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TECHNICAL ARTICLES

SOIL CARBON SEQUESTRATION TO MITIGATE CLIMATE CHANGE AND ADVANCE FOOD SECURITY

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World soils have been a source of atmospheric carbon dioxide since the dawn of settled agriculture, which began about 10 millennia ago. Most agricultural soils have lost 30% to 75% of their antecedent soil organic carbon (SOC) pool or 30 to 40 t C ha^{-1}. The magnitude of loss is often more in soils prone to accelerated erosion and other degradative processes. On a global scale, CO_2-C emissions since 1850 are estimated at 270 ± 30 giga ton (billion ton or Gt) from fossil fuel combustion compared with 78 ± 12 Gt from soils. Consequently, the SOC pool in agricultural soils is much lower than their potential capacity. Furthermore, depletion of the SOC pool also leads to degradation in soil quality and declining agronomic/biomass productivity. Therefore, conversion to restorative land uses (e.g., afforestation, improved pastures) and adoption of recommended management practices (RMP) can enhance SOC and improve soil quality. Important RMP for enhancing SOC include conservation tillage, mulch farming, cover crops, integrated nutrient management including use of manure and compost, and agroforestry. Restoration of degraded/desertified soils and ecosystems is an important strategy. The rate of SOC sequestration, ranging from 100 to 1000 kg ha^{-1} year^{-1}, depends on climate, soil type, and site-specific management. Total potential of SOC sequestration in the United States of 144 to 432 Mt year^{-1} (288 Mt year^{-1}) comprises 45 to 98 Mt in cropland, 13 to 70 Mt in grazing land, and 25 to 102 Mt in forestland. The global potential of SOC sequestration is estimated at 0.6 to 1.2 Gt C year^{-1}, comprising 0.4 to 0.8 Gt C year^{-1} through adoption of RMP on cropland (1350 Mha), and 0.01 to 0.03 Gt C year^{-1} on irrigated soils (275 Mha), and 0.01 to 0.3 Gt C year^{-1} through improvements of rangelands and grasslands (3700 Mha). In addition, there is a large potential of C sequestration in biomass in forest plantations, short rotation woody perennials, and so on. The attendant improvement in soil quality with increase in SOC pool size has a strong positive impact on agronomic productivity and world food security. An increase in the SOC pool within the root zone by 1 t C ha^{-1} year^{-1} can enhance food production in developing countries by 30 to 50 Mt year^{-1} including 24 to 40 Mt year^{-1} of cereal and legumes, and 6 to 10 Mt year^{-1} of roots and tubers. Despite the enormous challenge of SOC sequestration, especially in regions of warm and arid climates and predominantly resource-poor farmers, it is a truly a win-win strategy. While improving ecosystem services and ensuring sustainable use of soil resources, SOC sequestration also mitigates global warming by offsetting fossil fuel emissions and improving water quality by reducing nonpoint source pollution. (Soil Science 2007;172:943–956)

Key words: Global warming, soil quality, soil degradation, conservation tillage, biofuel, nonpoint source pollution.

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ATMOSPHERIC concentration of several greenhouse gases (GHG) has changed drastically since the industrial revolution because of fossil fuel combustion, cement manufacturing, land use change, and the attendant agricultural practices, such as plowing, biomass burning, use of fertilizers, and manure. The concentration of CO_2, responsible for 62% of the total radiative forcing by Earth, has increased by 35% from 280‰ around 1750 to 377‰ in 2004. It is presently increasing at the rate of 1.8‰ or 0.47% year^{-1} (WMO, 2006). Principal sources of CO_2 in 2005 were fossil fuel combustion (7 giga ton or billion ton or Gt year^{-1}) and tropical deforestation (0.6–2.5 Gt year^{-1}). Since 1958, about 55% of the CO_2 emitted by fossil fuel combustion has been absorbed into the atmosphere (WMO, 2006). Total CO_2-C emitted by anthropogenic activities between 1850 and 2000 is estimated at 270 + 30 Gt by fossil fuel combustion and 136 ± 55 Gt by land use change and deforestation (IPCC, 1999; 2001). The concentration of methane (CH_4), responsible for 20% of the radiative forcing of the Earth, has increased by 155% from about 700 ppb around 1750 to 1783 ppb in 2004. It is presently increasing at the rate of 5 to 13 ppb year^{-1} (WMO, 2006). Principal anthropogenic sources of CH_4 are fossil fuel exploitation, rice paddy cultivation, ruminant animals, biomass burning, and land fills. The atmospheric concentration of nitrous oxide (N_2O), responsible for about 6% of the radiative forcing of the Earth, has increased by 18% from about 270 ppb around 1750 to 318.6 ppb in 2004 (WMO, 2006). It is presently increasing at the rate of 0.8 ppb year^{-1}. Anthropogenic sources of N_2O are fertilizer use, biomass burning, and industrial processes.

Soil cultivation is not as obvious a source of atmospheric CO_2 as are fossil fuel combustion, deforestation, and biomass burning. Yet, world soils have been a dominant source of CO_2 ever since the dawn of settled agriculture (Ruddiman, 2003; 2005). In contrast, soils can also be a major sink of atmospheric CO_2 with adoption of recommended management practices (RMP). Thus, the objective of this article is to describe the importance of world soils as source and sink of GHG, outline processes and practices that make soil a sink for atmospheric CO_2, and describe ancillary benefits and ecosystem services enhanced by soil quality improvement through C sequestration in soil.

