ELSEVIER

Environmental Pollution 116 (2002) 353–362

ENVIRONMENTAL POLLUTION

www.elsevier.com/locate/envpol

Soil carbon dynamics in cropland and rangeland

R. Lal*

School of Natural Resources, The Ohio State University, 2021 Coffey Road, Columbus, OH 43210, USA

Received 1 July 2001; accepted 24 July 2001

"Capsule": *Increasing soil carbon sequestration is cost-effective and credible at all levels.*

Abstract

Most soils in the Midwestern USA have lost 30 to 50% of their original pool, or 25 to 40 Mg C/ha, upon conversion from natural to agricultural ecosystems. About 60 to 70% of the C thus depleted can be resequestered through adoption of recommended soil and crop management practices. These practices include conversion from plow till to no till, frequent use of winter cover crops in the rotation cycle, elimination of summer fallow, integrated nutrient management along with liberal use of biosolids and biological nitrogen fixation, precision farming to minimize losses and enhance fertilizer use efficiency, and use of improved varieties with ability to produce large root biomass with high content of lignin and suberin. The gross rate of soil organic carbon (SOC) sequestration ranges from 500 to 800 kg/ha/year in cold and humid regions and 100 to 300 kg/ha/year in dry and warm regions. The rate of SOC sequestration can be measured with procedures that are cost effective and credible at soil pedon level, landscape level, regional or national scale. In addition to SOC, there is also a large potential to sequester soil inorganic carbon (SIC) in arid and semi-arid regions. Soil C sequestration has numerous ancillary benefits. It is truly a win-win situation: extremely cost-effective, and a bridge to the future until alternative energy options take effect.

Keywords: Soil carbon sequestration; Hidden carbon costs; Agricultural soils; Grazing lands; Greenhouse effect

1. Introduction

Global increase in atmospheric concentration of CO_2 and other greenhouse gases is attributed to fossil fuel combustion and cement manufacturing, and land use change. The latter involves deforestation, biomass burning, draining of wetlands, plowing, use of fertilizers and manure and other agricultural practices. The rate of global CO_2 emission from fossil fuel combustion and cement manufacturing during the second half of the 20th century was 1.64 Pg C/year in 1950, 2.59 Pg C/year in 1960, 4.08 Pg C/year in 1970, 5.29 Pg C/year in 1980, 6.10 Pg C/year in 1990 and 8.05 Pg C/year in 2000 (Marland et al., 1999). Between 1850 and 1995, a total of 270 ± 30 Pg C has been emitted from fossil fuel combustion and cement manufacturing, and 136 ± 55 Pg C from land use change and deforestation (IPCC, 2000). CO_2 emission from land use change and deforestation includes those from soil estimated to range from 55 ± 30 Pg (IPCC, 1995) to 78 ± 17 Pg (Lal, 1999).

World soils play an important role in the global carbon cycle. The soil carbon pool comprises soil organic carbon (SOC) estimated at 1550 Pg and soil inorganic carbon (SIC) about 750 Pg both to 1-m depth (Batjes, 1996). Thus the total soil C pool of 2300 Pg is three times the atmospheric pool of 770 Pg and 3.8 times the biotic pool of 610 Pg. The atmospheric pool has steadily increased since about 1850, and is currently increasing at the rate of 0.5%/year or 1.8 ppmv/year. Prudence dictates that technologies be identified and developed to limit the increase in atmospheric CO_2 and other greenhouse gases (GHGs) namely CH_4, N_2O and NO_x.

This manuscript discusses principles and practices governing dynamics of C pool in agricultural soils of the USA, and critically reviews the potential of soil C sequestration through adoption of recommended practices for sustainable management of soil, water, crops and vegetation.

1.1. Soil carbon pool and its dynamics

The SOC pool in soils of the USA is about 5% of the global pool, and is estimated at 75–80 Pg C (Waltman

* Tel.: +1-614-292-9069; fax: +1-614-292-7432.
E-mail address: lal.1@osu.edu (R. Lal).

PII: S0269-7491(01)00211-1

and Bliss, 1997). The SOC pool is strongly influenced by precipitation and temperature (Jenny, 1980). In natural ecosystems, both SOC and N pools decrease exponentially with increase in temperature (Univ. of Missouri, 1930). Similar relationships exist for soils of India (Jenny and Raychaudhary, 1960), New Zealand (Tate, 1992), and tropical America (Rossell and Galantini, 1998). The antecedent level of C for the upper 20-cm layer of the undisturbed soil under natural vegetation ranges from 60 to 70 Mg C/ha for the central US Corn Belt, and is less for soils of the arid regions (Waltman and Bliss, 1997). Conversion from natural to agricultural land use, especially to cropland, leads to a rapid depletion of the SOC pool. Agricultural practices that have contributed to the depletion of SOC pool are: (1) deforestation and biomass burning, (2) drainage of wetlands, (3) plowing and other forms of soil disturbance, (4) inadequate management of soil fertility, (5) removal of crop residues, (6) summer fallowing and clean cultivation, and (7) excessive use of pesticides and other chemicals (Fig. 1). A new equilibrium level is reached in about 50 years at about 30–50% of the original level (Donigian et al., 1994; Paustian et al., 1997; Bowman et al., 1999). Thus, most cultivated soils in the Midwestern USA have lost 25–40 Mg C/ha, and their SOC content is below the potential levels. Conversion of natural to agricultural ecosystems in the USA has depleted the SOC pool by 3 (Kern and Johnson, 1993) to 5 Pg (Lal et al., 1998).

The depletion of the SOC pool upon cultivation is attributed to three processes: (1) oxidation or mineralization due to breakdown of aggregates leading to exposure of carbon, and change in temperature and moisture regimes, (2) leaching and translocation as dissolved organic carbon (DOC) or particulate organic carbon (POC), and (3) accelerated erosion by water runoff or wind. Eroded soil profiles contain considerably less SOC pool than uneroded phases (Rhoton and Tyler, 1990). Although some of the C translocated by erosion may be buried/sequestered in depressional sites and aquatic ecosystems (Stallard, 1998; Dean and Gorham, 1998), a considerable amount is oxidized and emitted into the atmosphere (Lal, 1995). Soil erosion plays an important role in SOC dynamics (De Jong and Kochanoski, 1988), and its importance cannot be over-emphasized. Lal et al. (1998) estimated that soil erosion by water leads to emission of 15 million metric ton (MMT) C/year from soils of the USA. Soil degradation leads to depletion of the SOC pool and emission of greenhouse gases from soil to the atmosphere. Principal degradative processes are physical degradation, chemical degradation, and biological degradation (Fig. 2), which lead to reduction in biomass production and the amount returned to the soil, decline in soil quality (Doran and Jones, 1996), and emission of trace gases (CO_2, CH_4, N_2O) to the atmosphere.

