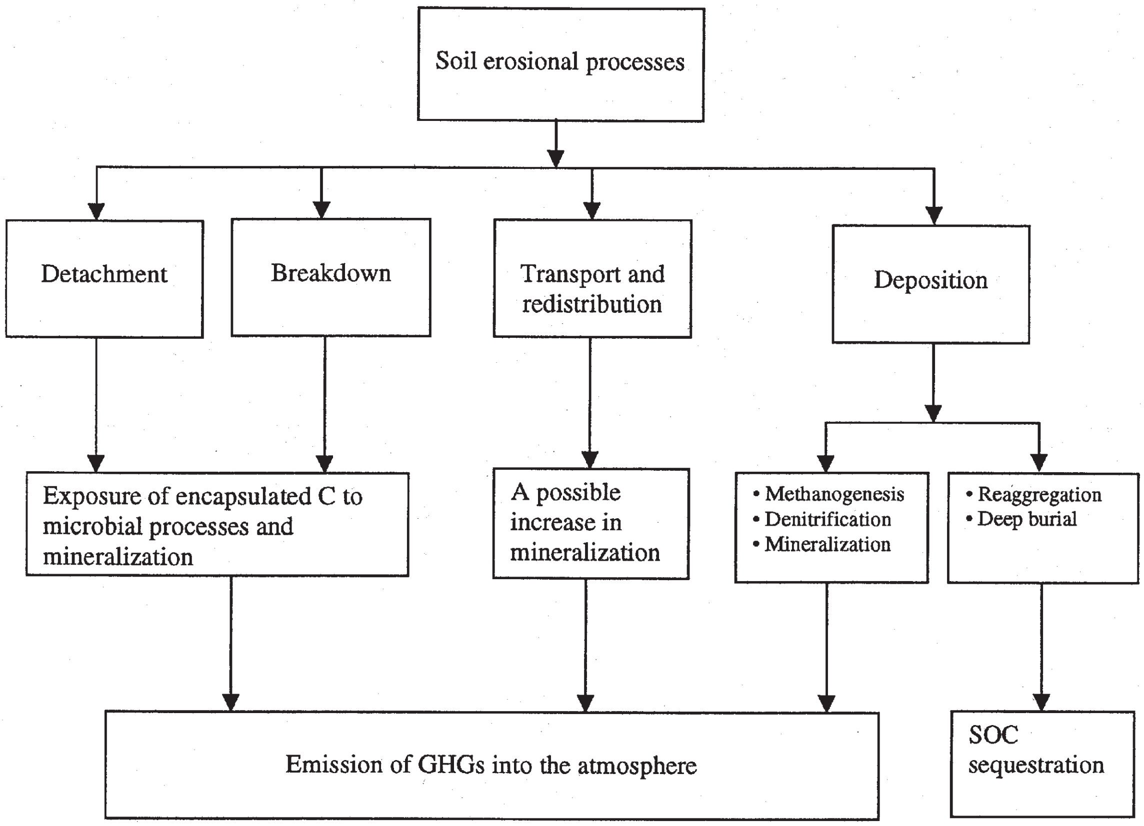

FIGURE 3. Fate of the eroded and redistributed carbon and the impact of erosional processes on gaseous emissions.

loss from water erosion occurred primarily in the mid to lower backslope position. The decline in overall soil productivity was greater when both processes were combined compared to either process acting alone. Water erosion contributed to nearly all the decline in soil productivity in the backslope position when both tillage and water erosion processes were combined. While there are many other reasons for intensive tillage, tillage sets up the soil to be loose, open, and very susceptible to high-intensity rainfall and subsequent erosion. The net effect of soil translocation from the combined effects of tillage and water erosion was an increase in spatial variability of crop yield and a likely decline in overall soil productivity (Schumacher et al., 1999).

On relatively flat soils with no erosion risks, mineralization predominates over erosion at all times. For example, Rasmussen et al. (1998) and Ritchie and Rasmussen (2000) 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 lands, however, erosional processes may be the principal cause of SOC depletion even during the initial years (Lal, 1976). 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 SOC pool. Lal (1999) estimated that of the 78 ± 12 Pg of the historic SOC loss, 26 ± 9 Pg is caused by erosion-induced mineralization. Annual emission of C due to erosion is estimated at 15 Tg in the U.S. (Lal et al., 1998) and 1.14 Pg in the world (Lal, 1995). In contrast, however, some sedimentologists argue that transport and burial of C into aquatic ecosystems and depressional sites may lead to C sequestration (Stallard, 1998; Smith et al., 2001). Stallard and Smith et al. assume, however, that there is no oxidation of C during the erosion. On the contrary, Schlesinger (1995) argued that organic C transported by erosion is largely oxidized. A special case of biological degradation from intensive tillage is change in the predominant vegetation and soil fauna, with adverse impact on SOC pool. Jackson et al. (2002) reported that invasion of grassland by woody vegetation caused depletion of SOC pool. The losses of SOC were substantial enough at the wetter sites to offset increase in any plant biomass carbon (Table 4).

It is because of the historic loss of SOC pool (by mineralization, leaching, erosion, or shift in vegetation), estimated at 30 to 60 Mg C/ha or 50 to 70% of the antecedent pool (Lal, 2000), that most agricultural and degraded soils now contain lower SOC pool than their potential determined by the specific climatic conditions and soil profile characteristics. The SOC pool can be enhanced by conversion to an appropriate land use, adoption of recommended management practices, and restoration of degraded soils. Thus, an important strategic question is "to what extent can we use SOC sink capacity to scrub the dirty atmosphere and mitigate global warming?"

VI. TECHNOLOGICAL OPTIONS OF SOIL CARBON SEQUESTRATION

The term "soil C sequestration" implies net removal of atmospheric CO_2 by plants and its storage as soil organic matter. Processes of SOC sequestration include humification, aggregation, deep incorporation of C in the subsoil, and calcification. Humification involves conversion of plant and animal residues into complex humic substances, which are stable and recalcitrant. Carbon is only one of several building blocks needed for conversion of crop residue into humus. Other building blocks include N, P, S, and several micronutrients. In addition to nutrient requirements for plant growth, these elements are also needed for humification. To sequester 10,000 kg of C in humus, 833 kg of N, 200 kg of P and 143 kg of S are needed assuming C:N ratio of 12:1, C:P ratio of 50:1 and C:S ratio of 70:1 (Himes, 1998). Aggregation involves the formation of organo-mineral complexes and stable micro-aggregates that encapsulate C and protect it from microbial processes. Soil organic matter that becomes encrusted by mineral material dominated by small pores may become the center of water-stable aggregates (Waters and Oades, 1991; Kay, 1998). Microbial byproducts of decomposition bond mineral grains and increase the strength of the bonds and enhance aggregate stability. Fungal byproducts, glamalin, also help bind soil particles in no till systems (Wright et al., 1999). Glomalin is identified as vital to the formation and strength of soil structure, and its concentration in soil increases with conversion to a no till system (Wright and Anderson, 2000; Wright and Upadhyaya, 1998). More stable and deeper in the subsoil, the more stable and effective is the sequestration. Mycorrhizal fungi also contribute to SOC sequestration and increases aggregation (Rillig et al., 1999, 2000, 2001, 2002).

Calcification involves formation of pedogenic or secondary carbonates and leaching of carbonates into the ground water. Therefore, in this context, agriculture may be defined as an anthropogenic manipulation of C through uptake, fixation, emission and transfer. Thus, the management of agroecosystems is an important strategy to enhance C uptake plus fixation and decrease emission plus transfer. In addition to management of agricultural soils, land use change with conversion of agriculturally marginal soils to restorative land use is an important instrument of SOC change (Post and Kwon, 2000). The sink capacity of soil organic matter for atmospheric CO_2 can be greatly enhanced by: (1) restoring degraded soils and ecosystems, (2) converting agriculturally marginal soils to natural vegetation or replanted to perennial vegetation, and (3) adopting recommended management practices on agricultural soils (Figure 4). Under these conditions, SOC can accumulate in soils because biomass production is enhanced on degraded soils, soil disturbance, and risks of degradation are reduced on highly erodible lands, and production is enhanced through agricultural intensification on prime lands.

TABLE 4
Depletion of Soil Organic Carbon Pool by Encroachment of Grasslands by Woody Species on Three Sites in Texas, USA (Recalculated from Jackson et al., 2002)

Site	Mean annual precipitation (mm)	SOC pool to 3-m depth		SOC loss	
		Grassland	Shrub/woodland	Amount	%
		----------------Mg/ha	-------------	----------Mg C/ha	--------
Vernon	660	86.1	78.5	7.6	8.8
Riesel	840	27.8	216	62	22.3
Engeling	1070	73.8	41.7	32.2	43.6

These strategies conserve soil and water, improve soil quality, and enhance SOC pool. Incorporating SOC into the subsoil by growing deep-rooted plants and enhancing the activity of soil fauna (e.g., earthworms) can increase its mean residence time (MRT). Paul et al. (2001) reported that the MRT was 560 years in the surface horizon, 1700 years at 25 to 50 cm depth, and 2757 years at 50 to 100 cm depth. Land use and management systems that increase depth distribution of SOC also increase the MRT and longevity of C in the soil. The SOC pool, composition, and depth distribution enhance soil quality, improve biomass yield, increase aggregation, and improve available water capacity (Diaz-Zorita et al., 1999). Thus, conversion of an agricultural to a natural or a restorative land use essentially reverses some of the effects responsible for SOC depletion that occurred after conversion of natural to managed ecosystems.

The applications of ecological concepts to management of natural resources (e.g., nutrient cycling, energy budget, soil engineering by macroinvertebrates, and enhanced soil biodiversity) may be important factors leading to improvements in soil quality and SOC sequestration (Lavelle, 2000). Recommended agricultural practices improve SOC by increasing the input of C through crop residues and biosolids with less intensive tillage (Paustian et al., 1997). The SOC concentration in the surface layer usually increases with increasing inputs of biosolids (Graham et al., 2002), manure (Rasmussen et al., 1998), 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. Specific practices to enhance SOC include the following:

1. Mulch Farming and Conservation Tillage

Agricultural soils are depleted of SOC due to mechanical tillage and accelerated soil erosion. Thus, soils can store C after conversion from intensive mechanical tillage to conservation tillage, with the ultimate purpose of converting no till or direct seeding. Conservation tillage is defined as any method of seedbed preparation that leaves at least 30% of ground covered by crop residue mulch (Lal, 1997b). The presence of crop residue mulch on the soil surface is an integral part of conservation tillage. The adoption of conservation tillage increases SOC concentration by reducing soil disturbance, decreasing soil erosion, increasing infiltration, conserving soil water, and increasing soil biodiversity (Table 5) (Del Grosso et al., 2002). Elimination of summer fallowing in arid and semiarid regions, and adoption of conservation tillage with residue mulching improves soil structure, lowers bulk density, and increases infiltration capacity (Shaver et al., 2002). The benefits of conservation tillage 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). In rolling Pampa region of Argentina, Alvarez et al. (1998) observed that the annual C budget was negative under both moldboard plow and no till systems, and no till system lost 0.7 to 1.5 Mg/ha/yr more C than did plow tillage. In southern Ontario, Canada, Van den Bygaart et al. (2002)