WORLD SOILS AND CLIMATE CHANGE

Principal global C pools comprise oceanic (38,000 Gt), geologic (4,130 Gt), pedological (2,500 Gt), atmospheric (760 Gt), and biotic (560 Gt). These pools are interconnected with sizeable fluxes among them (Table. 1). For example, the atmospheric pool is increasing at the rate of 3.3 Gt C year^{-1}. The oceanic pool is absorbing about 92 Gt C year^{-1} and emitting 90 Gt year^{-1}, with a net gain of 2 Gt year^{-1}. The biotic pool photosynthesizes 120 Gt C year^{-1} from the atmospheric pool, of which 60 Gt C year^{-1} is returned to the atmosphere through plant respiration and the remaining 60 Gt C year^{-1} by soil respiration.

World soils or the pedological pool comprises two distinct components: soil organic carbon (SOC) and soil inorganic carbon (SIC) pools estimated at 1576 Gt and 938 Gt to 1-m depth, respectively (Post et al., 1982; Schlesinger, 1995; Eswaran et al., 1993). The SOC pool is concentrated in soils of arctic, boreal, and temperate regions, and the SIC pool in those of arid and semiarid climates (Table 2). The SOC pool includes highly active humus and relatively inert charcoal C (Schnitzer, 1991; Stevenson, 1994; Wagner, 1981; Paul and Clark, 1996). The SIC pool includes elemental C and carbonate minerals, such as calcite, dolomite, and gypsum. There are two types of carbonates in soils: primary or lithogenic carbonates and secondary or pedogenic carbonates (Lal et al., 2000; Lal, 2004a).

TABLE 1

Global carbon pool and fluxes among them

Pool	Reservoir (Gt)	Flux (Gt C year^{-1})
Oceanic	3800	90-92 months the atmospheric
Geologic	2500	7.4 to the atmospheric pool
Coal	1550	
Oil	950	
Gas	4130	
Others	3510	
Pedologic	250	60 months biotic and 1 month the oceanic
SOC	140	
SIC	250	
Atmospheric	760	120 months the biotic pool
Biotic	560	60 months the pedological pool

(Adapted from Batjes, 1996; Houghton, 1995; 1999; Bouwman, 1990; Eswaran et al., 1995; Sombroek, 1995; Lal, 2004a, 2004b.)

TABLE 2

Estimates of global soil C pool due to 1-m depth

Soil order	Area (10^3 km^2)	SOC Pool (Gt)	SIC Pool (Gt)
Alfisols	18,283	127	43
Andisols	2552	78	0
Aridisols	31,743	110	456
Entisols	14,921	148	263
Histosols	1745	357	0
Inceptisols	21,580	352	34
Mollisols	5480	72	116
Oxisols	11,772	119	0
Spodosols	4878	71	0
Ultisols	11,330	105	0
Vertisols	3287	19	21
Others	7644	18	5
Total	135,215	1576	938

Source: Eswaran et al., 1993; 1995; 2000; Batjes, 1996.

Under undisturbed natural conditions, the soil C pool is in equilibrium and the input of C (litter fall, root biomass, C brought in by run-on, dust) is balanced by output (erosion, decomposition, and leaching) (Lal, 2004a). Conversion of natural to agricultural ecosystems, however, typically reduces the amount of C input and increases the magnitude of output. The reduction in C input is caused by a decline in biomass production and reduction in the fraction returned to the soil. The increase in C output is attributed to increase in oxidation of soil organic matter (SOM) because of change in soil moisture and temperature regimes, and increase in losses caused by soil erosion and leaching.

Emission of CO_2 from soil-related processes began with the onset of settled agriculture about 10,000 years ago, and that of CH_4 with the cultivation of rice paddies and domestication of animals about 5000 years ago (Ruddiman, 2003; 2005). Anthropogenic disturbance of terrestrial biosphere can deplete the SOC pool (Schlesinger, 1993). Tropical deforestation continues to be a major source of CO_2 (Wallace, 2007). Soil tillage, extractive farming practices, and accelerated soil erosion cause a rapid depletion of the SOC pool. The magnitude of depletion is more in drastically disturbed soils, such as mined soils and severely eroded/gullied soils. Many cultivated soils have lost 50% to 75% of their antecedent SOC pool (Lal, 2004a). Estimates of the historic loss of SOC pool from world soils vary widely. The loss of C pool from world soils was estimated at 40 Gt by Houghton (1995), 55 Gt by IPCC (1995) and Schimel (1995), 150 Gt by Bohn (1978), 500 Gt by Wallace (1994), 537 Gt by Buringh (1984), and 320 Gt by Ruddiman (2003). Lal (1999) estimated the historic loss at 78 ± 12 Gt. The wide range in estimates of the historic loss is attributed to differences in methods used, variability in the available data, and the baseline used as a reference point. The rate of C loss from world soils caused by current land use change and soil cultivation is also variable and estimated at 0.6 to 2.6 Gt year^{-1} by Lashof and Hare (1999) and 1 to 2 Gt year^{-1} by Bohn (1978). Accelerated erosion transports a large amount of C over the landscape, of which 1 Gt C year^{-1} is emitted into the atmosphere by erosion-induced mineralization (Lal, 2003), and 0.5 Gt is deposited into aquatic ecosystems and depressional sites (Stallard, 1998).