1.2. Land use and carbon dynamics in soils of the USA

The USA has a large land area and ample renewable water resources. The per capita arable land was 0.85 ha in 1975, 0.64 ha in 2000 and is projected to be 0.55 ha in

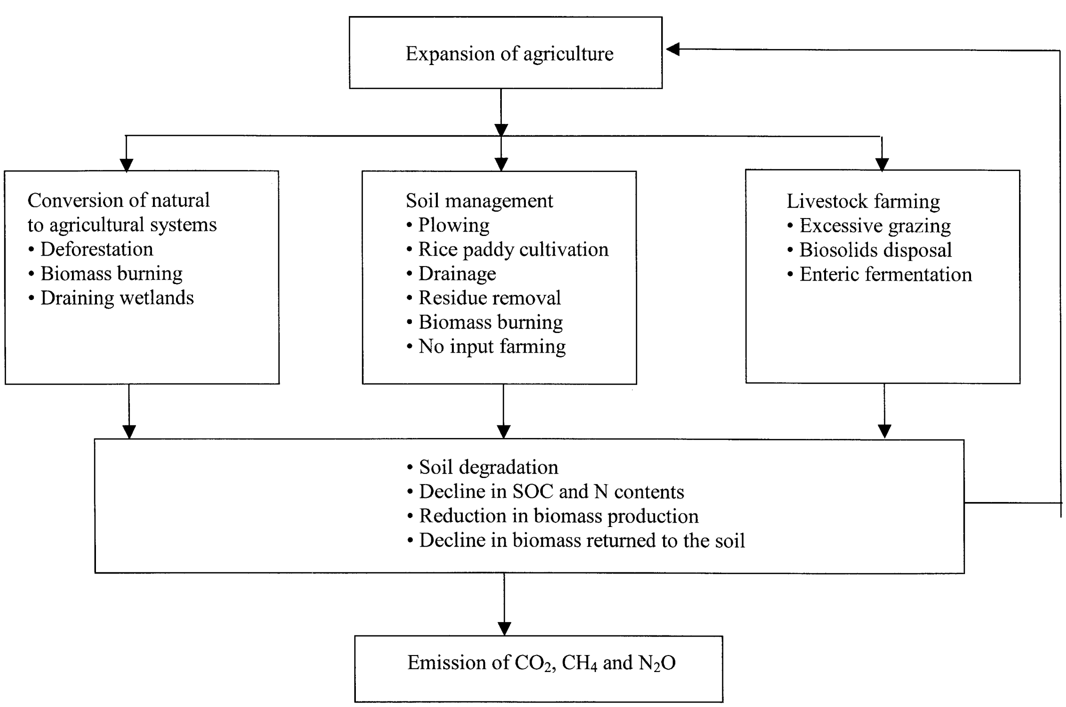

Fig. 1. Agricultural activities and emission of greenhouse gases from soil and terrestrial/aquatic ecosystems to the atmosphere.

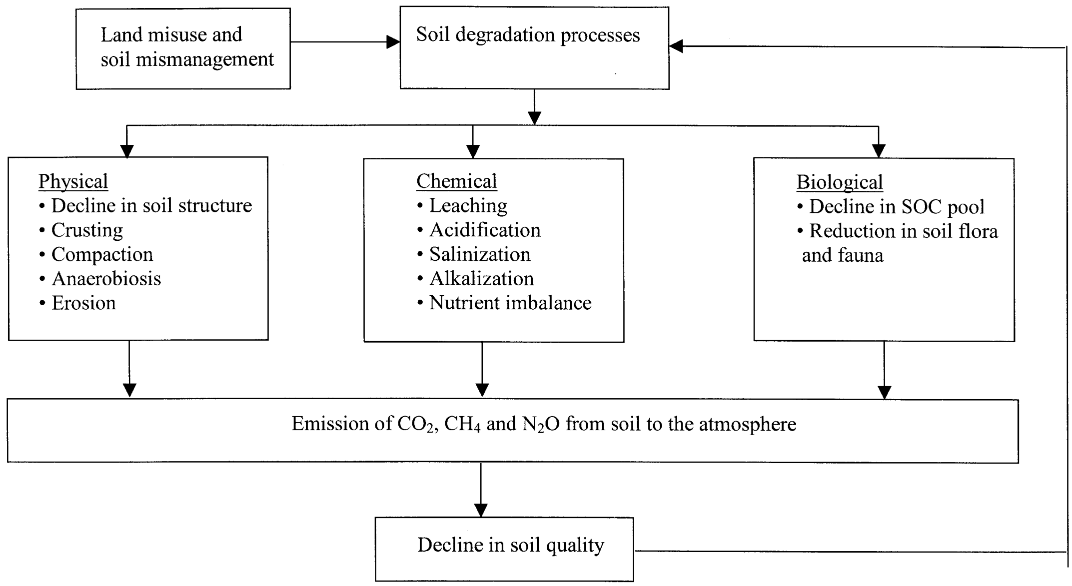

Fig. 2. Soil degradation and emission of greenhouse gases to the atmosphere.

2025. The affluent lifestyle in the USA, based on high per capita energy use, leads to CO_2 emission of 5.4 metric ton of carbon equivalent (MTCE)/person/year (Table 1) compared with the global average of about 1 MTCE/person/year. The data in Table 2 show change in land use in the USA during the last quarter of the 20th century. The land use has remained practically stable, slight reduction in areas of arable and grazing lands is accompanied by an equivalent increase in forest cover.