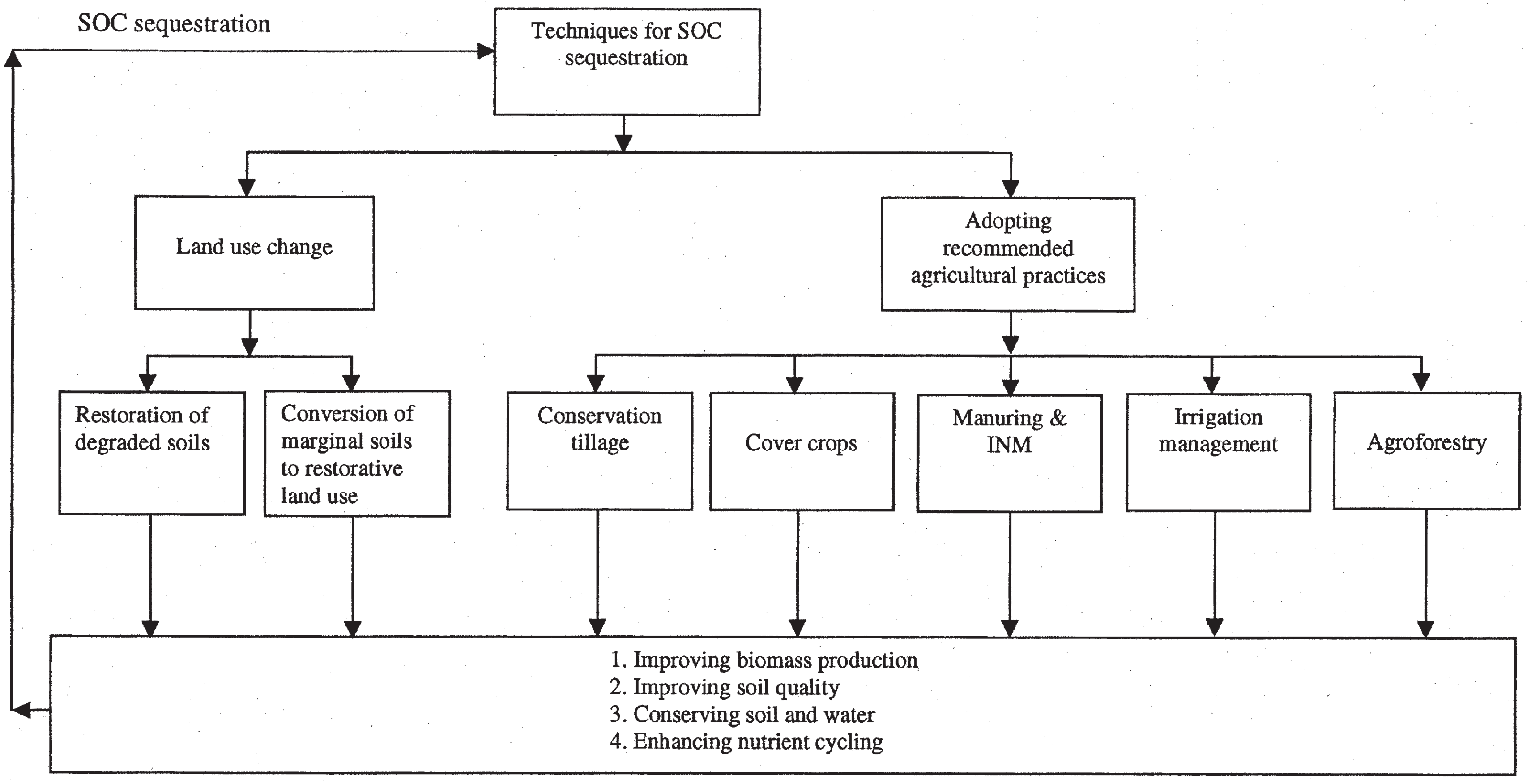

FIGURE 4. Techniques of SOC sequestration.

TABLE 5
Soil Organic Carbon Sequestration by Adoption of Conservation Tillage

Country	Location	Soil	SOC gain	Reference
Brazil	Southern	Sandy clay loam, Acrisol	44 Mg C/ha over 9 yrs	Bayer et al. (2000)
Canada	Saskatchewan	Black Chernozemic	--	Bergstrom et al. (2001)
India	U.P.	Tropical dryland	2.3 g/kg	Kushwaha et al. (2001)
Morocco	Semi-arid	Calcixeroll	13.6% over 11 yrs	Mrabet et al. (2001)
USA	Conterminous USA	All soils	371 kg C/ha/yr	West and Marland (2002)
USA	Conterminous USA	All soils	12.2 Tg C/yr (+25%)	Uri (2001)
USA	Wisconsin	Prairie soils	28-42% over 24 yrs to 1-m depth	Kucharik et al. (2001)
USA	Kansas	Argiudoll, Haplustoll, Hapludoll	SOC increased with quantity of residue returned	Havlin et al. (1990)
USA	Eastern corn belt	Miscellaneous	300-600 kg/ha/yr	Dick et al. (1998)

also observed a decline in SOC under conservation tillage. An important constraint to adopting conservation tillage by resource-poor farmers of the tropics is the lack of access to herbicides for weed control, inadequate amount of crop residue mulch, and nonavailability of appropriate seeding equipment on an untilled and mulched soil. Yet, no till farming has been dubbed as a way for the future even in dryland agriculture where water conservation is important (Papendick and Parr, 1997).

2. Cover Crops

The benefits of adopting conservation tillage for SOC sequestration are greatly enhanced by growing cover crops in the rotation cycle (Table 6). Growing leguminous cover crops enhances biodiversity and the quality of residue input. It is well established that ecosystems with high biodiversity absorb and sequester more C than those with low or reduced biodiversity. Gregorich et al. (2001) concluded that residue quality also plays a key role in retention of soil C and that soils under legume-based rotation tend to be more "preservative" of residue C inputs particularly from root biomass than soils under monoculture. Growing winter cover crops may increase SOC in intensively managed summer cropping systems (Mendes et al., 1999). In Alabama, USA, Nyakatawa et al. (2001) observed an increase in SOC by growing winter rye (*Lolium multiflorum*) in the rotation. Also in Alabama, Entry et al. (1996) and Mitchell and Entry (1998) reported that long-term planting of winter legumes in cotton (*Gossipium hirsutum*) drastically increased SOC concentration in the plow layer. 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 (*Vicia* spp.) can improve SOC concentration. Franzluebbers et al. (2001) also observed in Georgia, USA, that improved forage management can enhance SOC pool. On a Vertisol in Ethiopia, Lulu and Insam (2000) observed positive effects of alley cropping (i.e., agroforestry) with *Sesbania* on SOC pool. However, use of cover crops as a short-term green manure may not necessarily enhance the long-term SOC pool (N'Dayegamiye and Tran, 2001) if it is plowed in.

Despite numerous benefits, many farmers cannot afford to grow cover crops for economic reasons or limited water. In some cases, such as in humid regions of West Africa, there are no economic uses of cover crops (e.g., fodder). Suppressing or controlling cover crops requires herbicides that may not be available. Biological N fixation by leguminous cover crops may not be a strong enough incentive to forego a grain crop. Further, a cover crop may not fit into the cropping system socially and economically acceptable to the farming community. Success of cover crops often depends on available rainfall so both the cover crop and following agronomic crop have adequate water for growth and yield.

3. Nutrient Management

Judicious nutrient management is crucial to humification of C in the residue and to soil C sequestration (Table 7). Over and above nutrients required for crop growth, additional nutrients (e.g., N, P, S) are needed for humification. Soil humus has narrow C:N, C:P and C:S ratios than those in the crop residue. Thus, humification efficiency depends on the availability of N, P, and S. In general, cropping systems (i.e., rotation or monoculture, cover crops, etc.) have more effect on SOC level than application of different rates of fertilizer (Gregorich et al., 2001). The fertilizer effects on SOC pool are related to the C:N ratio and the amount of biomass C produced/returned to the soil and its humification. Van Kessel et al. (2000) observed under the elevated CO_2 concentrations that the amount of new C sequestered in the soil was influenced by plant species and the response of root biomass to CO_2 and N fertilization.

4. Manure Management

Many civilizations have been nurtured by food grown on soils whose initial organic matter contents and productivity were high. In some cases

TABLE 6
Soil Organic Carbon Sequestration by Growing Cover Crops and Meadows in the Rotation Cycle

Country	Location	Soil	SOC gain	Reference
Australia	NSW	Alfisols	11.6 mg/kg	Chan et al. (2001)
Canada	Saskatchewan	Prairie	minor	Curtin et al. (2000)
Canada	Saskatchewan	Prairie	1.2-2.4 Mg C/ha/yr	Curtin et al. (2000)
Norway	Western	--	357 kg C/ha/yr	Uhlen and Tveitnes (1995); SkØien (1993)
USA	Colorado	Weld loam, Paleustolls	20% in 0-5 cm depth	Bowman et al. (1999)

TABLE 7
Soil Organic Carbon Sequestration by Use of Manure, Compost and Fertilizer

Country	Location	Soil	SOC gain by manuring or fertilizer use	Reference
Australia	Victoria	Vertisols	11.8 Mg C/ha over 68 years	Ridley et al. (1990)
Austria	--	Phaeozems, Chernozems, Kastanozems	2.1 Mg C/ha over 36 years	Dersch and Böhm (2001)
Canada	Alberta	Chernozems	18.5-23.4 Mg C/ha over 15 years	Malhi et al. (1997)
Denmark	Askov	Sandy loam soil	11% over 90 years	Schjonning et al. (1994)
Denmark	Askov	--	10% higher SOC by manuring over 100 years	Christensen (1996)
Germany	Bad Lauchst	--	22% over 90 years	Korschens and Muller (1996)
Ghana	155 villages	Alfisols	--	Quansah et al. (2001)
India	Central India	Vertisol (Typic, Haplustert)	85-739 kg C/ha/yr	Kundu et al. (2001)
Norway	Aas	--	347 kg C/ha/yr	Uhlen and Tveitnes (1995)
Sweden	Ultuna	--	44% over 31 years	Witter et al. (1993)
U.K.	Rothamsted	Broadbalk site	100% over 144 years	Jenkinson (1990)
USA	Kansas	Argiudoll, Haplustoll	28% increase in 5-6 yrs	Grant et al. (2002)
USA	Maine	Typic Haplosthods	SOC increased with N	Havlin et al., (1990)
USA	Colorado	Prairie soils	40% increase in SOC of 0-5 cm depth	Bowman and Halverson (1998)

TABLE 8
Soil Organic Carbon Sequestration by Use of Agroforestry

Country	Location	Soil	SOC gain	Reference
Africa	Sub-Saharan	Low input systems	--	Buresh & Tian (1997)
Niger	Niamey	Ferriginous	0.48%	Guillaume et al. (1999)
USA	Central Iowa	--	8.6% over 6 seasons	Marquez et al. (1998)

TABLE 9
Soil Organic Carbon Sequestration by Conservation Reserve and Wetland Restoration Program

Country	Location	Soil	SOC gain	Reference
U.K.	Shropshire	Hilton Experimental Site	0.78% in 4 yrs by grass ley	Fullen (1998)
USA	Wyoming	Sandy loam	40-60% in 2.5 cm layer in 5 yrs	Reeder et al. (1998)
USA	Great Plains	Grassland soils	570 to 910 kg C/ha/yr	Follett et al. (2001)
USA	Wyoming	Semi-arid	1.23 $g/m^2/d$	Robles and Burke (1998)
USA	Wyoming	Semi-arid	Slight over 6 yrs	Robles and Burke (1997)
USA	Colorado	Semi-arid grassland	50 yrs is an adequate time for recovery	Burke et al. (1995)
USA	Eastern Washington	Silt loam to sandy loam	Increase observed in one year	Gewin et al. (1999)
USA	Kentucky	Wetland	Increase	Kolka et al. (200)

these soils were used so intensively that their soil organic matter was depleted. Yields declined, crop residues were consumed for fuel and fodder, and erosion ultimately carried the topsoil away and civilizations declined. Recognizing these lessons of history and observing the erosion and declining productivity in the early part of the 20th century, scientists at many locations (e.g., those at Rothamstad, England; Pendelton, Oregon; Champaign, Illinois Morrow plots; and Columbia, Missouri Sanborn plots initiated long-term studies on effects of crop rotation, crop fertilization, manure additions, and residue management on the productivity and organic matter content of cropped soils.

In general, soil cultivation of Morrow plots (including moldboard plowing) caused a decline in organic carbon (which constitutes about half of the organic matter). In most cases, the decline was rapid in the early years and slowed with time. However, it appears that organic matter in the Morrow plots is still declining after 100 years of cultivation that has always included rnoldboard plowing. The rate of decline was less for small grains and hay than for clean tilled row crops. Six tons of manure added per acre per year to half of the wheat and corn plots at Sanborn Field appeared to slow the decline in soil organic matter during the first 20 or 30 years of intensive data collection. However, organic matter contents dropped below those of the original prairie, and appeared to stabilize during the 1940 to 1962 period.