Most prime agricultural soils have lost 30 to 50 t C ha^{-1} (Lal et al., 1998; Lal, 2004a). Such estimates of historic C loss provide a reference point with regard to the potential for C sequestration. In general, 60% to 75% (about two thirds) of the C lost can be resequestered through adoption of RMP (IPCC, 1995). In some cases, it may be possible to achieve the SOC levels in managed soil higher than those in natural ecosystems. This is possible in those ecosystems where there are severe soil-related constraints to crop production under natural conditions, and adoption of RMP can effectively alleviate them (e.g., P deficiency, Fe/Mn toxicity, low pH, drought stress) (Fisher et al., 1994; Cerri et al., 1991; Neill et al., 1997).

FUTURE CLIMATE CHANGE AND SOIL CARBON POOL

Global surface temperatures have increased by 0.4 to 0.8 °C during the 20th century. Doubling of atmospheric CO_2 concentration of the preindustrial level by 2100 is expected to increase the global temperature by 1.5 to 5.8 °C, enhance precipitation by 18.5 mm d^{-1} or by 10%, and increase sea level by 18 to 75 cm (Prentice and Fung, 1990; IPCC, 2001; 2007; Cheddadi et al., 2001; Hennessey et al., 1997). The rate of increase of global temperature has been 0.15 °C decade^{-1} since 1975. The attendant change in soil moisture and temperature regimes can alter growing season duration, species composition (Buckland et al., 2001), and net primary productivity (NPP). An increase of 1 °C in temperature would prolong the growing season by about 10 days in northern Europe and Canada (Kleemola et al., 1995), leading to introduction of new/more productive cultivars. Furthermore, the NPP may also increase because of the CO_2 fertilization effect (Sohlenius and Bostrom, 1999). In some cases, winter wheat production may increase by 10% to 20% depending on soil type and site-specific edaphic conditions (Eckersten et al., 2001). However, increase in global temperature may have a positive feedback leading to the release of large amounts of soil C from frozen or permafrost soils (Lal et al., 2000b).

Despite the increase in NPP, the SOC pool may decline with increase in mean global temperatures. There may be a net transfer of 30 to 50 Gt of terrestrial C to the atmospheric pool, equivalent of 15‰ to 25‰ of CO_2 (Prentice and Fung, 1990). Increase in soil temperature would accelerate the rate of mineralization of SOM through alteration of the decomposition processes. Yet, the by-products of decomposition produced at higher temperatures may be more recalcitrant than those at lower temperatures. Increase in soil temperature may have more drastic effects on Cryosols in higher (which represent 25% of the global SOC pool) latitudes than in soils of midlatitudes (Lal et al., 2000). Much of the C is mixed deep by cryoturbation in the permafrost soils of the cold regions. Global warming may thaw and enhance mineralization with a positive feedback. It is widely feared that Cryosols will become a major source of CO_2 with the projected increase in temperature (Sohlenius and Bostrom, 1999). Bottner et al. (1995) estimated that a 3 °C increase in temperature would cause an average altitudinal upward shift of the vegetation belts in the Mediterranean basin by 500 m. Bottner et al. (1995) also estimated that an increase in temperature would decrease the SOC pool by 28% in the hyperhumid zone, 20% in the subhumid zone, and 15% in the hyperarid warm or cool zones of the Mediterranean region. The depletion of SOC pool may be confined to the uppermost layers in soil. In Europe, Duckworth et al. (2000) predicted that a 2 °C increase in temperature would shift vegetation zones by 100 km. Theoretically, an average rise in mean annual temperature of 1 °C is the equivalent of an approximate poleward shift of vegetation zones by 200 km (Ozenda and Borel, 1990).

Decrease in the SOC pool would have adverse effects on soil quality. Reduction in aggregation may exacerbate the problem of crusting, compaction, water runoff, and erosion. Increase in losses of plant nutrients, both inherent and applied, and water would decrease use efficiency and reduce productivity. The extent and severity of soil degradation may strongly increase by physical (erosion, compaction, anaerobiosis), chemical (salinization, elemental imbalance, decline in pH and acidification), and biological (depletion of the SOC pool, shift in activity of soil flora and fauna) degradation processes.

CARBON SEQUESTRATION

The Department of Energy (2006) refers to carbon sequestration as "...the provision of long-term storage of carbon in the terrestrial biosphere, underground, or the oceans so that the buildup of CO_2 (the principal GHG) concentration in the atmosphere will reduce or slow." The C sequestration process may be naturally or anthropogenic-driven. The natural process includes terrestrial sequestration in soil (humification and formation of secondary carbonates) and trees (biomass production and storage in aboveground and below ground components). These natural processes can be managed, and their rate and magnitude can be enhanced in some ecosystems.