Table 1
Land and water resources of the USA

Item	1975	1996	2000	2025
Population (10^6)	220	269	278	325
Renewable water ($10^3 m^3$/capita)	11.2	–	8.9	7.6
Arable land (Ha/person)	0.85	–	0.64	0.55
Forest cover (Ha/person)	–	–	0.77	0.71
CO_2 emission (MTCE/person)	–	5.4	–	–

Population Action International (2000); MTCE, metric ton of carbon equivalent.

Table 2
Land use of the USA

Category	1975 (MHa)	2000 (MHa)
Arable land	188	179
Forest cover	216	231
Grazing land	219	212

Population Action International (2000); Follett et al. (2000).

2. Materials and methods

2.1. Energy use in USA agriculture

Agriculture in the USA is an energy-intensive industry. Conversion of solar energy into food, feed, fiber and fuel involves input of energy to power farm machinery and irrigation equipment, to manufacture and apply fertilizers and other chemicals, and dry grain and transport produce. The data on fuel purchased for on-farm use in the USA from 1974 to 2000 shows a gradual decline in the use of gasoline and LP gas but a steady use or a slight increase in that of diesel production (Table 3) (Marland and Turhollow, 1991).

All input and output of agricultural production systems are C-based. For example, the C/energy input for production of fertilizer is 820 kg C/Mg for N (Lal et al., 1998). Energy use for irrigation in USA ranges from 85 to 334 kg C/ha/year, with a mean of 150 kg C/ha/year (Follett, 2001). Irrigation may increase biomass productivity and, when used in conjunction with conservation tillage, may also increase SOC content by 50–150 kg/ha/year (Lal et al., 1998). However, lifting irrigation water requires C-based energy input. Further, there may also be emission of CO_2 dissolved in the ground water (Schlesinger, 1999). Tillage operations and use of herbicides are also energy-intensive activities. Diesel consumption (and the equivalent energy value) depends on the type of implement involved (Table 4), and is highest for moldboard plow and lowest for rotary hoe. Fuel consumption for various tillage operations involves 12.4 l/ha (557 MJ/ha) for moldboard plow, 9.2 l/ha (416 MJ/ha) for chisel plow, 6.5 l/ha (293.7 MJ/ha) for disking, 4.0 l/ha (18 MJ/ha) for cultivator, 3.6 l/ha (162 MJ/ha) for inter-row cultivator and 2.9 l/ha (131 MJ/ha) for rotary hoe (Lobb, 1989). The data on fuel requirements for different operations indicate that use of conservation

Table 3
Fuel purchased for on-farm use in the USA

Year	Gasoline (10^9 gallons)	Diesel (10^9 gallons)	LP gas (10^9 gallons)
1974	3.7	2.6	1.4
1975	4.5	2.4	1.0
1976	3.9	2.8	1.2
1977	3.8	2.9	1.1
1978	3.6	3.2	1.3
1979	3.4	3.2	1.1
1980	3.0	3.2	1.1
1981	2.7	3.1	1.0
1982	2.4	2.9	1.1
1983	2.3	3.0	0.9
1984	2.1	3.0	0.9
1985	1.9	2.9	0.9
1986	1.7	2.9	0.7
1987	1.5	3.0	0.6
1988	1.6	2.8	0.6
1989	1.3	2.5	0.7
1990	1.5	2.7	0.6
1991	1.4	2.8	0.6
1992	1.6	3.1	NA

1 Mg of gasoline = 42.2 GJ; 13.78 kg C/GJ of natural gas; 19.94 kg C/GJ of petroleum liquids; 1 Mg of straw = 3×10^6 k cals (USDA-ERS, 1994).

Table 4
Fuel consumption in tillage operations

Implement	Fuel consumption (L/ha)	Energy value (MJ/ha)
Moldboard plow	12.4	557
Chisel plow	9.2	416
Disk	6.5	294
Cultivator	4.0	182
Inter-row cultivator	3.6	162
Rotary hoe	2.9	131

Lobb (1989); Clements et al. (1995).

tillage or reduced tillage systems saves C/energy input. Energy input is also needed in production of herbicides. The most energy-intensive herbicides are paraquat, glyphosate and Bentazon (Table 5). Energy used for production of active ingredients of some herbicides is 278 MJ/kg for Alachlor, 190 MJ/kg for Atrazine, 460 MJ/kg for Paraquat and 454 MJ/kg for glyphosate (Green, 1987; Clements et al., 1995).

Clements et al. (1995) estimated energy input for crop production in Ontario, Canada. They assessed energy input for four variables (weed control, seedbed preparation, operations, fertilizer manufacture) at three levels (high, low, zero) of herbicide use. Total energy use, respectively for high, low and zero herbicide use was 13.5, 10.3 and 3.9 GJ/ha for corn (*Zea mays*) production; 3.8, 3.3 and 1.8 GJ/ha for soybean (*Glycine max*) production; and 8.0, 3.9 and 3.3 GJ/ha for wheat (*Triticum sativum*) production in corn–soybean–wheat rotation.

Table 5
Energy value for production of common herbicides

Herbicide	Energy value (MJ/kg^{-1})
Paraquat	460
Glyphorate	454
Bentazon	434
Chlorsulfuron	365
Dicamba	295
Linuron	290
Alachlor	278
Metolachlor	276
Diuron	270
Cyanazine	201
Atrazine	190
Chloramben	170
EPTC	160
Trifluralin	150
Butyrate	141
Dinoseb	80

Green (1987); Clements et al. (1995).

2.2. Assessing sustainability of farming systems through carbon budgeting

All input and output in agricultural systems being C based, efficiency and sustainability of production systems are appropriately assessed by determining the C budget. Sustainability on the basis of C balance may be assessed as follows:

(1) *Energy Output–Input*: productivity and sustainability of a farming/cropping system can be expressed in terms of the ratio of C output to C input (Eq. 1):

$$S_{\mathrm{i}} = \left[\frac{C_{\mathrm{NPP}}}{\sum C_{\mathrm{i}}}\right] \tag{1}$$

where S_i is the index of sustainability, C_{NPP} is the C equivalent of the net primary productivity, C_i is the sum of all inputs expressed in C equivalent and t is time. A non-negative trend of S_i over time (25–50 years) is indicative that the system is sustainable.