Initial organic matter in the Sanborn Field plots at Columbia, MO, was only slightly different compared with the Morrow plots at Urbana, IL. The initial values represent best estimates at both locations and need to be interpreted with caution. Contributing factors may be the tight clay subsoil in Sanborn Field, which may limit rooting depth and frequently causes drought stress on the crops and lower fertility of Sanborn Field soil, which is much older. Both of these factors may reduce the native biomass production (and current crop production) on the Sanborn soils. Soil temperatures are also slightly higher at Sanbom Field, which accelerates the rate of biological oxidation of the organic matter.

At Pendleton, OR, the original soil organic matter (Rasmussen and Smiley, 1989) is estimated to have been a little more than 3%, but by 1931, after about 50 years of cultivation (biennial moldboard plowing with shallow secondary tillage) in a wheat-fallow rotation that was accompanied by some burning of the wheat stubble, the soil organic matter had dropped to 2%. Treatments were initiated in 1931 to determine effects of burning vs. not burning the stubble. Recognizing removal of about 40 pounds of N/acre (45 kg/ha) per cropping season, they added that amount of N fertilizer each growing season in one treatment. Because wheat-pea rotations were possible in the area and pea vines were available to provide needed nitrogen, they applied 1 ton of pea vines per acre every other year in another treatment. In an effort to increase organic matter on another treatment, they applied 10 tons/acre (23 tons/ha) of strawy manure in addition to the crop residue each growing season in a wheat/fallow rotation. All plots were moldboard plowed to incorporate the crop residues and manure. There were various secondary tillage operations to control weeds during the fallow year and prepare the seedbed for the next crop. During the first 20 years the heavy manure treatment and even the pea vine additions appeared to increase soil organic matter. However, from 1951 to date soil organic matter appears to have stabilized at about 2.1% in the heavy manure treatment and is declining significantly under all the other treatments. Fallowing, while it stabilizes crop production, is especially detrimental to soil organic matter maintenance because biological oxidation continues for a full year while no new crop residue is added. Cultivation for weed control during the fallow period may also enhance biological oxidation.

The data from Illinois, Missouri, and Oregon indicates that small grains and rotations including small grains and hay can reduce the rates at which soil organic matter is oxidized from these soils compared to continuous corn. Large manure applications (6 and 10 tons/acre/growing season) supplemented the crop residues and helped prevent further decline of the soil organic matter, but even when these larger amounts of manure and residues are being moldboard plowed into the soil we are not generally increasing soil organic matter.

In general, the use of organic manures and compost enhances SOC pool more than application of the same amount of nutrients as inorganic fertilizers. Long-term manure applications increase SOC pool and improves aggregation (Sommerfeldt et al., 1988; Gilley and Risse, 2000), and the effects may persist for a long period of a century or more (Compton and Boone, 2000). In southwest Michigan, Wilson et al. (2001) reported that microbial C was greater in treatments receiving compost rather than inorganic fertilizer. Izaurralde et al. (2001) observed from a 51–year-old experiment at Breton, Canada, that the return of 30% of the crop C as manure would sustain SOC sequestration. In central Europe, Mäder et al. (2002) reported enhanced soil fertility and more SOC pool in plots under organic than conventional farming systems. In New Zealand, Condron et al. (2000) reported more SOC concentration and biological activity under organic than under conventional systems. In the Guangdong province of China, Shen et al. (2001) reported that addition of manure and fertilizers enhanced microbial biomass and mineralizable C. In Japan, Aoyama and Kumakura (2001) observed that continuous application of cattle manure enhanced SOC concentration by 30% compared with equivalent NPK treatment.

5. Farming by Soil

Precision farming, farming by soil or soil-specific management, is another important strategy of decreasing losses and enhancing biomass production through alleviation of soil-related constraints (Larson and Robert, 1991). The application of nutrients and water as required for the specific soil conditions enhances use efficiency of inputs and improves crop yield. A judicious combination of integrated nutrient management and precision farming can enhance SOC concentration and improve soil quality (Leiva et al., 1997).

6. Soil Water Management

Similar to the addition of fertilizers and manures in a nutrient-depleted soil, increasing available water in the root zone of a drought-prone soil can enhance biomass production, increase the amount of above-ground and the root biomass returned to the soil and improve SOC concentration. The linear relation between biomass production and transpiration illustrates the important role of soil water. Water management in the root zone may involve soil water conservation in regions with adequate precipitation, supplemental irrigation, and water harvesting in arid and semiarid regions, and water table management in soils prone to high water table and periodic inundation. Supplemental irrigation, applied with an appropriate method at the critical time and at the desired rate, is essential for high yields in arid and semi-arid regions. In addition, enhancing irrigation efficiency can also decrease the hidden C costs (Sauerbeck, 2001; Andrews et al., 2002). In Texas, Bordovsky et al. (1999) observed that surface SOC concentration in plots with irrigated grain sorghum and wheat increased with time. Irrigation can also enhance SOC concentration in grassland. Conant et al. (2001) observed an increase in SOC pool by irrigation and reported that conversion of cultivation to grassland, introduction of earthworms, and the use of irrigation resulted in strong increases in SOC. In New Zealand, Barkle et al. (2000) reported an increase in SOC pool by land application of dairy farm effluent. Similarly, an application of long-term wastewater irrigation (up to 80 years) increased SOC concentration in Vertisols and Leptosols in the valley of Mezquital in Mexico (Friedel et al., 2000). In Vertisols, total SOC concentration increased 2.5-fold after 80 years of irrigation.

In addition to SOC, irrigation can also impact SIC dynamics, while ground water brought to the surface may release CO_2, use of good-quality irrigation water may also sequester SIC through leaching. The formation of secondary carbonates, aided by the activity of soil fauna (e.g., termites, earthworms), is an important process of SIC sequestration (Monger and Gallegos, 2000). Pedogenic carbonates formed from base-rich bedrocks or noncarbonate sediments are a sink, while those formed in calcareous parent material are not. The rates of pedogenic carbonate formation in arid climates are low, ranging from <0.1 to 15 g $CaCO_3/m^2/yr$ (Moner and Gallegos, 2000). There are two mechanisms of formation of secondary carbonates: abiotic and biotic. Biogenic carbonates are formed by activity of microorganisms, termites, and earthworms. In irrigated land with partial or complete soil leaching, the major mechanism of sequestering SIC is via movement of HCO_3 into ground waters. Some historic rates of SIC sequestration are 0.25 to 1.0 Mg C/ha/yr (Wilding, 1999).

While irrigation is essential to obtaining high yields in drought-prone soils, excessive and inappropriate irrigation can also cause rise of the water table, waterlogging, and salinization. Indeed, secondary salinization is a serious problem in irrigated agriculture (Postel, 1999; Oldeman, 1994; Babev, 2000). Risks of secondary salinization are greatly enhanced in soils with restricted surface or subsoil drainage and with poor quality of irrigation water (Gupta and Abrol, 1990; Rengesamy, 1998). Soil salinization reduces biomass productivity and decreases SOC pool. In contrast, reclamation of salt-affected soils can improve soil quality, increase biomass productivity, and enhance SOC pool.

7. Restoration of Degraded Soils

Restoration of degraded soils and ecosystems has a high potential of soil C sequestration. Most degraded soils have lost a large fraction of the antecedent SOC pool, which can be restored through adoption of judicious land use. Accelerated erosion (wind, water, and tillage) is the predominant soil degradative process (Oldeman, 1994; Lobb et al., 2000). The adoption of conservation effective measures can reduce erosion-induced emission of CO_2. In addition, the restoration of degraded soils can restore the depleted SOC pool. The Conservation Reserve Program (CRP) in the U.S. has been effective in reducing the sediment load and enhancing SOC pool. The rate of SOC sequestration under CRP may be 600 to 1000 kg C/ha/yr (Follett et al., 2001) In addition to erosion, other soil-degradative processes include nutrient depletion, acidification, compaction, and salinization (Lal et al., 1998b). The alleviation of soil-related constraints to biomass production can improve soil quality and increase SOC pool. In addition to applying nutrients in soils of low fertility and lime in acid soils, afforestation through establishing appropriate woody shrubs and trees is a widely applicable restorative measure. Garg (1998) monitored changes in properties of a sodic soil under four different tree species in north-central India. There was a marked increase in SOC concentration. The SOC pool increased from <10 Mg C/ha to about 45 Mg C/ha over an 8–year period under different tree species. Similarly, Bhojvaid and Timmer (1998) reported a large increase in SOC concentrations by reclamation of sodic soils in Haryana, India. With establishment of *Prospopis juliflora*, the SOC pool to 1.2 m depth increased from 11.8 Mg C/ha to 13.3 Mg C/ha in 5 years, 34.2 Mg C/ha in 7 years and 54.3 Mg C/ha in 30 years with an average rate of increase of 1.4 Mg C/ha/yr over a 30–year period.

Afforestation, however, may not always enhance SOC pool. In New Zealand, Groenendijk et al. (2002) reported that afforestation of pastures with radiata pine (*Pinus radiata*) decreased SOC concentration by 15% to a depth of 12 to 18 cm. These researchers concluded that afforestation of hill country pasture soils resulted in net mineralization of SOC pool. In 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 with pasture and Eucalyptus plantation. In Shropshire, U.K., Fullen (1998) observed that mean SOC concentration increased consistently and significantly on the set-aside plots under grass ley system at the rate of 0.78% in 4 years.

8. Management of Grazing Land

Grazing lands cover a large area worldwide. Land degradation and desertification are serious problems on grazing lands, especially in regions prone to excessive and uncontrolled grazing. Grazing lands in arid and semiarid regions are susceptible to both wind and water erosion. Desertification control can enhance soil quality and improve SOC pool. Several studies conducted in the Amazon Basin have shown that when forest is cleared and converted to pasture, the SOC content in surface layers often increase beyond that observed in the original forest within 10 years (Chone, 1991; Bonde et al., 1992; Cerri et al., 1992; Fiegl et al., 1995). Conversion to pasture may also increase the overall quality of surface soils. Follett et al. (2001) estimated that U.S. grazing lands have a potential to sequester 30 to 110 Tg of C/yr. Conant et al. (2001) outlined processes and practices of SOC sequestration in grasslands and observed that improving grazing land has a potential to sequester 0.54 Mg C/ha/yr. Conant and colleagues concluded that grasslands can act as a significant C sink with the implementation of improved management. Technological options to enhance SOC pool include nutrient management, growing appropriate species, fire management, controlled grazing, and restoring degraded soils. With a total global grazing land area of 3.46 billion ha and mean SOC sequestration rate of 0.54 Mg C/ha/yr, the potential of SOC sequestration in grazing land is 1.87 Pg C/yr.

9. Urban Forestry

Urban forestry is an important land use in North America, Europe, and elsewhere in developed countries. The transformation of landscapes from nonurban to urban land use has the potential to drastically alter the SOC pool and fluxes. Urban trees can play an important role in sequestering atmospheric CO_2 (Nowak, 1993). Analyzing soils from urban-rural land use gradient, Pouyat et al. (2002) observed higher SOC densities in urban than in suburban and rural lands. Preserving SOC at watershed level may also involve a judicious use of urban organic wastes (Binder and Patzel, 2001). Nowak and Crane (2002) reported that urban trees in the conterminous USA currently store 700 Tg of C with a grass sequestration rate of 22.8 Tg C/yr.