Geologic sequestration has received considerable attention because of its presumably large potential/capacity to store atmospheric C in diverse geologic strata (Lal, 2007). The four principal anthropogenic-driven geologic sequestration types involve injection of liquefied industrial CO_2 into: (i) porous and stable rock formations, (ii) coal seams to recover coal bed methane, (iii) old oil wells to enhance oil recovery, and (iv) saline aquifers. Geologic and oceanic sequestrations are expensive and have numerous uncertainties with regard to leakage. Carbon sequestration in humus is strongly related to soil management practices and especially to soil-conserving practices. Practices that increase SOM include: leaving crop residues in the field, choosing crop rotations that include high-residue plants, using optimal nutrient and water management practices to grow healthy plants with large amounts of roots and residues, growing cover crops, applying manure or compost, using low-or no-till (NT) systems, and mulching to help conserve the soil. Addition of manure enhances SOC pool and improves soil physical fertility (Blair et al., 2006a; 2006b). Use of organic amendments and nitrogenous fertilizers are important to enhancing SOC pool even in harsh climate of the West African Sahel (Ouédraog et al., 2006). Diversity over time can be increased by using long crop rotations (Blair et al., 2006c), especially the cereal-based cropping systems (Wang and Dalal, 2006).

Soil Quality and Soil Organic Matter

The term soil quality describes the combination of chemical, physical, and biological characteristics that enables soils to perform a wide range of functions in which SOM and soil biology play major roles (Evanylo and McGuinn, 2000). Many publications address what a healthy soil does and how to assess soil quality (Doran et al., 1994; Doran and Jones, 1996; Karlen et al., 1997; Sarrantonio et al., 1996; Anonymous, 2000).

Inherent soil quality is a soil's natural ability to function. Dynamic soil quality is the manner in which soil responds to how it is managed. Management choices affect the amount of SOM, soil structure, soil depth, and water- and nutrient-holding capacity. Soils respond differently to management depending on the inherent properties of the soil and the surrounding landscape (Andrews et al., 2006).

Soil Management and Organic Matter Depletion

Depletion of SOM is highly dependent on how soil is managed. Depletion of SOM reduces soil fertility and degrades soil physical properties such as infiltration rate, soil structure, and water-holding capacities (Houghton et al., 1983). Both the rate and extent of the decline are generally increased with increasing aridity and decreasing precipitation amounts (Stewart et al., 1991). Wilhelm et al. (2004) discussed the importance of crop residues for maintaining SOM levels, and preserving or enhancing productivity. The possibility of using crop residues as feedstock for fuel production makes the challenge of maintaining SOM levels even more daunting (Lal and Pimentel, 2007). Wilhelm et al. (2004) proposed development of a procedure (tool) for recommending maximum permissible removal rates of crop residues for ethanol production that ensure sustained soil productivity. The 25-25 goal, meeting 25% of the energy needs of the United States by 2025, is feasible only if sustainable sources of biofuel feedstocks are developed so that residues are not removed from cropland soils.

Tillage and especially bare soil conditions are the most important management practices leading to the depletion of SOM and SOC. The moldboard plow even became the centerpiece of the seal of the U.S. Department of Agriculture. However, bare soil is susceptible to wind and water erosion, drying, and crusting.

Although NT systems maximize the amounts of crop residues that remain on the soil surface, these systems are not always feasible or acceptable to producers for a variety of reasons. When NT systems are not feasible, less intensive tillage tools can be beneficial. Steiner et al. (1994) showed the percentage of residue remaining on the soil surface after a single

TABLE 3

Effect of different tillage systems on SOM, PAW water at time of wheat seeding, and yield of winter wheat at Bushland, Texas

System	SOM 1941 (%)	SOM 1970 (%)	Nitrate-N† (kg/ha)	PAW‡ (mm)	Average yield (kg/ha)	29-year yield range (kg/ha)
Continuous wheat						
One-way disk tillage§	2.44	1.61	417	91	593	0–1915
Subtilled with sweeps	2.44	2.02	179	103	694	0–2312
Wheat fallow‖						
One-way disk tillage	2.44	1.49	519	128	944	0–2427
Subtilled with sweeps	2.44	1.81	325	154	1058	0–2589
Delayed tillage with sweeps¶	2.44	2.24	88	144	1038	0–2440

†Nitrate-N in 180-cm soil profile at end of experiment.

‡Average plant-available water in 180-cm profile at seeding time.

§Winter wheat seeded at approximately October 1 and harvested at approximately July 1 of the following year.

‖Winter wheat seeded at approximately October 1 every second year with approximately 15 months fallow between crops and yields shown must be divided by two to indicate annual land production.

¶Tillage was delayed for approximately 10 months after wheat harvest with weeds and volunteer wheat being allowed to grow during the 10-month fallow period (adapted from Johnson et al., 1974).

PAW indicates plant available soil.

