This paper was not peer-reviewed.
Pages 459-465. In: D.E. Stott, R.H. Mohtar and G.C. Steinhardt (eds). 2001. Sustaining the Global Farm. Selected papers from the 10th International Soil Conservation Organization Meeting held May 24-29, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory.

Keynote: Soil Conservation For C Sequestration

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ABSTRACT

The atmospheric concentration of greenhouse gases (GHG) is increasing at the rate of 0.5% yr^{-1} (3.2 Pg C yr^{-1}) for CO_2, 0.6% yr^{-1} for CH_4 and 0.25 ppbv yr^{-1} for N_2O. The global radiative forcing due to three GHGs is contributed by 20% due to agricultural activities and 14% to change in land use and attendant deforestation. Principal agricultural activities that contribute to emission of GHGs include plowing, application of fertilizers and manures, soil drainage, biomass burning, residue removal. The loss of soil C is accentuated by soil degradation (due to erosion, compaction, salinization etc.) and the attendant decline in soil quality. Historic global C loss due to agricultural activities is estimated at 55 to 100 Pg from soil C pool and 100 to 150 Pg from the biotic C pool. Adoption of recommended agricultural practices can lead to increase in soil organic carbon (SOC) content and aggregation, and restoration of soil quality. Improved agricultural practices include mulching and conservation tillage, growing cover crops and eliminating summer fallow, using judicious inputs fertilizers including precision farming and use of biosolids, adopting improved cropping systems, managing soil-water through drainage and irrigation, and restoring degraded soils. The potential of C sequestration in soil, biota and terrestrial ecosystem may be as much as 3 Pg C yr^{-1}. However, this potential is finite and can be filled within 25 to 50 years. The long-term solution to the risk of potential global warming lies in finding alternatives to fossil fuel. Therefore, the strategy of soil C sequestration is a bridge to the future. Over the short-time horizon of 25 to 50 years, it is the simplest and most cost-effective option, and a win-win strategy.

Accelerated soil erosion, affecting 1094 million ha (MHa) by water erosion and 549 MHa by wind erosion (Oldeman, 1994), has local, regional and global impacts (Lal, 1998). Estimates of contemporary rates of soil erosion show total sediment discharge of 15 billion tons for the world comprising 7.6 billion tons from Asia, 2.4 billion tons from South America, 2.1 billion tons from North America, 1.7 billion tons from Africa and 1.2 billion tons form elsewhere (Lal, 1994; Walling, 1987). Erosional hot spots, countries and regions with severe rates of soil erosion measured on field runoff plots, include Jamaica (130-180 Mg ha^{-1} yr^{-1}), El-Salvador (100-130 Mg ha^{-1} yr^{-1}), Taiwan (60-210 Mg ha^{-1} yr^{-1}), Nigeria (5-120 Mg ha^{-1} yr^{-1}), Ivory Coast (60-570 Mg ha^{-1} yr^{-1}) and Senegal (5-12 Mg ha^{-1} yr^{-1}) (Lal, 1976; Lal, 1989). Other erosional hot spots comprise fragile ecosystems such as the Himalyan-Tibean ecoregion, the Andeas, the West African Sahel, East African Highlands, and the Caribbean region (Scherr and Yadav, 1995; Scherr, 1999). In addition to effects on productivity, soil erosion also profoundly impacts the environment.

Two principal impacts of erosion on environment include reduction in quality of water and air through pollution and eutrophication of surface water, and emissions of radioactively-active gases (e.g., CO_2, CH_4 and N_2O) to the atmosphere. Increasing atmospheric concentration of radioactively-active gases (0.5% yr^{-1} for CO_2, 0.6% yr^{-1} for CH_4, 0.25% yr^{-1} for N_2O) (IPCC, 1995) necessitates identifying sources and sinks for developing potential interventions towards mitigating the greenhouse effect. While the impact of land use change on soil C pool and fluxes is being widely recognized (Lal et al., 1995a; b; 1998a; b; c; 1999a; b; c; Paul et al., 1997; Janzen et al., 1998), that of soil erosion on C dynamics is not properly understood. The fate of C in soil subjected to erosional processes by wind and water is not known.