VII. IMPORTANCE OF SECONDARY CARBONATES IN SOIL CARBON SEQUESTRATION

The formation of secondary carbonates or PIC in soils of dry regions is a mechanism of SIC sequestration. The formation of PIC can also happen in soils of the humid regions (Schaetzl et al., 1986) and in other soil moisture and pedologic conditions (Khokhlova et al., 1997; Chen, 1997; Sharma and Tandon, 1983; Knuteson et al., 1989). However, some researchers argue that the rate of sequestration is too small to be of any consequence in mitigating the climate change. Schlesinger (1997) estimated that the magnitude of SIC flux with the atmosphere is low at about 0.023 Pg C/yr. Others (Monger et al., 2000; Nordt et al., 2000) argue that PIC formation is an important mechanism of SIC sequestration to mitigate climate change. Because of the long turnover time, however, the formation of PIC can be important over a long period of time. In addition to the long turnover time, another reason for the debate lies in the difficulty in identification of PICs from LICs (Rabenhorst et al., 1984). The formation of PIC depends on land use and soil/vegetation management practices. Soil management practices with notable effect on PIC formation include irrigation, addition of biosolids or manures, soil fertility management, soil and water conservation, enhancing soil biodiversity, etc. (Lal and Kimble, 2000). In some soils and ecosystems, the formation of PICs has an important impact on the C cycle and must be accounted for.

VIII. CARBON SEQUESTRATION IN SOILS OF THE TROPICS

Tropical soils generally have as much or more organic matter than their temperate counterparts (Moraes et al., 1995), and 32% of the global SOC pool is contained in soils of the tropics (Eswaran et al., 1993). If well managed, soils of the tropics could be large sinks for atmospheric C (Lugo and Brown, 1993; Lal, 2002). Basic principles of SOC sequestration are similar in soils of the tropics and temperate regions. However, the rates of SOC sequestration are generally lower in the tropics compared with soils of the temperate zone because of high temperatures and the attendant microbial activity throughout the year (Lal, 2002), and there may be differences in specific C fractions involved (Bayer et al., 2001). In highly weathered tropical soils, rates of C loss by cultivation are many times faster than those for temperate soils (Shang and Tiessen, 1997), leading to a rapid degradation in soil quality. Cadisch et al.

(1996) observed that losses of rainforest-derived C amounted to 73% (0 to 2 cm) and 40% (5 to 15 cm) of the initial SOC concentration after 18 years of conversion to pasture. Luizao et al. (1992) observed that soil biomass C in 0 to 5 cm depth decreased to 64% within 1 year of slash-and-burn. Further, soils with predominantly low-activity clays (e.g., Kaolinite) have low surface area, low CEC, low water- and nutrient-holding capacities and low ability to sequester C. Soil organic matter in many tropical soils may be less stable with high turnover rate than that of temperate soils due to a faster decomposition process (Jenkinson and Ayanaba, 1977) but also due to different mechanisms of organo-mineral stabilization (Shang and Tiessen, 1998).

In addition to differences in biophysical conditions, there are also differences in socioeconomic, cultural, and the human dimensions factors. Because of low external input and low productivity, organic input in many tropical farming systems may be of low quality and insufficient quantity. Besides, crop residues and other biosolids (e.g., cattle dung) are used for numerous other purposes (e.g., fuel, fodder, construction material, etc.), and materials good for enhancing short-term soil fertility may not build or maintain the desired level of SOC pool. Therefore, it may be difficult to identify practically feasible techniques of maintaining SOC pool in the African context where the need for short-term productivity increase takes precedence over long-term SOC enhancement (Palm et al., 2001). In low-resource agriculture, such as in sub-Saharan Africa, the strategy is to balance nutrients and SOC pool. In such situations, improved systems of SOC management include agroforestry, cover crops, and manuring (Ganry et al., 2001). In sloping lands where soil erosion is severe, using green hedgerows along contour lines and intercropping with legume species to cover the soil can decrease erosion and enhance SOC pool (Dang and Klinnert, 2001). Planting appropriate cover crops can be important to alleviating soil compaction, improving soil structure, and enhancing the SOC pool. In the Santa Cruz region of Bolivia, Barber and Navarro (1994) observed that grasses (e.g., Tobiata, Centenario, and Brizantha) were most promising for increasing SOC concentration. In the humid tropical region of Cameroon, Koutika et al. (2001) observed that *Pueraria phaseoloides* (Kudzu) and *Mucuna utilis* (velvet bean) enhanced the quality of particulate organic matter (POM).

Tropical forest ecosystems account for 20 to 25% of the world terrestrial (soil and vegetation) C (Dixon et al., 1994). Tropical deforestation is a principal source of CO_2, accounting for 20% of the annual global emissions (IPCC, 2001). Bernoux et al. (2001) estimated CO_2 emissions from mineral soils following land cover change in Brazil. The net emission of C was 25.4 Tg C/yr for the period 1970 to 1990 and 12.7 Tg C/yr for the period 1975 to 1995. The reduction in emission from 1990 to 1995 may be due to adoption of conservation tillage and other sustainable management practices.

Similar to the soils of the temperate regions, SOC sequestration rate can be improved by adopting improved rotations/cropping systems (rather than monoculture) and incorporating specific cover crops within the rotation cycle. In Francophone, Africa, Roose and Barthes (2001) observed that soil fertility is closely linked to the SOC pool whose status depends on input or biomass management. Considering social habits, Roose and Barthes recommended balancing grazing-manuring and mulching with minimum tillage. In southern Senegal, Fernandez et al. (2000) observed SOC dynamics in a 90–year-old cropping system study on a Haplic Acrisol. An annual application of 10 Mg/ha of dry matter of manure, combined with fertilizer, markedly increased SOC pool. On a Vertisol in central India, Kundu et al. (2001) observed that the application of farmyard manure increased SOC concentration at the rate of 18.1% of the annual gross C input. Also in India, Swarup et al. (2000) reported that an improvement in SOC level is possible with an increase in productivity through added nutrients in intensive cropping systems. High fertilizer application rates and manuring increases root biomass, thereby distributing SOC deeper in the soil. The SOC pool can also be enhanced by adding biosolids such as compost, manure, green manure, crop residues, etc.

No till farming is another option for enhancing the SOC pool in soils of the tropics. It is rapidly being adopted in the rice-wheat belt of the

Indo-Gangetic Plains. The soil data show a gradual improvement in SOC concentration over time (Hobbs et al., 1997). No till farming is also the preferred technique of seedbed preparation in intensive mechanized farming in Brazil, Argentina, and other regions of South America primarily because of cost reduction and soil erosion control (Machado and Silva, 2001). On a Paleudult in southern Brazil, Bayer et al. (2000) observed that adding crop residues with no till farming increased SOC pool in 0 to 17.5 cm depth. No tillage, combined with crop rotation and cover crops, leads to an increase in SOC pool in the surface soil layers. Bayer et al. (2001) observed that cropping systems that included cover crops increased SOC pool in both particulate and mineral-associated soil organic matter. Also in southern Brazil, Sa et al. (2001) observed high rates of SOC sequestration under on-farm conditions after conversion of plow till to no till system of seedbed preparation. The SOC sequestration rate for no till was 806 kg C/ha/yr for 0 to 20 cm depth and 994 kg C/ha/yr for 0 to 40 cm depth. The no till SOC sequestration potential for south Brazil with relatively high rainfall of 1500 mm/yr was 9.4 Tg C/yr.

Factors affecting rate of SOC sequestration are similar in soils of the tropics as those in temperate environments. Soil texture plays an important role in the below ground C storage in the lowland Amazonian forest ecosystem (Silver et al., 2000). The effect of texture on SOC storage is related to its impact on ability of soils to retain C, water, and nutrients and on soil air permeability for gaseous exchange. Soil texture alters the biogeochemical cycling of important elements (e.g., C, N, P, S) and H_2O. In addition to particle size, crystallinity of Fe oxides and of microaggregation between oxides, organic matter, and other minerals is important in tropical soils (Shang and Tiessen, 1998). Bayer et al. (2001) observed a negative relationship between decay rates of soil organic matter and the concentration of Fe oxides and Kaolinite, indicating that physical stability of SOC is caused by interaction with variable charge minerals. Maintaining any vegetation cover with a deep root system is important to providing a permanent input of organic matter into deep soil layers (Sommer et al., 2000). The conversion of forest to annuals, with a shallow root system, can cause significant losses of SOC pool. Similar to soils of the temperate region, there is a strong linkage between availability of N, P, and S and SOC pool (Lilienfein et al., 2001).

IX. THE POTENTIAL OF WORLD SOILS TO SEQUESTER CARBON

There are several national and global estimates of soil C sequestration (Dumanski et al., 1998; Lal et al., 1999). Gupta and Rao (1994) estimated that present SOC pool in 329 Mha in soils of India at 24.3 Pg can be increased to 34.9 Pg by soil restoration and the adoption of recommended agricultural practices. Smith et al. (1997) estimated that the adoption of improved soil management and conversion of agriculturally marginal soils to restorative land uses in Europe has a potential to provide net sink for as much as 1.2% to 1.9% of the world's annual CO_2 release in the 1990s. Lal (2001) estimated the potential of world cropland soils to sequester C at the rate of 0.4 to 0.8 Pg/yr. In addition, desertification control has a potential to sequester 0.2 to 0.4 Pg C/yr (without considering erosion control and biofuel offset). Therefore, total potential of soil C sequestration may be 0.6 to 1.2 Pg C/yr. There is also a large potential of grassland management (Conant et al., 2001), most of which has been included in desertification control. Squire et al. (1995) estimated that world's drylands occupy 6.2 billion ha (41% of the worlds land area) and have the potential to sequester 1.0 Pg C/yr through desertification control. Based on these potentials, the global C budget can be computed. Thus, soil C sequestration would increase the oceanic/land uptake by an additional 0.9 ± 0.3 Pg C/yr for about 50 years with accumulative sink capacity of 30 to 60 Pg. These assessments contradict those by Schlesinger and Andrews (2000), who argue that large increases in the soil C pool seems unlikely.

Realization of this vast potential, however, depends on a coordinated effort at local, regional, national, and global levels. While the potential of SOC sequestration is much higher in impoverished and degraded soils of the developing than developed countries, realization of this potential is also very challenging because of weak institutions, the lack of relevant research information, and lack of appropriate policy instruments that encourage farmers to adopt recommended land use and soil/vegetation management practices.

X. THE WAY FORWARD

There are several options of mitigating the threat of climate change. These options include reducing emission and/or sequestering atmospheric C. Reducing emissions involve finding non-carbon sources of fuel and improving energy use efficiency. Sequestering atmospheric C has abiotic and biotic options. Abiotic options involve capturing, compressing, transporting, and injecting CO_2 emitted by point sources into geological strata, saline aquifers, and oceans (Halman and Steinberg, 1999; DOE, 1999). This option has a vast capacity but is very expensive. Biotic options involving capturing atmospheric CO_2 through photosynthesis and storing the biomass thus produced as forest products with long turnover time, peat in wetlands of the Boreal/Tundra and other regions, or storing it in soil as SOC or humus. Battelle (2000) reported that sequestration of SOC is the most cost-effective and a feasible option for the first half of the 21^{st} century until alternatives to fossil fuel take effect. Indeed, SOC sequestration, because of its economics and numerous ancillary benefits for the environment, is a win-win strategy.

In addition to decreasing the rate of enrichment of atmospheric concentration of CO_2, enhancement of the SOC pool would improve soil quality and agronomic/biomass productivity. Increasing SOC in agricultural and degraded soils could offset emissions of CO_2 from fossil fuel combustion, in the context of the Kyoto Protocol. In addition to the policy issues involved in facilitating adoption of recommended agricultural practices, it is also important to develop systems of trading C as a marketable commodity. 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) will be needed to meet the food demands of the growing population regardless of the threat of global warming. Further, adoption of recommended management practices would lead to 10 to 40% reduction of the present agricultural energy requirements (Sauerbeck, 2001). Adopting recommended management practices is necessitated for the need to produce food, and SOC sequestration is a byproduct or an ancillary benefit of this activity. Because loss of SOC and decline in soil structure and overall degradation of the soil resources are standard features of nonsustainable land use (Carter, 2002), adopting sustainable land use practices would improve soil quality and sequester C. The fact that sequestered C spends a relatively long time in soil (Swift, 2001), it is withheld in the soil pool and decreases the rate of enrichment of atmospheric CO_2 concentration.