(2) *Emission of greenhouse gases*: agricultural activities lead to emission of several GHGs (e.g. CO_2, CH_4 and N_2O), that differ with regards to the ability to absorb long-wave radiation depending on their specific radiative forcing and residence time in the atmosphere. The relative ability of gases, also called the global warming potential (GWP), is computed relative to CO_2. The GWP is 1 for CO_2, 21 for CH_4, 310 for N_2O, 1800 for O_3 and 4000–6000 for CFCs (IPCC, 1995). With the information on the flux of GHGs over the growing season for a specific farming/cropping system, the GWP of a production system may be expressed in terms of CO_2 equivalent (Eq. 2):

$$\text{GWP(CO}_2\text{ equivalent)} = \text{CO}_2 + 58(\text{CH}_4) + 310(\text{N}_2\text{O}) \quad (2)$$

This technique has been used by Robertson et al. (2000) for assessing the GWP equivalent of a range of land uses and soil/crop management practices in the Midwestern USA.

(3) *Carbon budgeting*: the instantaneous level of SOC pool can be assessed by computing the balance between input and output (Eqs. 3, 4). The depletion of SOC pool occurs when input of biosolids is less than the output (Eq. 5).

$$(\text{SOC})_g = \text{antecedent pool} + \text{input} - \text{losses} \quad (3)$$

$$(\text{SOC})_g = C_o + (C_r + C_b) - (C_e + C_l + C_m) \quad (4)$$

where $(\text{SOC})_g$ is the gross SOC pool, C_o is the antecedent SOC pool, C_r is the addition of C in crop residue and C_b is the addition as other biosolids. The losses of soil C may be due to accelerated erosion (C_e), leaching as DOC (C_l) and mineralization or oxidation (C_m).

$$-\Delta\text{SOC if } (C_r + C_b) < (C_e + C_l + C_m) \quad (5)$$

Soil degradative systems are those in which C input into the soil ($C_r + C_b$) is less than the output ($C_e + C_l + C_m$). Traditional agricultural systems, based on fertility-mining and soil exploitative practices, lead to SOC depletion. The term C_e represents the net erosion loss, because some of the C in the sediments may be buried in depressional sites and aquatic ecosystems (Stallard, 1998). Considering all input and output, it is important to compute the net C balance $(\text{SOC})_n$ for each production system (Eq. 6).

$$(\text{SOC})_n = (\text{SOC})_g - \left(C_f + C_p + C_t + C_i + C_d\right) \quad (6)$$

where carbon input into the production system includes that due to fertilizer (C_f), pesticides (C_p), irrigation (C_i), tillage and harvest traffic (C_t) and grain/produce drying (C_d). It was on the basis of this analyses that Robertson et al. (2000) reported that the conservation tillage system was a carbon neutral practice, that is, there was neither grain nor loss of C from the system. They, however, did SOC assessment only for the top 7.5-cm layer. Similar analyses were made for soils of Canada (Smith et al., 2000).

3. Results

3.1. Agricultural practices and soil carbon sequestration

Two principal strategies of SOC sequestration in cropland soils are: (1) restoration of degraded soils and ecosystems, and (2) adoption of recommended agricultural practices on prime soils. Restoration of degraded soils enhances biomass production, increases SOC content, and improves water quality. Degradative trends on cropland soils can also be reversed by adoption of recommended agricultural practices (Izaurralde et al., 1998). There is a wide range of recommended management practices with potential for soil carbon sequestration (Fig. 3). These include conservation tillage (Weil et al., 1988; Mahboubi et al., 1993; Franzlubbers et al., 1995; Cole et al., 1995; Paustian et al., 1997; Buyanovski and Wagner 1998a, b; Dick et al., 1998; Rasmussen et al., 1998a, b); judicious fertilizer use (Paustian et al., 1992; Gregorich et al., 1996; Omay et al., 1997; Salinas-Garcia et al., 1997), manuring (Odell et al., 1984; Jenkinson, 1991; Uhlen, 1991; Buyanovsky and Wagner, 1997); mulching (Duiker and Lal, 1999); growing winter cover crops (Hargrove, 1986; McVay et al., 1989; Kuo et al., 1997a, b) crop rotations (Havlin et al., 1990; Omay et al., 1997); CRP (Eve et al., 2000; Follett et al., 2001); and water recycling through sub-irrigation (Lal et al., 1998). There exists a linear relationship between SOC content and C input from residues (Campbell and Zentner, 1997; Paustian et al., 1997; Duiker and Lal, 1999). The potential rate of SOC sequestration through adoption of these and other recommeneded practices is 400–800 kg/ha/year for cool and humid climates and 200–400 kg/ha/year for warm and dry climates (Lal et al., 1998). There is also a potential of SOC seqestration in grazing lands (Follett et al., 2001). All other factors remaining the same, grazing land soils have more SOC pool than cropland soils because of: (1) low soil disturbance due to lack of plowing, (2) more root biomass and residue returned, and (3) return of cattle dung and manure. Data from several long-term experiments show more SOC pool under soils of well-managed (e.g. controlled grazing, improved species, recommeneded rates of fertilizers) pastures than those under croplands (Garwood et al., 1977; Rice and Owensby, 2000; Schrabel et al., 2000; Schuman et al., 2000). The USA grazing lands occupy 212 Mha of privately owned and 124 Mha of publicly owned lands. The gross soil C sequestration potential of USA grazing lands is 29.5–110.0 MMTC/year (Follett et al., 2000).

The principal strategy is agricultural intensification through adoption of recommended agricultural practices. Agricultural intensification implies use of prime soils for cultivation with best recommended practices to obtain optimum sustainable yield so that marginal agricultural lands can be saved for nature conservancy. A judicious use of input and widespread adoption of recommended practices can increase SOC content, improve soil quality and agricultural productivity, enhance water quality by decreasing water runoff and sediment yield, and reduce risks of accelerated greenhouse effect. Soil C sequestration is a cost-effective option of mitigating the greenhouse effect.