TABLE 4

Percentage of crop residues remaining on soil surface after different tillage operations or after surface decomposition

Tillage implement or decomposition conditions	Nonfragile crops†	Fragile crops‡
	% Residues remaining	
Tillage implement		
Moldboard plow	0–10	0–5
Disk plow	10–20	5–15
Chisel plow with straight chisel spike points	50–70	30–40
Chisel plow with sweeps	70–85	50–60
Sweep v-blade greater than 75 cm wide	85–95	70–80
Paratill/paraplow	80–90	75–85
One-way disk harrow with 30-cm spacings	40–50	20–40
Strip-tillage machines	60–75	50–60
Anhydrous ammonia applicators	75–85	45–70
Single-disk opener drills	80–100	60–80
No-till drills in standing stubble	85–95	70–85
Row planters	85–95	80–90
Decomposition during fallow period§		
Warm humid locations	65–85	60–80
Warm dry locations	70–90	65–85
Cool humid locations	70–90	65–85
Cool dry locations	75–95	75–90

†Nonfragile crops include most forage and cereal crops.
‡Fragile crops include most bean, pea, and vegetable crops.
§Loss of cover from decomposition is highly variable and depends on length of fallow, climate, crop material, and initial amount of residue.

operation (Table 3). In addition to ground cover, living cover crops provide additional organic matter and continuous cover and food for soil organisms. Chisel plows with straight spikes or sweeps are widely used where erosion is a concern to leave more residues on the surface. The percentage amounts remaining on the surface shown in Table 4 are for one operation. Thus, even with an implement that leaves 60% of the residue on the surface, little residue remains on the surface if the implement is used multiple times during the fallow period.

Potential Soil Organic Carbon Sequestration in the United States

Cropland Soils

Adoption of RMP has great potential to increase the amount of C sequestered (Cole et al., 1993; Lal et al., 1997; 1999). Carbon sequestering practices to enhance SOC sequestration on cropland include improved use of crop residues; increased use of conservation tillage or CT (especially NT), crop residue, and other biomass management approaches; reduction of fallow; use of organic materials and systems that enhance belowground root biomass including that from weeds (Follett, 2001). Cropping systems to increase SOC include the use of rotations, planting winter cover crops, and placing land into the conservation reserve program (CRP). Cropland soils in the United States have the potential to sequester 55 to 165 Mt C year^{-1} (Table 5). Pacala and Socolow (2004) estimated that conversion of all cropland to no-till has a potential C sink capacity of 1 Gt year^{-1}.

Grazing Land Soils

Grazing lands represent the largest and most diverse single land resource in the United States and in the world. Pastures and rangelands together make up about 55% of the total land surface in the United States, and more than half of the earth's surface. Grazing lands are highly diverse (Table 6, Follett and Schuman, 2005; Follett et al., 2001). Grazing lands (pastures and rangelands) in the United States are currently

TABLE 5

Selected carbon sequestering practices in the United States

Scenario	Mt C year^{-1}	Mt C year^{-1}
Tillage management/cropping systems		30.2–105.4
Conservation tillage	17.8–35.7	
Crop residue/biomass management	11–67	
Fallow reduction	1.4–2.7	
Increasing land cover		13.9–28.6
Rotations and winter cover crops	5.1–15.3	
Conservation reserve program	8.8–13.3	
Production inputs (nutrients and water)†		10.6–30.2
Fertilizer management	6–18	
Livestock manure	3.6–9.0	
Supplemental irrigation	1.0–3.2	
Total (range)‡		54.7–164.2
Average		109.4

†Neither the direct N_2O emissions resulting from N-fertilizer application nor from livestock-manures applications were calculated, but their importance is discussed by IPCC (2001) and Mosier et al. (1998). ‡These estimates of C sequestration either do not include all of the categories or estimates are different than those made by Lal et al. (1998). For example, C sequestration resulting from land and soil restoration is not included in the above estimate.

managed using relatively low rates of management inputs but high potential rates of SOC sequestration under those conditions where the use of fertilizer, pesticide, improved species can be justified economically (especially on pastureland). Arid and semiarid grazing lands have a positive potential to sequester SIC. The potential SOC sequestration for the sum of U.S. cropland and grazing lands is about 180 Mt SOC $year^{-1}$ (range, 85–275).

GHG Inventories

The Department of Energy (2006) indicates that C sequestration in some cases "...is accomplished by maintaining or enhancing natural processes...." Recent inventories indicate that total emissions from cropland agriculture from N_2O, CH_4, and CO_2 from mineral and organic soils and agricultural liming resulted in GHG emissions of 237.6 Mt CO_2 eq (64.8 Mt CO_2-C eq) in 2004 (USDA, 2007). For grazed lands, the total (not including from feedlots or from enteric fermentation) was 53 Mt CO_2 eq (14.4 Mt CO_2-C eq). Thus, the total emitted from cropland and grazed land combined was 291 Mt CO_2 eq (79.4 Mt CO_2-C eq) in 2004. By comparison, cropland soils had a net storage of 31.7 Mt CO_2 (8.6 Mt CO_2-C eq) in 2004, with mineral soils storing 66.0 Mt CO_2 eq (18.0 Mt CO_2-C eq) and organic soils and liming of soils emitting a total of 34.3 Mt CO_2 eq (9.4 Mt CO_2-C eq). For grazed lands, the net storage was 11.5 Mt CO_2 (3.1 Mt CO_2-C) in 2004 (USDA, 2007). Thus, based upon the inventory estimates, cropland and grazed land soils stored enough CO_2 to offset about 15% of the total emissions produced by cropland and grazing land agriculture in the United States. Unfortunately, net U.S. emissions continue to grow, having increased by 21% between 1990 and 2004 (to 6294 Mt CO_2 eq or 1716 Mt CO_2-C), with the energy generation and transportation sectors growing most rapidly (US EPA, 2006) and becoming ever more difficult to significantly offset these large emission loads.