The potential of SOC sequestration is finite. Therefore, it is only a short-term solution. The long-term solution lies in developing alternatives to fossil fuel. Yet, SOC sequestration buys us time during which alternatives to fossil fuel can take effect. It is a bridge to the future. It also leads to improvement in soil quality. Thus, it is a truly win-win strategy. The SOC sequestration is needed regardless of the risks of global warming. The SOC has been depleted from past land misuse, and it is something that we cannot afford not to do for the environment and our quality of life.

REFERENCES

Alvarez, R., Russo, M.E., Prystupa, P., Scheiner, J.D., and Blotta, L. 1998. Soil carbon pools under conventional and no-tillage systems in the Argentine Rolling Pampa. *Agric. J.* **90**: 138–143.

Andrews, S.S., Mitchell, J.P., Mancinelli, R., Karlen, D.L., Hartz, T.K., Horwath, W.R., Pettygrove, G.S., Scow, K.M., and Munk, D.S. 2002. On-farm assessment of soil quality in California's central valley. *Agron. J.* **94**: 12–23.

Aoyama, M. and Kumakura, N. 2001. Quantitative and qualitative changes of organic matter in an Ando soil induced by mineral fertilizer and cattle manure applications for 20 years. *Soil Sci. Plant Nut.* **47**: 241–252.

Babev, A.G. (Ed.) 2000. *Desert Problems and Desertification in Central Asia*. Springer-Verlag, Berlin, 293pp.

Barber, R.G. and Navarro, F. 1994. Evaluation of the characteristics of 14 cover crops used in a soil rehabilitation trial. *Land Deg. Rehab.* **5**: 201–214.

Barkle, G.F., Stenger, R., Singleton, P.L., and Painter, D.J. 2000. Effect of regular irrigation with dairy farm effluent on soil organic matter and soil microbial biomass. *Aust. J. Soil Res.* **38**: 1087–1097.

Batjes, N.H. 1996. The total C and N in soils of the world. *Europ. J. Soil Sci.* **47**: 151–163.

Battelle 2000. Global energy technology strategy: addressing climate change. Initial findings from an international public-private collaboration, Washington, D.C., 60pp.

Bayer, C., Mielniczuk, J., Amado, T.J.C., Martin-Neto, L., and Fernandes, S.V. 2000. Organic matter storage in a sandy loam Acrisol affected by tillage and cropping systems in southern Brazil. *Soil Till. Res.* **54**: 101–109.

Bayer, C., Martin-Neo, L., Mielniczuk, J., and Ceretta, C.A. 2000. Effect of no-till cropping systems on soil organic matter in a sandy clay loam Acrisol from Southern Brazil monitored by electron spin resonance and nuclear magnetic resonance. *Soil Till. Res.* **53**: 95–104.

Bayer, C., Martin-Neto, L., Mielniczuk, J., Pillon, C.N., and Sangoi, L. 2001. Changes in soil organic matter fractions under subtropical no-till cropping systems. *Soil Sci. Soc. Am. J.* **65**: 1473–1478.

Bergstrom, D.W., Monreal, C.M., and St. Jacques, E. 2001. Influence of tillage practice on carbon sequestration is scale-dependent. *Can. J. Soil Sci.* **81**: 63–70.

Bernoux, M., Carvalho, M.D.C.S., Volkoff, B., and Cerri, C.C. 2001. CO_2 emission from mineral soils following land-cover change in Brazil. *Global Change Biol.* **7**: 779–787.

Bezdicek, D.F., Papendick, R.I., and Lal, R. 1996. Importance of soil health to sustainable land management. **In:** *Methods for Assessing Soil Quality*. pp.1–8. Doran, J.W., and Jones, A.J., Eds., Soil Sci. Soc. Am. Special Publ. #49, Madison, WI.

Bhojvaid, P.P. and Timmer, V.R. 1998. Soil dynamics in an age sequence of *Prosopis juliflora* planted for sodic soil restoration in India. *For. Ecol. Manage.* **106**: 181–193.

Binder, C. and Patzel, N. 2001. Preserving tropical soil organic matter at watershed level. A possible contribution of urban organic wastes. *Nut. Cycl. Agroeco.* **61**: 171–181.

Bonde, T.A., Christensen, B.T., and Cerri. C.C. 1992. Dynamics of soil organic matter as reflected by natural ^{13}C abundance in particle size fractions of forested and cultivated Oxisols. *Soil Biol. Biochem.* **24**: 275–277.

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

Bowman, R.A. and Halvorson, A.D. 1998. Soil chemical changes after 9 years of differential N fertilization in a not ill dryland wheat-corn fallow rotation. *Soil Sci.* **163**: 241–247.

Bowman, R.A., Vigil, M.F., Nielsen, D.C and Anderson, R.L. 1999. Soil organic matter changes in intensively cropped dryland systems. *Soil Sci. Soc. Am. J.* **63**: 186–191.

Buresh, R.J. and Tian, G. 1997. Soil improvement by trees in sub-Saharan Africa. *Agrofor. Syst.* **38**: 51–76.

Buringh, P. 1984. Organic carbon in soils of the world. **In:** *The Role of Terrestrial Vegetation in the Global Carbon Cycle: Measurement by Remote Sensing*. pp. 91–109. Woodwell, G.M., Ed., Wiley, New York.

Burke, I.C., Lauenroth, W.K., and Coffin, D.P. 1995. Soil organic matter recovery in semi-arid grasslands-implications for the conservation reserve program. *Eco. Appl.* **5**: 793–801.

Cadisch, G., Imhof, H. Urquiaga, S., Boddey, R.M., and Giller, K.E. 1996. Carbon turnover ($\delta^{13}C$) and nitrogen mineralization potential of particulate light soil organic matter after rainforest clearing. *Soil Biol. Biochem.* **28**: 1555–1567.

Carter, M.R. 2002. Soil quality for sustainable land management: organic matter and aggregation interactions that maintain soil functions. *Agron. J.* **94**: 38–47.

Cerri, C.C., Moraes, J.F.l., and Volkoff, B. 1992. Dinâmica do carbono orgânico em solos vinculados a pastagents da Amazônia Brasileira. Rev. INIA Inv. Agr. No. 1, Tomo I: 95–102.

Chan, K.Y., Bowman, A.M., Smith, W., and Ashley, R. 2001. Restoring soil fertility of degraded hard-setting soils in semi-arid areas with different pastures. *Aust. J. Exp. Agric.* **41**: 507–514.

Chen, X.Y. 1997. Pedogenic gypcrete formation in arid central Australia. *Geoderma* **77**: 39–61.

Chonè, T., Correa, A.F., Volkoff, J.C., and Cerri, C.C. 1991. Changes in organic matter in an Oxisol from the Central Amazon forest during eight years as pastures, determined by ^{13}C isotopic composition. **In**: *Diversity of Environmental Biogeochemistry*, Berthelin, M., Ed., pp. 397–405, Elsevier, Holland.

Christensen, B.T. 1996. The Askov long-term experiment on animal manures and mineral fertilizers. **In:** *Evaluation of Soil Organic Matter: Models Using Existing Datasets*. pp. 301–312. Powlson, D.S., Smith, P., and Smith, J.U., Eds., Springer, Heidelberg, NATO/ASI 138.

Compton, J.E. and 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., and Elliott, E.T. 2001. Grassland management and conversion into grassland: effects on soil carbon. *Ecol. Appl.* **11**: 343–355.

Condron, L.M., Cameron, K.C., Di, H.J., Clough, T.J., Forbes, E.A., McLaren, R.G., and Silva, R.G. 2000. A comparison of soil and environmental quality under organic and conventional farming systems in New Zeal. *New Zealand J. Agric. Res.* **43**: 443–466.

Curtin, D., Wang, H., Selles, F., Zentner, R.P., Biederbeck, V.O., and Campbell, C.A. 2000a. Legume green manure as partial fallow replacement in semi-arid

Saskatchewan: Effect on carbon fluxes. *Can. J. Soil Sci*. **80**: 499–505.

Curtin, D., Selles, F., Wang, H., Zentner, R.P., and Campbell, C.A. 2000b. Restoring organic matter in a cultivated, semi-arid soil using crested wheatgrass. *Can. J. Soil Sci*. **80**: 429–435.

Curitn, D., Wang, H., Selles, F., McConkey, B.G., and Campbell, C.A. 2000c. Tillage effects on carbon fluxes in continuous wheat and fallow-wheat rotations. *Soil Sci. Soc. Am J*. **64**: 2080–2086.

Dang, N.T. and Klinnert, C. 2001. Problems with and local solutions for organic matter management in Vietnam. *Nut. Cycl. Agroeco*. **61**: 89–97.

De Jong, E. and Kachanoski, R.G. 1988. The importance of erosion in the carbon balance of prairie soils. *Can. J. Soil Sci*. **68**: 111–119.

Del Grosso, S., Ojima, D., Parton, W., Mosier, A., Peterson, G., and Schimel, D. 2002. Simulated effects of dryland cropping intensification on soil organic matter and greenhouse gas exchanges using the DAYCENT ecosystem model. *Env. Poll*. **116**: S75–S83.

Department of Energy. 1999. Carbon Sequestration: Research and Development. Office of Science, Office of Fossil Energy, Springfield, VA.

Dersch, G. and Böhm, K. 2001. Effects of agronomic practices on soil carbon storage potential in arable farming in Austria. *Nutr. Cycl. Agroecosys*. **60:** 49–55.

Diaz-Zorita, M. Buschiazzo, D.E., and Peinemann, N. 1999. Soil organic matter and wheat productivity in the semi-arid Argentine Pampas. *Agron. J*. **91**: 276–279.

Dick, W.A., Blevins, R.L., Frye, W.W., Peters, S.E., Christenson, D.R., Pierce, F.J., and Vitosh, M.L. 1998. Impacts of agricultural management practices on C sequestration in forest-derived soils of the eastern Corn Belt. *Soil Till. Res*. **47**: 235–244.

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., and Wisniewski, J. 1994. Carbon pool and flux of global forest ecosystems. *Science* **263**: 1985–1990.

Doran, J.W. and Parkin, T.B. 1994. Defining and assessing soil quality. **In:** *Defining Soil Quality for a Sustainable Environment*. pp. 3–21. Doran, J.W., Coleman, D.C., Bezdicek, D.F., and Stewart, B.A., Eds., Soil Sci. Soc. Amer. Special Publ. #35, Madison, WI.

Drinkwater, L.E., Wagoner, P., and Sarrantonio, M. 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. *Nature* **396**: 262–265.

Dumanski, J., Desjardins, R.L., Tarnocai, C., Montreal, C., Gregorich, E.G., Kirkwood, V., and Campbell, C.A. 1998. Possibilities for future carbon sequestration in Canadian agriculture in relation to land use changes. *Climatic Change* **40**: 81–103.

Entry, J.A., Mitchell, C.C., and Backman, C.B. 1996. Influence of management practices on soil organic matter, microbial biomass and cotton yield in Alabama's "Old Rotation," *Biol. Fert. Soils* **23**: 353–358.

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

Eswaran, H., Van den Berg, E., Reich, P., and Kimble, J.M. 1995. Global soil carbon resources. **In:** *Soils and Global Change*. pp. 27–43. Lal, R., Kimble, J.M., Levine, E., and Stewart, B.A., Eds., CRC/Lewis Publishers, Boca Raton, FL.

Etheridge, D.M., Steele, L.P., Langenfelds, R.L., Francey, R.J., Barnola, J.-M., and Morgan, V.I. 1996. Natural and anthropogenic changes in atmospheric CO_2 over the last 1000 years from air in Antarctic ice and fern. *J. Geophys. Res*. **101**: 4115–4128.

Fausey, N.R. and Lal, R. 1989. Drainage-tillage effects on Crosby-Kokomo soil association in Ohio. III. Organic matter content and chemical properties. *Soil Technol*. **5**: 1–12.

Feigl, B.J., Melillo, J., and Cerri, C.C. 1995. Changes in the origin and quality of soil organic matter after pasture introduction in Rondonia, Brazil. *Plant Soil* **175**: 21–29.