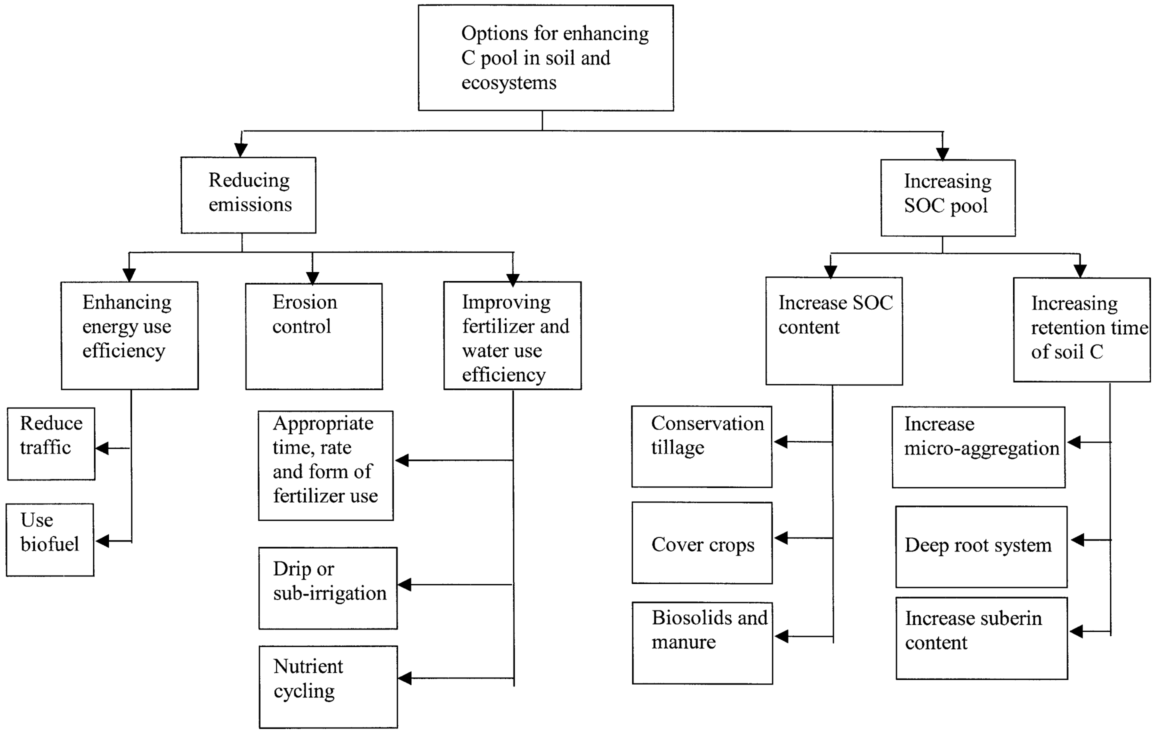

Fig. 3. Technological options for enhancing C pool in soil and ecosystems.

In addition to SOC, there is also a potential to sequester SIC. There are two mechanisms of sequestering SIC in semi-arid and sub-humid regions. One involves the formation of secondary carbonates (Monger and Gallegos, 2000) at the rate of about 50–100 kg C/ha/year. Soil biotic activity (e.g. termites, roots growth) play an important role in the formation of secondary carbonates. The second involves leaching of carbonates into the ground water (Wilding, 1999; Nordt et al., 2000). Leaching of carbonates can be particularly significant in irrigated agriculture that is highly productive. Irrigated agriculture is practiced on only 17% of cropland area but it produces 40% of the global food production (Postel, 1999).

The potential of SOC sequestration in world soils is outlined in Table 6 (Squires et al., 1995; Lal and Bruce, 1999; Izaurralde et al., 2001; Lal, 2001). This vast potential is realizable over the next 25 years (by 2025) to 50 years through conversion of marginal agricultural land to natural ecosystems, restoration of degraded soils and adoption of recommended agricultural practices on prime soils. The strategy of soil C sequestration is a bridge to the future, it buys us time until other energy-related options could take effect.

3.2. *Monitoring and verification*

The importance of SOC content to soil quality has been recognized for several centuries. Measurement of soil carbon, in relation to management-induced changes in soil fertility, has been practiced since the beginning of the 20th century. Significant advances in measurements, reliably and accurately, have been made (Lal et al., 2000). There are 10 steps in assessment of soil carbon at a field scale. These include the following:

1. Prepare a detailed soil map of the farm (1:50,000 scale or less).
2. Identify sampling location on the basis of soil series.
3. Take soil samples to 2-m depth for 0–5, 5–10, 10–20 cm and on the basis of genetic horizon for layers beneath.
4. Take three sub-samples for each depth and composite, and obtain three profiles for each land use/soil management treatment.
5. Measure soil bulk density for each layer by the core or the clod method (Blake and Hartge, 1986).
6. Conduct aggregate analyses by the Yoder (1936) method, and determine SOC content in each aggregate size fraction (5–8, 2–5, 1–2, 0.5–1, 0.1–0.5 and <0.1 mm).
7. Perform mechanical analyses by a combination of the hydrometer method (Gee and Bauder, 1986) and sieving, and determine SOC content in sand (0.2–2 mm), silt (0.2–0.002 mm) and clay (<0.002 mm) fractions.
8. Determine SOC content by dry combustion method using C:N analyzer (Swift, 1996), and verify the analytical data by comparing with the analyses of standard samples.

Table 6
SOC sequestration potential of adopting recommended agricultural practices on world croplands and restoring desertified and degraded ecosystems

Ecosystem	Potential of C sequestration	Reference
1. Wold cropland soils	0.7–0.9 Pg C/year	Lal and Bruce (1999)
2. World desertified lands	0.9–1.9 Pg C/year	Lal et al. (1999)
3. World degraded lands	3.0 Pg C/year	Lal (1997)
4. USA cropland	75–208 Tg C/year	Lal et al. (1998)
5. USA grazing land	18–90 Tg C/year	Follett et al. (2000)
6. Restoration of degraded lands	1.5–2 Pg C/year	Squires et al. (1995)

9. Correct the data for carbonates.
10. Express results in Mg C/ha, with mean ($\pm$standard deviation) based on several measurements over the landscape or farm unit.

While models can be used in combination with field measurements, modeling cannot entirely replace soil sampling and analyses. Models of all types are simplified, incomplete mathematical descriptions of the *real* world which, because we are modeling, we do not fully understand. Thus, models can never be fully verified. Models are representations, useful for guiding further study, but they can never fully reflect reality (Philip, 1991). Assessment of SOC pool is an easy and routine procedure, statistical techniques are available to minimize the variability, and models can be used to extrapolate the data to similar soils and ecoregions.