TABLE 6

Pasture and rangeland management effects on soil carbon sequestration rates

Pasture lands	t C/ha $year^{-1}$†	Mt C $year^{-1}$
Unmanaged	0.05–0.2	
Improved management	0.15–0.6	
Fertility (N and lime)	0.1–0.2	
Application of CAFO manure	0.2–0.5	
Planting improved species	0.1–0.3	
From Improved practices:		10.6–34.4
Arid/semi-arid grazing lands (Mt C/ha $year^{-1}$)‡		
Shortgrass Steppe	<0.1–0.25	
Northern mixed-grass prairie	<0.25–0.5	
Northern mixed-grass prairie (fertilized)	<0.25–0.5	
Tall grass prairie with fertilization	>0.5	
Southern mixed-grass prairie	no change	
From Improved practices:		5.4–16.0
From Other lands/activities		
Land Conv. and Restoration		17.6 to 45.7
Unmanaged sequestration		(4.1) to 13.9
Total Gain		29.5 to 110.0
Average		69.8

†The data shown for pasture lands are based upon extensive and important literature citations to which the reader is referred for additional information and that are included within the book edited by Follett et al. (2001). ‡The data shown for arid and semiarid grazing lands are based upon extensive literature citations to which the reader is referred for additional information and that are included with the original article by Follett and Schuman (2005) and Follett et al. (2001).

GLOBAL ESTIMATES OF SOIL CARBON SEQUESTRATION

Global estimates of soil C sequestration range from 0.4 to 1.2 Gt C $year^{-1}$, of which 0.4 to 0.8 Gt C $year^{-1}$ is from adoption of RMP on croplands (see Fig. 1). Large areas of world soils being degraded (Oldeman, 1994), thus, desertification control and restoration of degraded soils is an important strategy to sequester C in the biosphere. Both global and national evaluations are especially important to help provide a basis for additional scientific research, to intergovernmental discussions, and for those who make policies (Lal et al., 2003). Follett and Schuman (2005) estimated the SOC sequestration rate at 0.2 Gt $year^{-1}$ on 3.5 billion ha, whereas Lal (2004a) estimated 0.1 to 0.3 Gt SOC and SIC $year^{-1}$ on 3.7 billion ha. These regional and global estimates, however, do not consider the hidden C costs of input based on fossil fuel consumption (Lal, 2004b).

LONG-TERM STORAGE OF SEQUESTRATION CARBON

Atmospheric CO_2 can be transferred into long-lived soil/pedological pools (Lal, 2005). However, soil sink capacity and permanence are related to clay content and mineralogy, structural stability, landscape position, moisture and temperature regimes, and ability to form and retain stable microaggregates (Lal, 2004a). Once sequestered, C remains in the soil as long as restorative land use, NT farming, and other RMP are followed. Another question is how long can sequestration rates for SOC additions to the soil continue? Lal et al. (1998) indicated that achieving a practical upper limit may require at least 50 years. Sá et al. (2001), for their Brazilian study, predicted that an equilibrium or steady-state level would occur 40 years after the adoption of NT with high inputs of crop residues. Qian and Follett (2002) showed that SOC sequestration in golf courses continued for up to about 31 years in fairways and 45 years in putting greens, with the most rapid increase during the first 25 to 30 years after turfgrass establishment. Thus, it can be stated that once SOC is sequestered, it remains in the soil as long as restorative land use or RMP are followed, and sequestration rates can continue for 30 and up to 50 years (Lal, 2004a).

SOIL ORGANIC CARBON AND PRODUCTIVITY

Soil degradation is the simple, greatest threat to global food production and security (Lafond et al., 2006), and the SOC pool plays an important role in sustainable use of agricultural soils (Mulongoy and Merckx, 1993). Thus, increasing SOC pool of degraded soils increases crop yields by improving soil quality through: (i) increasing available water capacity, (ii) improving supply of nutrients, and (iii) enhancing soil structure and other physical properties. There exists a strong relationship between the SOC pool and soil physical fertility (Blair et al., 2006a; 2006b). Some experiments have shown that the plant available water capacity increases by 1 to 10 g for every 1 g increase in SOM concentration