Fernandez, P., Oliver, R., and Diatta, S. 2000. Changes in organic mater of a ferrallitic tropical soil degraded by cropping systems: the case of Southern Senegal. *Arid Soil Res. Rehab*. **14**: 137–150.

Folland, C.K. and Karl, T.R. 2001. Observed climate variability and change. **In:** *Climate Change 2001: The Scientific Basis*. pp. 99–181. Intergovernmental Panel on Climate Change, Cambridge Univ. Press, U.K.

Follett, R.F. 2001. Soil management concepts and carbon sequestration in cropland soils. *Soil Tillage Res*. **61:** 77–92.

Follett, R.F., Samson-Liebig, E., Kimble, J.M., Pruessner, E.G., and Waltman, S. 2001. Carbon sequestration under CRP in the historic grassland soils of the U.S. **In:** *Soil Carbon Sequestration and the Greenhouse Effect*. pp. 27–40. Lal, R., Ed., Soil Sci. Soc. Amer. Special Publ. #57, Madison, WI.

Follett, R.F., Kimble, J.M., and Lal, R. 2001. The potential of U.S. grazing lands to sequester soil carbon. **In:** *The Potential of U.S. Grazing Land to Sequester Carbon and Mitigate the Greenhouse Effect*. pp. 401–430. Follett, R.F., Kimble, J.M., and Lal, R., Eds., CRC/Lewis Publishers, Boca Raton, FL.

Franzluebbers, A.J., Haney, R.L., Honeycutt, C.W., Arshad, M.A., Schomberg, H.H., and Hons, F.M. 2001. Climatic influences on active fractions of soil organic matter. *Soil Biol. Biochem*. **33**: 1103–1111.

Franzluebbers, A.J., Stuedemann, J.A., and Wilkinson, S.R. 2001. Bermudagrass management in the southern piedmont USA. I. Soil and surface residue carbon and sulfur. *Soil Sci. Soc. Am. J*. **65**: 834–841.

Freixo, A.A., Machado, P.L.O.D., dos Santos, H.P., Silva, C.A., and Fadigas, F.D. 2002. Soil organic carbon and fractions of a Rhodic Ferralsol under the influence of tillage and crop rotation systems in southern Brazil.

Friedel, J.K., Langer, T., Siebe, C., and Stahr, K. 2000. Effects of long-term wastewater irrigation on soil organic matter, soil microbial biomass and its activities in central Mexico. *Biol. Fert. Soils* **31**: 414–421.

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 Till. Res.* **46**: 41–49.

Ganry, F., Feller, C., Harmand, J.M., and Guiber, H. 2001. Management of soil organic matter in semi-arid Africa for annual cropping systems. *Nut. Cycl. Agroeco.* **61**: 105–118.

Garg, V.K. 1998. Interaction of tree crops with a sodic soil environment: potential for rehabilitation of degraded environments. *Land Degrad. Dev.* **9**: 81–93.

Gewin, V.L., Kennedy, A.C., Veseth, R., and Miller, B.C. 1999. Soil quality changes in eastern Washington with Conservation Reserve Program (CRP) take out. *J. Soil Water Cons.* **54**: 432–438.

Gilley, J.E. and Risse, L.M. 2000. Runoff and soil loss as affected by the application of manure. *Trans. ASAE* **43**: 1583–1588.

Glaser, B., Lehmann, J., Fuhrboter, M., Solomon, D., and Zech, W. 2001. Carbon and nitrogen mineralization in cultivated and natural savanna soils of Northern Tanzania. *Biol. Fert. Soils* **33**: 301–309.

Govers, G., Vandaele, K., Desmet, P.J.J., Poesen, J., and Bunte, K. 1994. The role of tillage in soil redistribution on hillslopes. *Europ. J. Soil Sci.* **45**:469–478.

Graham, M.H., Haynes, R.J., and 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 Biol. Biochem.* **34**: 93–102.

Grant, C.A., Peterson, G.A., and Campbell, C.A. 2002. Nutrient considerations for diversified cropping systems in northern Great Plains. *Agron. J.* **94**: 186–198.

Gregorich, E.G. and 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., and Liang, B.C. 1998. Carbon distribution and losses: erosion and deposition effects. *Soil Till. Res.* **47**: 291–302.

Gregorich, E.G., Drury, C.F., and Baldock, J.A. 2001. Changes in soil carbon under long-term maize in monoculture and legume-based rotation. *Can. J. Soil Sci.* **81**: 21–31.

Groenendijk, F.M., Condron, L.M., and Rijkse, W.C. 2002. Effects of afforestation on organic carbon, nitrogen and sulfur concentrations in New Zealand hill country soils. *Geoderma* **108**: 91–100.

Guillaume, K., Abbadie, L., Mariotti, A., and Nacro, H. 1999. Soil organic matter dynamics in tiger bush (Niamey, Niger). Preliminary results. *Acta Oecologica-International J. Ecol.* **20**: 185–195.

Gupta, R.K. and Abrol, I.P. 1990. Salt-affected soils: their reclamation and management for crop production. *Adv. Soil Sci.* **11**: 224–288.

Gupta, R.K. and Rao, D.L.N. 1994. Potential of wastelands for sequestering carbon by reforestation. *Curr. Sci.* **66**: 378–380.

Hairiah, K., Van Noordwijk, M., and Cadisch, G. 2000. Crop yield, C and N balance of three types of cropping systems on an Ultisol in Northern Lampung. *Netherlands J. Agric. Sci.* **48**: 3–17.

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

Hao, X., Change, C., and Lindwall, C.W. 2001. Tillage and crop sequence effects on organic carbon and total nitrogen content in an irrigated Alberta soil. *Soil Till. Res.* **62**: 167–169.

Harvell, C.D., Mitchell, C.E., Ward, J.R., Altizer, S., Dobson, A.P., Ostfeld, R.S., and Samuel, M.D. 2002. Climate warming and disease risks for terrestrial and marine biota. *Science* **296**: 2158–2162.

Havlin, J.L., Kissel, D.E., Maddux, L.D., Claassen, M.M., and Long, J.H. 1990. Crop rotation and tillage effects on soil organic carbon and nitrogen. *Soil Sci. Soc. Am. J.* **54:** 448–452.

Himes, F.L. 1998. Nitrogen, sulfur and phosphorus and the sequestering of carbon. **In**: *Soil Processes and the Carbon Cycle*, pp. 315–319, Lal, R., Kimble, J.M., Follett, R.F., and Stewart, B.A., Eds., CRC, Boca Raton, FL.

Hobbs, P.R., Tiri, G.S., and Grace, P. 1997. Reduced and zero tillage options for the establishment of wheat after rice in South Asia. Rice-Wheat Consortium Paper #2, CIMMYT, Mexico.

Houghton, R.A. 1999. Changes in the storage of terrestrial carbon since 1850. **In:** *Soils and Global Change*. pp. 45–65. Lal, R., Kimble, J.M., Levine, E., and Stewart, B.A., Eds., CRC/Lewis Publishers, Boca Raton, FL.

Houghton, R.A. 1999. The annual net flux of carbon to the atmosphere from changes in land use 1850 to 1990. *Tellus* **50B**: 298–313.

Houghton, R.A., Hackler, J.L., and Lawrence, K.T. 1999. The U.S. carbon budget: contributions from land use change. *Science* **285**: 574–578.

Houghton, R.A., Lawrence, K.T., Hackler, J.L., and Brown, S. 2001. The spatial distribution of forest biomass in the Brazilian Amazon: A comparison of estimates. *Global Change Biol.* **7**: 731–746.

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

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, U.K.

Izaurralde, R.C., McGill, W.B., Robertson, J.A., Juma, N.G., and Thurston, J.J. 2001. Carbon balance of the Breton Classical Plots over half a century. *Soil Sci. Soc. Am. J.* **65**: 431–441.

Jackson, R.B., Banner, J.L., Jobbagy, E.B., Pockman, W.T., and Wall, D.H. 2002. Ecosystem carbon loss with woody plant invasion of grasslands. *Nature* **418**: 623–626.

Jenkinson, D.S. 1990. The turnover of organic carbon and nitrogen in soil. *Phil. Trans. Royal Soc. London Bull.* **329**: 361–368.

Jenkinson, D.S. and Ayanaba, A. 1977. Decomposition of ^{14}carbon labeled plant material under tropical conditions. *Soil Sci. Soc. Am. J.* **41**: 912–915.

Jenny, H. 1941. *Factors of Soil Formation: A System of Quantitative Pedology*. McGraw-Hill Book Co., Inc., New York, 281pp.

Jenny, H. 1980. *Soil Resource: The Origin and Behavior.* Ecol. Studies 37, Springer Verlag, New York.

Jenny, H. and Raychaudhuri, S.P. 1960. *Effect of Climate and Cultivation on Nitrogen and Organic Matter Reserves in Indian Soils.* ICAR, New Delhi, India.

Kay, B.D. 1998. Soil structure and organic carbon: a review. **In:** *Soil Processes and the Carbon Cycle*, pp. 169–197, Lal, R., Kimble, J.M., Follett, R.F., and Stewart, B.A., Eds, CRC Press, Boca Raton, FL.

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

Khokhlova, O.S., Arlashina, E.A., and Kovalevskaya, I.S. 1997. The effect of irrigation on the carbonate status of Chernozems of Central Precaucasus (Russia). *Soil Tech.* **11:** 171–184.

Knuteson, J.A., Richardson, J.L., Patterson, D.D., and Prunty, L. 1989. Pedogenic carbonates in a Calciaquoll associated with a recharge wetland. *Soil Sci. Soc. Am. J.* **53:** 495–499.

Kolka, R.K., Nelson, E.A., and Trettin, C.C. 2000. Conceptual assessment framework for forested wetland restoration: the Pen Branch experience. *Ecol. Eng.* **15**: S17–S21.

Korschens, M. and Muller, A. 1996. The static experiment at Bad Lauchst, Germany. **In:** *Evaluation of Soil Organic Matter: Models Using Existing Datasets*. pp. 369–378. Powlson, D., Smith, P., and Smith, J.U., Eds., Springer Heidelberg, NATO ASI 138.

Koutika, L.S., Hauser, S., and Henrot, J. 2001. Soil organic matter assessment in natural regrowth, Pueraria phaseoloids and Mucuna pruriens fallow. *Soil Bio. Biochem.* **33**: 1095–1101.

Kucharik, C.J., Brye, K.R., Norman, J.M., Foley, J.A., Gower, S.T., and Bundy, L.G. 2001. Measurements and modeling of carbon and nitrogen cycling in agroecosystems of southern Wisconsin: potential for SOC sequestration during the next 50 years. *Ecosystems* **4**: 237–258.

Kundu, S., Singh, M., Saha, J.K., Biswas, A., Tripathi, A.K., and Acharya, C.L. 2001. Relationship between C addition and storage in a Vertisol under soybean-wheat cropping system in subtropical central India. *J. Plant Nut. Soil Sci.* **164**: 483–486.

Kushwaha, C.P., Tripathi, S.K., and Singh, K.P. 2001. Soil organic matter and water-stable aggregates under different tillage and residue conditions in a tropical dryland agroecosystem. *Appl. Soil Ecol.* **16**: 229–241.

Lal, R. 1976. *Soil Erosion Problems on Alfisols in Western Nigeria and Their Control*. IITA Monograph 1, IITA, Ibadan, Nigeria, 208pp.

Lal, R. 1997a. Degradation and resilience of soils. *Phil. Trans. Royal Soc. London B*. **352**: 957–1010.

Lal, R. 1997b. Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO_2 enrichment. *Soil Tillage Res*. **43**: 81–107.

Lal, R. 1999. Soil management and restoration for C sequestration to mitigate the accelerated greenhouse effect. *Prog. Env. Sci*. **1**: 307–326.

Lal, R. 2000. World cropland soils as a source or sink for atmospheric carbon. *Adv. Agron*. **71**: 145–191.

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

Lal, R. 2002. The potential of soils of the tropics to sequester carbon and mitigate the greenhouse effect. *Adv. Agron*. **74**: 155–192.