The verification of the effect of a land use/soil management practices on SOC pool and dynamics is to be done on the basis of the following steps:

1. Establish a matrix of the rates of SOC sequestration for principal soil types in the region on the basis of the measurements done on long-term soil/crop management experiments conducted on the same soil type within the ecoregion.
2. Validate the rates for ground truth measurements with a spot check on a few locations.
3. Determine land use and soil management practices using remote sensing techniques (e.g. aerial photography, satellite imagery).
4. Use pedotransfer functions to estimate SOC content on the basis of easily measured parameters (e.g. clay content).
5. Use models to estimate SOC pool.

4. Discussion

The historic loss of SOC, due to inappropriate land use and soil mismanagement practices, has caused decline in soil quality and emission of C into the atmosphere. The magnitude of SOC loss from croplands in the USA is in the range of 30 to 50 Mg C/ha, or about 50% of the antecedent level. The loss of SOC is exacerbated by degradative processes including accelerated erosion, nutrient depletion, acidification and salinization. About 60–70% of the SOC loss can be resequestered through agricultural intensification based on adoption of recommended agricultural practices (IPCC, 1995, 2000). The objective is to adopt land saving technologies such that marginal lands can be taken out of production for nature conservancy. Most of the agricultural input (e.g. fertilizers, pesticides, irrigation, farm operations) has hidden C cost. Thus, the gross rate of SOC sequestration needs to be corrected to obtain the net rate. In addition to SOC, soils of arid and semiarid regions also have a potential to sequester SIC as secondary carbonates and leaching of carbonates into sub-soil or ground water.

Contrary to general perception, the SOC can be measured accurately, precisely and in a cost-effective manner (IPCC, 2000). Furthermore, scaling procedures exist to assess C pool and fluxes over the landscape scale and can be projected to regional scale. Verification of the SOC sequestration rate can be achieved through a combination of practice-based approaches, ground truth assessments for benchmark locations, and model development.

Soil C sequestration has numerous ancillary benefits. Important among these is producing food to meet the demands of a growing population. Global food security is closely linked to high soil quality, which depends on an adequate level of SOC content. While growing forest is important, even with debatable effects on C sequestration (Schulze et al., 2000), C sequestration in agricultural soils has its own importance and a definite niche in the environmental context. It increases soil quality and agronomic productivity, improves water quality, and decreases risks of accelerated greenhouse effect. In this context, it is truly a win-win situation. Over a short period of 25–50 years, it is the most cost-effective option. Furthermore, it buys us time while alternative energy options take effect. It is truly a bridge to the future.

5. Conclusions

The accelerated greenhouse effect is an important issue of the 21st century. The net emissions of greenhouse gases by anthropogenic activities can be reduced by biosequestration in soils and vegetation. Soil carbon sequestration, through adoption of recommended agricultural practices and restoration of degraded soils, has numerous ancillary benefits especially in terms of improving the quality of natural waters and reducing the net gaseous emissions. While soil carbon is rapidly lost by erosion and/or plowing, enhancing soil carbon pool is a slow process. Gross rates of soil carbon sequestration may be greater in cool and humid regions than in warm and dry climates. Assessing the net rate of soil C sequestration involves accounting of C through management input (e.g. tillage, herbicides, fertilizers, irrigation). Recent advances have been made in methods of monitoring soil carbon pool. Assessment of soil carbon pool at different scales requires remote sensing, GIS and modeling.

Acknowledgements

This paper was presented at the USDA Forest Service Southern Global Change Program sponsored Advances in Terrestrial Ecosystem: Carbon Inventory, Measurements, and Monitoring Conference held 3–5 October 2000 in Raleigh, North Carolina.

References

Batjes, N.H., 1996. The total C and N in soils of the world. European Journal Soil Science 47, 151–163.

Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Methods of Soil Analysis, Part 1, ASA Monograph 9, 2nd Edition. ASA, Madison, WI, pp. 363–375.

Bowman, R.A., Vigil, M.F., Nielsen, D.C., Anderson, R.L., 1999. Soil organic matter changes in intensively cropped dryland systems. Soil Science Society of American Journal 63, 186–191.

Buyanovsky, G.A., Wagner, G.H., 1997. Crop residue input to soil organic matter on Sanborn field. In: Paul, E.A., Elliott, E.T., Paustian, K., Cole, C.V. (Eds.), Soil Organic Matter in Temperate Agroecosystems. CRC Press, Boca Raton, FL, pp. 73–83.

Buyanovski, G.A., Wagner, W.H., 1998b. Carbon cycling in cultivated lands and its global significance. Global Change Biology 4, 131–141.

Buyanovski, G.A., Wagner, W.H., 1998a. Changing role of cultivated land in the global carbon cycle. Biology & Fertility of Soils 27, 242–245.

Campbell, C.A., Zentner, R.P., 1997. Crop production and soil organic matter in long-term crop rotations in the semi-arid northern Great Plains of Canada. In: Paul, E.A., Elliott, E.T., Paustian, K., Cole, C.V. (Eds.), Soil Organic Matter in Temperate Agroecosystems. CRC Press, Boca Raton, FL, pp. 317–334.

Clements, D.R., Neise, S.F., Brown, R., Stonehouse, D.P., Hume, D.J., Swanton, C.J., 1995. Agriculture, Ecosystem and Environment 52, 119–128.

Cole, C.V., Cerri, C., Minami, K., Mosier, A., Rosenberg, N., Sauerbeck, D., 1995. Agricultural Options for Mitigation of Greenhouse Effect. IPCC Working Group 2. Cambridge University Press, Cambridge.

Dean, W.E., Gorham, E., 1998. Magnitude and significance of carbon burial in lakes, reservoirs and peatland. Geology 26, 535–538.

DeJong, E., Kochanoski, R.G., 1988. The importance of erosion in the carbon balance of prairie soils. Canadian Journal of Soil Science 68, 111–119.