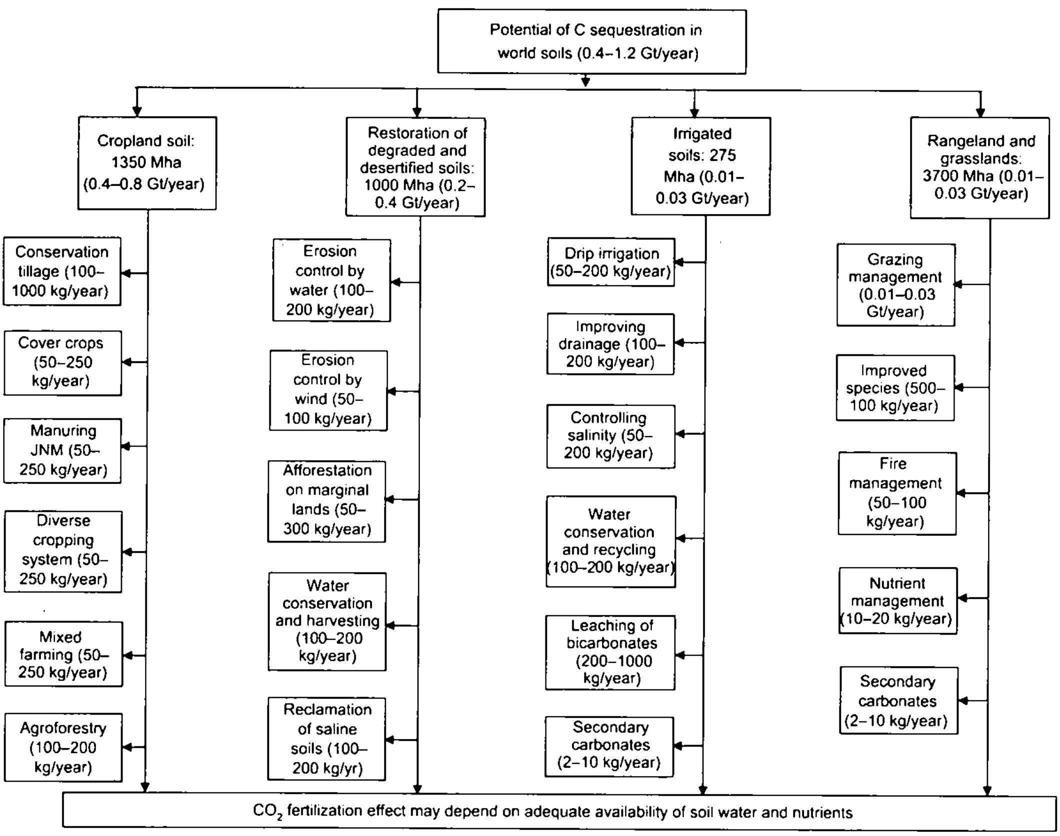

Fig. 1. Global potential of soil C sequestration in managed ecosystems (adapted from Lal, 2004a).

(Emerson, 1995). The increase is small and usually happens only in medium-textured soils, but is critical to sustaining crop growth between rainless periods of 5 to 15 days.

Increasing the SOC pool can be a major challenge, especially in arid and semiarid climates. If achievable, enhancing the SOC pool would increase crop yield over and above that because of other agronomic practices. Lal (2006) reported that increase in SOC pool by 1 t ha^{-1} $year^{-1}$ would lead to a total increase in food grain production of 30 to 50 Mt $year^{-1}$ in the developing countries. Of the total increase, 24 to 39 Mt $year^{-1}$ would occur in the tropics and subtropics, composed of 4 to 6 Mt $year^{-1}$ in Africa, 6 to 10 Mt $year^{-1}$ in Latin America, and 14 to 23 Mt $year^{-1}$ in Asia (Table 7). Thus, the importance of SOC sequestration in achieving global food security cannot be overemphasized. In addition to improving the quantity of food, the attendant improvement in soil quality will also alleviate the hidden hunger affecting billions of people. The latter is caused by the deficiency of micronutrients (e.g., Fe, I, Mo, Cu, Zn) in food grown in soils depleted of essential nutrients.

CHALLENGES AND LIMITATIONS TO SOIL CARBON SEQUESTRATION

Sequestration of C requires other nutrients because SOM is made up of the residues of plants and microorganisms, and these require many elements. Hines (1997) stated that on a weight basis, the C/N ratio of SOM was 12/1, C/P was 50/1, and C/S was 70/1. Therefore, to sequester 1 t of C, 83 kg of N, 20 kg of P, and 14 kg of S are required. These are huge amounts and would likely not be available in many cases. To restore 10 t of SOM in 180 Mha of U.S. cropland would need almost 150 Mt of N and 36 Mt of P that has been mineralized. These amounts are about 15 times greater than the amounts of N and P added to cropland each year in the United States. If SOM is increased by keeping more of the crop residues in the soil as SOM, there will be less recycling of plant nutrients, so subsequent growing plants will be required to obtain more of their nutrients from other sources. It is estimated that 1% to 1.5% of the SOM is mineralized each year, and although the C mineralized is lost as CO_2, the N and P mineralized are available for plant uptake. In response to the question posed by Faulkner (1963), farmers have traditionally tilled the soil to provide nutrients, establish a good seedbed, and control weeds. This allowed farmers to grow bountiful crops in many areas for many years without adding commercial fertilizers. In recent years, however, most farmers are tilling the soil less intensively and fewer times, and an increasing number are using NT or only tilling the strips of the soil where seeds are planted.