Lal, R. and Kimble, J.M. 2000. Pedogenic carbonates and the global carbon cycle. **In:** *Global Climate Change and Pedogenic Carbonates*, pp. 1–13, Lal, R., Kimble, J.M., Eswaran, H., and Stewart, B.A., Eds., CRC/Lewis Publishers, Boca Raton, FL.

Lal, R., Hall, G.F., and Miller, F.P. 1989. Soil degradation. I. Basic processes. *Land Degrad. Rehab.* **1**: 51–69.

Lal, R., Blum, W.H., Valentine, C., and Stewart, B.A., Eds. 1998. *Methods for Assessment of Soil Degradation*. pp. 558. CRC/Lewis Publishers, Boca Raton, FL.

Lal, R., Follett, R.F., Kimble, J.M., and Cole, C.V. 1999. Managing U.S. cropland to sequester C in soil. *J. Soil Water Conserv*. **54**: 374–381.

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

Larson, W.E. and Robert, P.C. 1991. Farming by soil. **In:** *Soil Management for Sustainability,* pp. 103–111, Lal, R. and Pierce, F.J., Eds, Soil Water Conserv. Soc., Ankeny, IA.

Lavelle, P. 2000. Ecological challenges for soil science. *Soil Sci*. **165**: 73–86.

Leiva, F.R., Morris, J., and Blackmore, B.S. 1997. Precision farming techniques for sustainable agriculture. Proc. First European Conference on Precision Agriculture, Warwick, Sept. 8–10, 1997: 957–966.

Lilienfein, J., Wilcke, W., Thomas, R., Vilela, L., Lima, S.D.C., and Zech, W. 2001. Effects of *Pinus caribaea* forests on the C, N, P and S status of Brazilian savanna Oxisols. *Forest Ecol. Manage*. **147**: 171–182.

Lindstrom, M.J., Nelson, W.W., and Schumacher T.E. 1992. Quantifying tillage erosion rates due to moldboard plowing. *Soil Tillage Res.* **24**: 243–255.

Lobb, D.A. and Kachanoski, R.G. 1999. Modelling tillage translocation using steppe, near plateau, and exponential functions. *Soil Tillage Res.* **51**:261–277.

Lobb, D.A., Kachanoski, R.J., and Miller, M.H. 1995. Tillage translocation and tillage erosion on shoulder slope landscape positions measured using l37cesium as a tracer. *Can. J. Soil Sci.* **75**: 211–218.

Lobe, I., Amelung, W., and DuPreez, C.C. 2001. Losses of carbon and nitrogen with prolonged arable cropping from sandy soils of the South African Highveld. *Eur. J. Soil Sci.* **52**: 93–101.

Lugo, A.E. and Brown, S. 1993. Management of tropical soils as sinks or sources of atmospheric carbon. *Plant Soil* **149**: 27–41.

Luizao, R.C.C., Bonde, T.A., and Rosswell, T. 1992. Seasonal variation of soil microbial biomass: the effects of clearing a tropical rainforest and establishment of pasture in the Central Amazon. *Soil Biol. Biochem.* **24**: 805–813.

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

Machado, P.L.O.D., and Silva, C.A. 2001. Soil management under no tillage systems in the tropics with special reference to Brazil. *Nut. Cycl. Agroeco.* **61**: 119–130.

Mäder, P., Fließach, A., Dubois, D., Gunst, L., Fried, P., and Niggli, U. 2002. Soil fertility and biodiversity in organic farming. *Science* **296**: 1694–1697.

Malhi, S.S., Nyberg, M., Harpiak, J.T., Heier, K., and Flore, N.A. 1997. Increasing organic carbon and nitrogen under brome grass with long-term N fertilization. *Nutr. Cycl. Agroeco.* **49:** 155–160.

Marland, G., Anders, R.J., Boden, T.A., Johnston, C., and 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.

Marquez, C.O., Cambardella, C.A., Isenhart, T.M., and Schultz, R.C. 1998. Assessing soil quality in a riparian buffer by testing organic matter fractions in central Iowa, USA. *Agrofor. Syst.* **44**: 133–140.

Mendes, I.C., Bandick, A.K., Dick, R.P., and Bottomley, P.J. 1999. Microbial biomass and activities in soil aggregates affected by winter cover crops. *Soil Sci. Soc. Am. J.* **63**: 873–881.

Mitchell, C.C. and Entry, J.A. 1998. Soil C, N and crop yields in Alabama's long-term 'Old rotation' cotton experiment. *Soil Till. Res.* **47**: 331–338.

Monger, H.C. and 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:** *Global Climate Change and Pedogenic Carbonates*, pp. 273–289, Lal, R., Kimble, J.M., Eswaran, H., and Stewart, B.A., Eds., CRC/Lewis Publishers, Boca Raton, FL.

Monreal, C.M., Zentner, R.P., and Robertson, J.A. 1997. An analysis of soil organic matter dynamics in relation to management, erosion and yield of wheat in long-term crop rotation plots. *Can. J. Soil Sci.* **77**: 553–563.

Moraes, J.L., Cerri, C.C., Melillo, J.M., Kicklighter, D., Neill, C., Skola, D.L., and Steudler, P.A. 1995. Soil carbon stocks of the Brazilian Amazon Basin. *Soil Sci. Soc. Am. J.* **59:** 244–247.

Mosier, A.C., Kroeze, C., Nevison, C., Oenema, O., Seitziner, S., and Van Cleemput, O. 1998. Closing the global N_2O budget: N_2O emissions through the agricultural nitrogen cycle – OECD/IPCC/IEA Phase II development of IPCC guidelines for national greenhouse gas inventory methodology. *Nutrient Cycling in Agroecosystems* **52**: 225–248.

Mrabet, R., Saber, N., El-Brahli, A., Lahlou, S., and Bessam, F. 2001. Total, particulate organic matter and structural stability of a Calcixeroll soil under different wheat rotations and tillage systems in a semi-arid area of Morocco. *Soil Till.* Res. **57**: 225–235.

N'Dayegamiye, A. and Tran, T.S. 2001. Effects of green manures on soil organic matter and wheat yields and N nutrition. *Can. J. Soil Sci.* **81**: 371–382.

Neue, H.-U. and Sass, R. 1998. The budget of CH_4 from rice fields. *IG Activities newsletter* **12**: 3–11.

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

Nordt, L.C., Wiliding, L.P., and Drees, L.R. 2000. Pedogenic carbonate transformations in leaching soil systems: implications for the global carbon cycle. **In:** *Global Climate Change and Pedogenic Carbonates*, pp. 43–63, Lal, R., Kimble, J.M., Eswaran, H., and Stewart, B.A., Eds., CRC/Lewis Publishers, Boca Raton, FL.

Novotny, E.H., Blum, W.E.H., Gerzabek, M.H., and Mangrich, A.S. 1999. Soil management system effects on size fractionated humic substances. *Geoderma* **92**: 87–109.

Nowak, D.J. 1993. Atmospheric carbon reduction by atmospheric trees. *J. Environ. Manage.* **37**: 207–212.

Nowak, D.J. and Crane, D.E. 2002. Carbon storage and sequestration by urban trees in the USA. *Environ. Pollut.* **116**: 381–389.

Nyakatawa, E.Z., Reddy, K.C., and Sistani, K.R. 2001. Tillage, cover cropping and poultry letter effects on selected soil chemical properties. *Soil Till Res.* **58**: 69–79.

Oberthür, S. and Ott, H.E. 2000. *The Kyoto Protocol: International Climate Policy for the 21st Century.* Springer-Verlag, Berlin.

Odell, R.T., Meisted, S.W., and Walker, W.M. 1984. Changes in organic carbon and nitrogen of Morrow plots soils under different treatments. 1904–1973. *Soil Sci.* **137**: 160–171.

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

Palm, C.A., Giller, K.E., Mafongoya, P.L., and Swift, M.J. 2001. Management of organic matter in the tropics: translating theory into practice. *Nut. Cycl. Agroeco.* **61**: 63–75.

Papendick, R.I. and Parr, J.F. 1997. No till farming: the way of the future for a sustainable dryland agriculture. *Annals Arid Zone* **36**: 193–208.

Paul, E.A., Collins, H.P., and Leavitt, S.W. 2001. Dynamics of resistant soil carbon of midwestern agricultural soils measured by naturally occurring ^{14}C abundance. *Geoderma* **104**: 239–256.

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

Peck, T.R. 1989. Morrow plots-long term University of Illinois field research plots 1876–present. **In:** *Proceedings of the Sanborn Field Centennial: A celebration of 100 years of agricultural research*, pp. 49–52, Brown, J.R., Ed., Presented June 27, 1989 at the Jesse Wrench auditorium, Univ. of Missouri, Columbia, Publ. SRA15.

Poesen, J., Wesenael, B., Govers, O., Martinez-Fernadez, J., Desmet, B., Vandaele, K., Quine, T., and Degraer, G. 1997. Patterns of rock fragment covered generated by tillage erosion. *Geomorphology* **18**: 193–197.

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

Postel, S. 1999. *Pillars of Sand: Can the Irrigation Miracle Last?* W.W. Norton, New York.

Pouyat, R., Groffman, P., Yesilonis, I., and Hernandez, L. 2002. Soil carbon pools and fluxes in urban ecosystems. *Env. Poll.* **116**: S107–S118.

Prather, M. and Ehhalt, D. 2001. Atmospheric chemistry and greenhouse gases. **In:** *Climate Change 2001: The Scientific Basis*. pp. 239–287. Intergovernmental Panel on Climate Change, Cambridge Univ. Press, U.K.

Prentice, I.C. 2001. The carbon cycle and the atmospheric carbon dioxide. **In:** *Climate Change 2001: The Scientific Basis*. pp. 204–237. Intergovernmental Panel on Climate Change, Cambridge Univ. Press, U.K.

Pulleman, M.M., Bouma, J., van Essen, E.A., and Meijles, E.W. 2000. Soil organic matter content as a function of different land use history. *Soil Sci. Soc. Am. J.* **64**: 689–693.

Quansah, C., Drechsel, P., Yirenkyi, B.B., and Asante-Mensah, S. 2001. Farmers' perceptions and management of soil organic matter – a case study from west Africa. *Nut. Cycl. Agroeco.* **61**: 205–213.

Rabenhorst, M.C., Wilding, L.P., and West, L.T. 1984. Identification of pedogenic carbonates using stable carbon isotope and microfabric analyses. *Soil Sci. Soc. Am. J.* **48:** 125–131.

Ramaswamy, V. 2001. Radiative forcing of climate change. **In:** *Climate Change 2001: The Scientific Basis*, pp. 349–416, IPCC, Cambridge Univ. Press.

Rasmussen, P.E. and Smiley, R.W. 1989. Long-term management effects on soil productivity and crop yield in semi-arid regions of eastern Oregon. Station Bull. 675. USDA-Agriculture Research Service and Agriculture Experiment Station, Oregon State University. 58 pages.

Rasmussen, P.E. and Parton, W.J. 1994. Long-term effects of residue management in wheat-fallow. I. Inputs, yield and soil organic matter. *Soil Sci. Soc. Am. J.* **58**: 523–S30.

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

Reeder, J.D., Schuman, G.E., and Bowman, R.A. 1998. Soil C and N changes on conservation reserve program lands in the Central Great Plains. *Soil Till. Res.* **47**: 339–349.

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

Rengasamy, P. 1998. Sodic soils. **In:** *Methods for Assessment of Soil Degradation*, pp. 265–276, Lal, R., Blum, W.H., Valentine, C., and Stewart, B.A., Eds., CRC/Lewis Publishers, Boca Raton, FL.

Ridley, A.M., Slattery, W.J., Helyer, K.R., and Cowling, A. 1990. The importance of the carbon cycle to acidification of the grazed pasture. *Aust. J. Exp. Agric.* **30**: 539–594.

Rillig, M.C., Wright, S.F., Allen, M.F., and Field, C.B. 1999. Rise in carbon dioxide changes soil structure. *Nature* **400**: 628.

Rillig, M. C., Wright, S.F., and Eviner, V.T. 2002. The role of arbuscular mycorrhizal fungi and glomalin in soil aggregation: comparing effects of five plant species. *Plant Soil* **238**: 325–333.