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

Donigian Jr., A.S., Barnwell, T.O., Jackson, R.B., Patwardhan, A.S., Weinreich, K.B., Rowell, A.L., Chinnaswamy, R.V., Cole, C.V., 1994. Assessment of Alternative Management Practices and Policies Affecting Soil Carbon in Agroecosystems of the Central United States. UESEPA, Athens, GA. (Publication #EPA/600/R-94/067).

Doran, J.W., Jones, A.D. (Eds.), 1996. Methods for Assessing Soil Quality. Soil Science Society of America, Madison, WI. (Special Publication No. 49).

Duiker, S.W., Lal, R., 1999. Crop residue and tillage effects on C sequestration in a Luvisol in central Ohio. Soil & Tillage Res. 52, 73–81.

Eve, M.D., Paustian, K., Elliott, E.T., 2001. An inventory of carbon emissions and sequestration in U.S. cropland soils. In: Lal, R. (Ed.), Soil Carbon Sequestration and the Greenhouse Effect. Soil Science Society of America, Madison, WI. (Special Publication) 57, 51–65.

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

Follett, R.F., Kimble, J.M., Lal, R., 2000. The potential of U.S. grazing lands to sequester soil carbon. In: Follett, R.F., Kimble, J.M., Lal, R. (Eds.), The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. CRC/Lewis Publishers, Boca Raton, FL, pp. 401–438.

Follett, F.R., Pruessner, E.G., Samson-Liebig, S.E., Kimble, J.M., Waltman, S.W., 2001. Carbon sequestration under the Conservation Reserve Program in the historic grassland soils of the United States of America. In: Lal, R. (Ed.), Soil Carbon Sequestration and the Greenhouse Effect. Soil Science Society of America, Madison, WI. (Special Publication) 57, 27–39.

Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1995. Tillage and crop effects on seasonal soil carbon and nitrogen dynamics. Soil Sci. Soc. Am. J. 59, 1618–1624.

Garwood, E.A., Tyson, K.C., Clement, C.R., 1977. A Comparison of Yield and Soil Conditions During 20 Years of Grazed Grass and Arable Cropping (Tech. Report No. 21). Grassland Res. Inst., Hurley, UK.

Gee, G.W., Bauder, J.W., 1986. Particle size analysis. In: Klute, A. (Ed.), Methods of Soil Analyses, Part 1, ASA Monograph 9, 2nd Edition. ASA, Madison, WI, pp. 383–411.

Green, M.B., 1987. Energy in pesticide manufacture, distribution and use. In: Stout, B.A., Mudahar, M.S. (Eds.), Energy in Plant Nutrition and Pest Control. Elsevier, Amsterdam, pp. 165–177.

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

Hargrove, W.L., 1986. Winter legumes as nitrogen source for no-till grain sorghum. Agron. J. 78, 70–74.

Havlin, J.L., Kissel, D.E., Maddux, L.D., Claasen, M.M., Long, J.H., 1990. Crop rotation and tillage effects on soil organic carbon and nitrogen. Soil Sci. Soc. Am. J. 654, 448–452.

IPCC, 1995. Climate Change 1995. Working Group 1. IPCC, Cambridge University Press, Cambridge, UK.

IPCC, 2000. Land Use, Land Use Change and Forestry. IPCC, Cambridge University Press, Cambridge, UK.

Izaurralde, R.C., Rosenberg, N.J., Lal, R., 2001. Mitigation of climatic change by soil carbon sequestration: issue of science, monitoring and degraded lands. Adv. Agon. 70, 1–75.

Izaurralde, R.C., Nyborg, M., Solberg, E.D., Janzen, H.H., Arsha, M.A., Malhi, S.S., Molina-Ayala, M., 1998. Carbon storage in eroded soils after 5 years of reclamation techniques. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Soil Processes and the Carbon Cycle. CRC Press, Boca Raton, FL, pp. 369–385.

Jenkinson, D.S., 1991. The Rothamsted long-term experiments: Are they still of use? Agron. J. 83, 2–10.

Jenny, H., 1980. The Soil Resource. Springer, New York, USA.

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

Kern, J.S., Johnson, M.G., 1993. Conservation tillage impacts on national soil and atmospheric carbon levels. Soil Sci. Soc. Am. J. 57, 200–210.

Kuo, S., Sainju, U.M., Jellum, E.J., 1997a. Winter cover crop effects on soil organic carbon and carbohydrates. Soil Sci. Soc. Amer. J. 61, 145–152.

Kuo, S., Sainju, U.M., Jellum, E.J., 1997b. Winter cover cropping influence on nitrogen in soil. Soil Sci. Soc. Am. J. 61, 1392–1399.

Lal, R., 1995. Global soil erosion by water and carbon dynamics. In: Lal, R., Kimble, J.M., Levine, E., Stewart, B.A. (Eds.), Soils and Global Change. CRC/Lewis Publishers, Boca Raton, FL, pp. 131–142.

Lal, R., 1997. 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., 2001. World cropland soils as a source or sink for atmospheric carbon. Adv. Agron. 71, 145–191.

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

Lal, R., Hassan, H.M., Dumanski, J.W., 1999. Desertification control for C sequestration to mitigate the greenhouse effect. In: Rosenberg, N.J., Izaurralde, R.C., Malone, E.L. (Eds.), Carbon Sequestration in Soils: Science, Monitoring and Beyond. Battelle Press, Columbus, OH, pp. 83–107.

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

Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), 2000. Assessment Methods for Soil Carbon. CRC/Lewis Publishers, Boca Raton, FL.

Lobb, D., 1989. A Study of the Impact of No Till on Tractor Fuel Cost vs. Crop Returns. Agriculture Energy Center, Guelph, Ontario.

Mahboubi, A.A., Lal, R., Fausey, N.R., 1993. Twenty-eight years of tillage effects on two soils of Ohio. Soil Sci. Soc. Am. J. 57, 506–512.

Marland, G., Turhollow, A.F., 1991. CO_2 emissions from the production and combustion of fuel ethanol from corn. Energy 16, 1307–1316.

Marland, G., Andres, R.J., Boden, T.A., Johnston, C., Brenkert, A., 1999. Global, Regional and National CO_2 Emission Estimates from Fossil Fuel Burning, Cement Production and Gas Flaring: 1751–1996 (Report NDP-030). Carbon Dioxide Information Analyses Center, ORNL, Oakridge, TN, USA.