Paustian et al. (1995) estimated that the 13.8 Mha under CRP in the United States could sequester about 25 Mt of SOC during a 10-year period. This potential could be realized only if N availability was not a limiting factor. Assuming that the sequestered C in SOM have a C/N ratio of 12:1, then more than 2 Mt of N would be needed, and this would require a net immobilization of 15 kg of N ha^{-1} $year^{-1}$. Follett (1993) estimated that the CRP lands could sequester 10 Mt of C during a 10-year period. Even this amount might be constrained by N and possibly other nutrients that must be sequestered along with C in SOM. It is also agreed that the net sequestration of SOC is small because of the hidden C costs of inputs such as nitrogenous fertilizers (Schlesinger, 1999; Lal 2004b).

Another constraint of sequestering C in the soil as SOM is the lack of understanding that tillage must be reduced permanently. If tillage is eliminated or substantially reduced, SOM will increase and C will be sequestered. However, one subsequent tillage operation can easily result in as much SOM loss as was accumulated in several years. The process of SOC sequestration is also soil and climate specific. Both the rate and magnitude of SOC sequestration are more in heavy-textured than light-textured soils, on poorly drained than well-drained landscapes, in cool than warm climates, and in humid than dry ecoregions. Despite its competing uses, residue retention as mulch is essential to SOC

TABLE 7

Estimates of increase in food production in developing countries by increasing SOC pool by 1 t/ha $year^{-1}$

Species	Area (Mha)	Production Increase (Mt $year^{-1}$)
Cereals	430	21.8–36.3
Legumes	68	2.0–3.2
Tubers	34	6.6–11.3
Total	532	30.4–50.8

Land area for roots and tubers (cassava, yam, sweet potatoes, and taro) were taken from FAO (2005). Increase in yield with increase in 1 t C/ha $year^{-1}$ was assumed at 0.2–0.4 t/ha for cassava, 0.2–0.3 t/ha for sweet potatoes, 0.1–0.2 t/ha for taro, and 0.22–0.4 t/ha for yam (adapted from Lal, 2006).

sequestration j(Dolan et al., 2006; Malhi et al., 2006; Blanco-Canqui et al., 2007). Indeed, it is easier to replace the depleted plant nutrients than to restore the SOC pool.

FARMING CARBON AND TRADING CARBON CREDITS

Carbon is a tradable commodity (Schlesinger, 2006). Farming C and trading credits is an important strategy to increase the income stream of farmers. Receiving additional income through trading of C credits is especially important to the resource-poor farmers of developing countries who are neither able to purchase essential input nor have money to invest in soil restoration. In addition to soil, C credits can also be earned through afforestation of degraded soils or agriculturally marginal lands. Farming C has been operationalized by Chicago Climate Exchange (CCX) (Breslau, 2006). The price of C in the Voluntary CCX Trading Program has increased from \$0.90 t^{-1} CO_2 in December 2003 to \$4.25 t^{-1} CO_2 in December 2006 (http://www.chicagoclimateexchange.com). A successful example of C trading is the Illinois Conservation and Climate Initiative. Farmers and landowners can earn revenue through the sale of GHG emission credits by adoption of RMP (e.g., CT, NT, afforestation, capturing CH_4 with manure digesters). Each RMP has a set credit, and farmers can enroll in the program and are paid by the CCX. Farmers and land managers in developing countries can receive payments through Clean Development Mechanism (CDM) under the Kyoto Treaty (Oberthür and Ott, 2001) or through the World Bank (2003).

CONCLUSIONS

The literature collected supports the following conclusions:

1) Anthropogenic emissions of CO_2 and other GHG are impacting global climate. World soils have been a major source of atmospheric CO_2. However, afforestation of degraded soils and adoption of RMP can sequester C in soil and offset fossil fuel emission. Soil C sequestration implies improving soil quality.
2) Long-term storage of C in the terrestrial biosphere so that the buildup of atmospheric CO_2 (the principal GHG) concentration in the atmosphere will reduce or slow can be accomplished by maintaining or enhancing natural processes to transfer it into long-lived pools to be stored securely and not immediately reemitted.
3) Much concern is needed regarding the 21% increase of U.S. GHG emissions alone between 1990 and 2004. Should similar rapid rates of increased emission occur as the result of increased industrial growth in other major emitting countries around the globe, or if warming results in increasing emissions from arctic/subarctic regions, then natural processes to transfer CO_2 into long-lived pools, such as the soil, or other CO_2-sequestering technologies will be unable to respond at an adequate level to provide sufficient global sink capacity.
4) Land use and management of agricultural lands using RMP effectively sequester SOC that once sequestered can remain in the soil, and sequestration rates can continue for 30 and up to 50 years.
5) The differences in potential rates of increasing soil C stocks that are identified in numerous publications are higher than those indicated by inventory methodology. This has been recognized previously by Sperow et al. (2003); Lal et al. (2003); and Follett (2007), where estimates of rate of SOC sequestration for cropland (IPCC methodology) were about 20% of the potential rate of C sequestration. However, when estimates were made using similar conditions to those of Bruce et al. (1999) and Lal et al. (1998; 2003) for potential soil C sequestration, the values obtained were similar to those of the other authors.
6) There is indeed a challenge to policy makers to address the issue of achieving soil carbon sequestration, as outlined by Lal et al. (2003), and development of effective policies to address the contributing factors required to also reduce GHG emissions in general.

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