Rillig, M.C., Wright, S.F., Kimball, B.A., Pinter, P.J., Wall, G.W., Ottman, M.J., and Leavitt, S.W. 2001. Elevated carbon dioxide and irrigation effects on water stable aggregates in a Sorghum field: a possible role for arbuscular mycorrhizal fungi. *Global Change Biol.* **7**: 333–337.

Rillig, M.C., Hernandez, G.Y., and Newton, P.C.D. 2000. Arbuscular mycorrhizae respond to elevated atmospheric $C0_2$ after long-term exposure: evidence from a $C0_2$ spring in New Zealand supports the resource-balance model. *Ecol. Lett.* **3**: 475–478.

Ritchie, J.C. and Rasmussen, P.E. 2000. Application of ^{137}cesium to estimate erosion rates for understanding soil carbon loss on long-term experiments at Pendleton, Oregon. *Land Deg. Dev.* **11**: 75–81.

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

Robinson, C.A., Cruse, R.M., and Ghaffarzadeh, M. 1996. Cropping system and nitrogen effects on Mollisol organic carbon. *Soil Sci. Soc. Am. J.* **60**: 264–269.

Robles, M.D. and Burke, I.C. 1997. Legume, grass and conservation reserve program effects on soil organic matter recovery. *Ecol. Appl.* **7**: 345–357.

Robles, M.D. and Burke, I.C. 1998. Soil organic matter recovery on conservation reserve program fields in southeastern Wyoming. *Soil Sci. Soc. Am. J.* **62**: 725–730.

Roose, E. and Barthes, B. 2001. Organic matter management for soil conservation and productivity restoration in Africa: a contribution from Francophone research. *Nut. Cycl. Agroeco.* **61**: 159–170.

Sa, J.C. de M., Cerri, C.C., Dick, W.A., Lal, R., Filho, S.P.V., Piccolo, M.S., and Fiegl, B.V. 2001. Organic matter dynamics and carbon sequestration rates in a no-tillage chronosequence in a Brazilian Oxisol. *Soil Sci. Soc. Am. J.* **65**: 1486–1499.

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

Sass, R.L., Fisher, F.M., Jr., Ding, A., and Huang, Y. 1999. Exchange of CH_4 from rice fields: national, regional and global budgets. *J. Geophys. Res.* **104**: 26943–26951.

Sauerbeck, D.R. 2001. CO_2 emissions and C sequestration by agriculture – perspectives and limitations. *Nut. Cycl in Agroeco.* **60**: 253–266.

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

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

Schjonning, P., Christensen, B.T., and Christensen, B. 1994. Physical and chemical properties of a sandy loam soil receiving animal manure, mineral fertilizer or no fertilizer for 90 years. *Eur. J. Soil Sci.* **45**: 257–268.

Schlesinger, W.H. 1995. Soil respiration and changes in soil carbon stocks. **In:** *Biotic Feedback in Global Climatic System: Will the Warming Feed the Warming?* pp. 159–168, Woodwell, G.M. and Mackenzie, F.T., Eds., Oxford Univ. Press, New York.

Schlesinger, W.H. 1997. *Biogeochemistry: An Analysis of Global Change*. 2nd ed., Academic Press, San Diego, CA, 588pp.

Schlesinger, W.H. 2000. Carbon sequestration in soils: some cautions amidst optimism. *Agric. Eco. Env.* **82**: 121–127.

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

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

Schumacher, T.E., Lindstrom, M.J., Schumacher, J.A., and Lemme, O.O. 1999. Modelling spatial variation and productivity due to tillage and water erosion. *Soil Tillage Res.* **51**: 331–339.

Shang, C. and Tiessen, H. 1997. Organic matter lability in a tropical Oxisol: evidence from shifting cultivation, chemical oxidation, particle size density and magnetic fractionations. *Soil Sci.* **162**: 795–807.

Shang, C. and Tiessen, H. 1998. Organic mater stabilization in two semi-arid tropical soils: size, density and magnetic separations. *Soil Sci. Soc. Am. J.* **62:** 1247–1257.

Sharma, R. and Tandon, S.K. 1983. Comparative petrology of pedogenic carbonates from quarternary deposits of Kashmir and Rajisthan. *J. Geol. Soc. India* **24:** 399–403.

Shaver, T.M., Peterson, G.A., Ahuja, L.R., Westfall, D.G., Sherrod, L.A., and Dunn, G. 2002. Surface soil physical properties after twelve years of dryland no till management. *Soil Sci. Soc. Am. J.* **66**: 1296–1303.

Shen, H., Xu, Z.H., and Yan, X.L. 2001. Effect of fertilization on oxidizable carbon, microbial biomass carbon, and mineralizable carbon under different agroecosystems. *Comm. Soil Sci. Plant Anal.* **32**: 1575–1588.

Silver, W.L., Neff, J., McGroddy, M., Veldkamp, E., Keller, M., and Cosme, R. 2000. Effects of soil texture on below ground carbon and nutrient storage in a lowland Amazonian forest ecosystem. *Ecosystems* **3**: 193–209.

Skjemstad, J.O., Dalal, R.C., Janik, L.J., and McGowan, J.A. 2001. Changes in chemical nature of soil organic carbon in Vertisols under wheat in southeastern Queensland. *Aust. J. Soil Res.* **39**: 343–359.

Skjemstad, J.O., Reicosky, D.C., Wilts, A.R., and McGowan, J.A. 2002. Charcoal carbon in U.S. agricultural soils. *Soil Sci. Soc. Am. J.* **66**: 1949–1255.

SkØien, S. 1993. Long-term effects of crop rotation, manure and straw on soil aggregation. *Norw. J. Agric. Sci.* **7:** 231–247.

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

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

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. Cycl.* **15**: 697–707.

Sokolov, V.I. 1999. Integrated water resources management in the Republic of Uzbekistan. International Water Resources Association. *Water Int.* **24**: 104–115.

Sommer, R., Denich, M., and Vlek, P.L.G. 2000. Carbon storage and root penetration in deep soils under small-farmer land-use systems in the Eastern Amazon region. *Plant Soil* **219**: 231–241.

Sommerfeldt, T.G., Chang, C., and Entz, T. 1988. Long-term annual manure applications increase soil organic matter and nitrogen and decrease carbon to nitrogen ratio. *Soil Sci. Soc. Am. J.* **52**: 1668–1672.

Squires, V.R., Glenn, E.P., and Ayoub, A.T., Eds. 1995. *Combating Global Climate Change by Combating Land Degradation.* UNEP, Nairobi, Kenya, 347pp.

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

Sullivan, M., Fausey, N.R., and Lal, R. 1998. Long-term effects of sub-surface drainage on soil organic carbon content and infiltration in the surface horizons of a lakebed soil in northwest Ohio. **In:** *Management of Carbon Sequestration in Soil,* pp. 73–82, Lal, R., Kimble, J.M., Follett, R.F., and Stewart, B.A., Eds., CRC/Lewis Publishers, Boca Raton, FL.

Swarup, A., Manna, M.C., and Singh, G.B. 2000. Impact of land use and management practices on organic carbon dynamics in soils of India. **In:** *Global Climate Change and Tropical Ecosystems*, pp. 261–281, Lal, R., Kimble, J.M., and Stewart, B.A., Eds., CRC/Lewis Publishers, Boca Raton, FL.

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

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

Uhlen, G. and Tveitnes, S. 1995. Effect of long-term crop rotations, fertilizer, farm manure and straw on soil productivity. II. Mineral composition of plants, nutrient balances and effect on soil. *Norw. J. Agric. Sci*. **9**: 143–161.

Uri, N.D. 2001. Conservation practices in US agriculture and their impact on carbon sequestration. *Env. Monit. Assess*. **70**: 323–344.

Van den Bygaart, A.J., Yang, X.M., Kay, B.D., and Aspinall, J.D. 2002. Variability in carbon sequestration potential in no till soil landscapes of southern Ontario. *Soil Till. Res*. **65**: 231–241.

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

Vanotti, M.B., Bundy, L.G., and Peterson, A.E. 1997. Nitrogen fertilizer and legume cereal rotation effects on soil productivity and organic matter dynamics in Wisconsin. **In**: *Soil Organic Matter in Temperate Agroecosystems: Long-Term Experiments in North America*, pp. 105–119, Paul, E.A. et al., Eds., CRC Press, Boca Raton, FL.

Vitosh, M.L., Lucas, R.E., and Silva, G.H. 1997. Long-term effects of fertilizer and manure on corn yield, soil carbon and other soil chemical properties in Michigan. **In:** *Soil Organic Matter in Temperate Agroecosystems: Long-Term Experiments in North America,* pp. 129–139, Paul, E.A. et al., Eds., CRC Press, Boca Raton, FL.

Wagner, G.H. 1959. Lessons in soil organic matter from Sanborn field. **In***: Proceedings of the Sanborn Field Centennial: A celebration of 100 years of agricultural research*, pp. 64–70, Brown, J.R. Ed., Presented June 27, 1989 at the Jesse Wrench auditorium, Univ. of Missouri, Columbia. Pubi. SR-415.

Wagner, G.H. 1981. Humus under different long-term cropping Systems. Colloque Humus-Azote p.23–29. Presented in Reims, France.

Wallace, A. 1994. Soil organic matter must be restored to near original levels. *Comm. Soil Sci. Plant Analyses* **25**: 29–35.

Wander, M.M., Bidar, M.G., and Aref, S. 1998. Tillage impacts on depth distribution of total and particulate organic matter in three Illinois soils. *Soil Sci. Soc. Am. J*. **62**: 1704–1711.

Waters, A.G. and Oades, G.M. 1991. Organic matter in water stable aggregates. **In:** *Advances in Soil Organic Matter Research: The Impact of Agriculture and the Environment*, pp. 163–174, Wilson, W.S., Ed., Roy. Soc. Chem., Cambridge, U.K.

West, T.O. and Marland, G. 2002. Net carbon flux from agricultural ecosystems: methodology for full carbon cycle analyses. *Env. Poll*. **116**: 439–444.

Wienhold, B.J. and Tanaka, D.L. 2001. Soil property changes during conversion from perennial vegetation to annual cropping. *Soil Sci. Soc. Am. J.* **65**: 1795–1803.

Wilding, L.P. 1999. Comments on paper by R. Lal. **In:** *Carbon Sequestration in Soils: Science, Monitoring and Beyond,* pp. 146–149, Rosenberg, N.A., Izaurralde, R.C., and Malone, E.L., Eds., Battelle Press, Columbus, OH.

Wilson, T.C., Paul, E.A., and Harwood,R.R. 2001. Biologically active soil organic matter fractions in sustainable cropping systems. *Appl. Soil Ecol*. **16**: 63–76.

Witter, E., Mortensson, A.M., and Garcia, F.V. 1993. Size of the microbial mass in a long-term field experiment as affected by different N fertilizers and organic manures. *Soil Biol. Biochem*. **28**: 659–669.

Wright, S. F. and Upadhyaya, A. 1998. A survey of soils for aggregate stability and glomalin, a glycoprotein produced by hyphae of arbuscular mycorrhizal fungi. *Plant Soil* **198**: 97–107.

Wright, S.F., Starr, J.L., and Paltineanu, I.C. 1999. Changes in aggregate stability and concentration of glomalin during tillage management transition. *Soil Sci. Soc. Am. J*. **63**: 1825–1829.

Wright, S F. and Anderson, R.L. 2000. Aggregate stability and glomalin in alternative crop rotations for the central Great Plains. *Biol. Fert. Soils* **31**: 249–253.

Zaujec, A. 2001. Soil organic matte as indicator of soil quality and human influences on agroecosystem and natural forest ecosystem. *Ekologia-Bratislava* **20**: 133–139.

Zech, W. and Guggenberger, G. 1996. Organic matter dynamics in forest soils of temperate and tropical ecosystems. **In:** *Humic Substances in Terrestrial Ecosystems,* pp. 101–170, Piccolo, A., Ed., Elsevier Science, Amsterdam, The Netherlands.