McVay, K.A., Radcliffe, D.E., Hargrove, W.L., 1989. Winter legume effects on soil properties and nitrogen fertilizer requirements. Soil Sci. Soc. Am. J. 53, 1856–1862.

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

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

Odell, R.T., Melsted, S.W., Walker, V.M., 1984. Changes in organic carbon and nitrogen of Morrow plots under different treatments 1904–1973. Soil Sci. Soc. Am. J. 137, 160–171.

Omay, A.B., Rice, C.W., Maddux, L.D., Gordon, W.B., 1997. Changes in soil microbial and chemical properties under long-term crop rotation and fertilization. Soil Sci. Soc. Am. J. 61, 1672–1678.

Paustian, K., Parton, W.J., Presson, J., 1992. Modeling soil organic matter in organic-amended and nitrogen-fertilized long-term plots. Soil Sci. Soc. Am. J. 56, 476–488.

Paustian, K., Collins, H.P., Paul, E.A., 1997. Management controls on soil carbon. In: Paul, E.A., Paustian, K., Elliott, E.T., Cole, C.V. (Eds.), Soil Organic Matter in Temperate Agroecosystems: Long-term Experiments in North America. CRC Press, Boca Raton, FL, pp. 15–49.

Paustian, K., Elliott, E.T., Carter, M.R., 1998. Tillage and crop management impacts on soil C storage: use of long-term experimental data. Soil Tillage Res. 47, vii–xii.

Philip, J.R., 1991. Soils, natural science and models. Soil Sci. 151, 91–98.

Population Action International, 2000. Nature's Place: Human Population and the Future of Biological Diversity. Population Action International, Washington, DC, 80pp.

Postel, S., 1999. Pillar of Sand. W.W. Norton & Co, New York.

Rasmussen, P.E., Albrecht, S.L., Smiley, R.W., 1998a. Soil C and N changes under tillage and cropping systems in semi-arid Pacific Northwest agriculture. Soil Tillage Res. 47, 197–205.

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

Rhoton, F.E., Tyler, D.D., 1990. Erosion-induced changes in properties of a Fragipan soil. Soil Science Society of American Journal 54, 223–228.

Rice, C.W., Owensby, C.E., 2000. The effects of fire and grazing on soil carbon in rangelands. In: Follett, R.F., Kimble, J.M., Lal, R. (Eds.), The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. CRC/Lewis Publishers, Boca Raton, FL, pp. 323–341.

Robertson, G.P., Paul, E.A., Harwood, R.R., 2000. Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science 289, 192–1924.

Rosell, R.A., Galantini, J.A., 1998. Soil organic carbon dynamics in native and cultivated ecosystems of South America. In: Lal, R., Kimble, J., Follett, R., Stewart, B.A. (Eds.), Management of Carbon Sequestration in Soil. CRC, Boca Raton, FL, pp. 11–33.

Salinas-Garcia, J.R., Hons, F.M., Matocha, J.E., 1997. Long-term effects of tillage and fertilization on soil organic matter dynamics. Soil Sci. Soc. Am. J. 61, 152–159.

Schlesinger, W.H., 1999. Carbon sequestration in soil. Science 284, 2095.

Schnabel, R.R., Franzluebbers, A.J., Stout, W.L., Sanderson, M.A., Stuedemann, J.A., 2000. The effect of pasture management practices. In: Follett, R.F., Kimble, J.M., Lal, R. (Eds.), The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. CRC/Lewis Publishers, Boca Raton, FL, pp. 291–321.

Schulze, E-D., Wirth, C., Heinman, M., 2000. Managing forests after Kyoto. Science 289, 2058–2059.

Schuman, G.E., Herrick, J.E., Janzen, H.H., 2000. The dynamics of soil carbon in rangelands. In: Follett, R.F., Kimble, J.M., Lal, R. (Eds.), The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. CRC/Lewis Publishers, Boca Raton, FL, pp. 267–289.

Smith, W.N., Desjardins, R.L., Pattey, E., 2000. The net flux of carbon from agricultural soils in Canada. Global Change Biology 6, 557–568.

Squires, V., Glenn, E.P., Ayoub, A.T., 1995. Combating global climate change by combating land degradation. In: Squires, V. et al. (Eds.), Proc. Workshop held in Nairobi, Kenya, 4–8 September 1995, UNEP, Nairobi, Kenya.

Stallard, R.F., 1998. Terrestrial sedimentation and the C cycle: coupling weathering and erosion to carbon burial. Global Biogeochemical Cycles 12, 231–237.

Swift, R.S., 1996. Organic matter characterization. In: Sparks, D.L. et al. (Eds.), Methods of Soil Analysis, Part 3, Chemical Methods. Soil Sci. Soc. Amer., Madison, WI, pp. 1011–1069.

Tate, K.R., 1992. Assessment based on a climosequence of soils in tussock grasslands of soil carbon storage and release in response to global warming. J. Soil Sci. 43, 697–707.

Uhlen, G., 1991. Long-term effects of fertilizers, manures, straw and crop rotation on total N and total C in soil. Acta. Agric. 41, 119–127.

University of Missouri, 1930. A Study on the Influence of Climate upon the Nitrogen and Organic Matter Content of the Soil (Res. Bull. 152). Agric. Exp. Stn., Columbia, MO.

USDA-ERS, 1994. Agricultural Outlook. May 1994. Economic Research Service, Washington, DC.

Waltman, S.W., Bliss, N.B., 1995. Estimates of SOC Content. NSSC, USDA-NRCS, Lincoln, NE.

Weil, R.R., Benedetto, P.W., Sikora, L.J., Bandel, V.A., 1988. Influence of tillage practices on phosphorus distribution and forms in three Ultisols. Agron. J. 80, 503–509.

Wilding, L.P., 1999. Comments on manuscript by R. Lal. In: Rosenberg, N.J., Izaurralde, R.C., Malone, E.L. (Eds.), Carbon Sequestration in Soils: Science, Monitoring and Beyond. Proc. St. Michael Workshop, December 1998. Battelle Press, Columbus, OH, pp. 146–149.

Yoder, R.E., 1936. The significance of soil structure in relation to the tilth problem. Soil Sci. Soc. Am. Proc. 2, 21–23.