Soil erosion is a 3-stage process involving detachment, transport and deposition of soil particles. Soil detachment, by kinetic energy of raindrop and blowing/flowing wind and water, leads to disruption of aggregates and exposure of C encapsulated within the micro-aggregates and clay domains. Transport of detached soil particles involves preferential removal of light fraction e.g. clay and soil organic matter. Consequently, soil C is preferentially removed and redistributed over the landscape. The enrichment ratio (ratio of the concentration of clay and organic matter in sediments to that of the surface soil) may be 2 to 5 for clay and 2 to 20 for organic matter, depending on the soil properties and erosivity of the event. In the Mallee area of southeastern Australia, Leys and McTainsh (1994) assessed the degradative effects of wind erosion on soil and environments. The wind-blown soil contained 11 times more soil organic carbon (SOC) than 0-1 cm topsoil left in the field. In Nigeria, Lal (1976) observed enrichment ratio of 2 to 5 for sediments transported by water runoff. Soil carbon transported in water runoff may include particulate organic material, and dissolved organic (DOC) and inorganic carbon (DIC). The fate of dissolved carbon is not known, and some of the DOC may be easily mineralized (Moore, 1998). While some of the C transported to depositional sites and aquatic ecosystems may be buried and sequestered (Stallard, 1998; Ludwig et al., 1996), a considerable part may be mineralized and released into the atmosphere as CO_2 (Lal, 1995). The exact fate of erosion-displaced soil C (e.g. fraction emitted to the atmosphere or redistributed over the landscape) depends on the site specific conditions including soil properties, landscape features, drainage conditions, and the

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degree of anoxia, temperature and moisture regimes, and properties of soil organic matter (e.g., C:N ratio, lignin content etc.).

The objective of this report is to conceptualize erosional impacts on soil C dynamics and to describe the effects on soil conservation measures on enhancement of soil carbon pool and attendant effects on mitigating the potential greenhouse effect.

Soil Erosion and Carbon Dynamics

Accelerated soil erosion affects C dynamics both on-site and off-site (Fig. 1). Soil erosion, both by water and wind, causes decline in SOC content on-site. Preferential removal of clay and soil organic matter content reduces SOC pool, lowers soil quality and declines biomass productivity. Several experiments have documented reduction in SOC content of soils subjected to moderate and severe soil erosion. In Kenya, Gachene et al. (1997) observed a linear decline in SOC content with cumulative soil erosion. In Canada, Gregorich et al. (1995) observed a rapid decline in SOC on an eroded compared with an uneroded cropland. SOC content in the top 30-cm layer decreased 20% in an uneroded soil and 70% in eroded soil following 80 years of cultivation. Several experiments conducted in North America have demonstrated the adverse impact of accelerated erosion on SOC pools (Massey and Jackson, 1952; Gregorich and Anderson, 1985; De Jong and Kochanoski, 1988; Kreznor et al., 1989; Geng and Coote, 1991; Gregorich et al., 1998). In Ohio, USA, Fahnestock et al. (1996) observed that SOC pool in the top 0-10 cm depth of a Miamian soil differed significantly among erosional and depositional phases. The SOC pool in the top 10-cm depth was 39.8 Mg C ha^{-1} for the uneroded soil, 15.6 Mg C ha^{-1} for slightly eroded, 14.6 Mg C ha^{-1} for moderately eroded, 13.4 Mg C ha^{-1} for severely eroded and 17.0 Mg C ha^{-1} for the depositional phases. These data show that severe erosion cause 2.2 Mg C depletion compared with slight erosion. The decline in SOC pool of the severely eroded soil was 26.4 Mg C ha^{-1} for 10-cm depth. In Tennessee, USA, Rhoton and Tyler (1990) observed severe decline in SOC pool due to soil erosion of a fragipan soil (Table 1). The SOC loss was 12.4 Mg C ha^{-1} due to moderate and 13.1 Mg C ha^{-1} due to severe erosion.

The data in Table 2 from Colombia show drastic reductions in SOC pool by accelerated soil erosion on bare fallow soil. The rate of SOC loss ranged from 20 to 700 kg C ha^{-1} yr^{-1} on cultivated land with improved cropping practices of grass barriers and intercropping.

Similar data from Nigeria show that rate of SOC loss ranged from 15 to 500 kg ha^{-1} yr^{-1} for uncropped (plowed fallow), and from 0 to 100 kg ha^{-1} yr^{-1} for cropland (Lal, 1976; 1980; Table 3). The data in Table 4 from Zimbabwe show SOC loss ranging from 15 to 1150 kg ha^{-1} yr^{-1} depending on cropping system and management practice. Accelerated soil erosion indeed can cause a rapid depletion of the SOC pool.

The global loss of SOC content due to soil erosion is shown in Table 5, and C emission due to water erosion is estimated at 1.1 Pg C yr^{-1} (Lal, 1995). Taking into consideration the land area affected, the historic C loss is

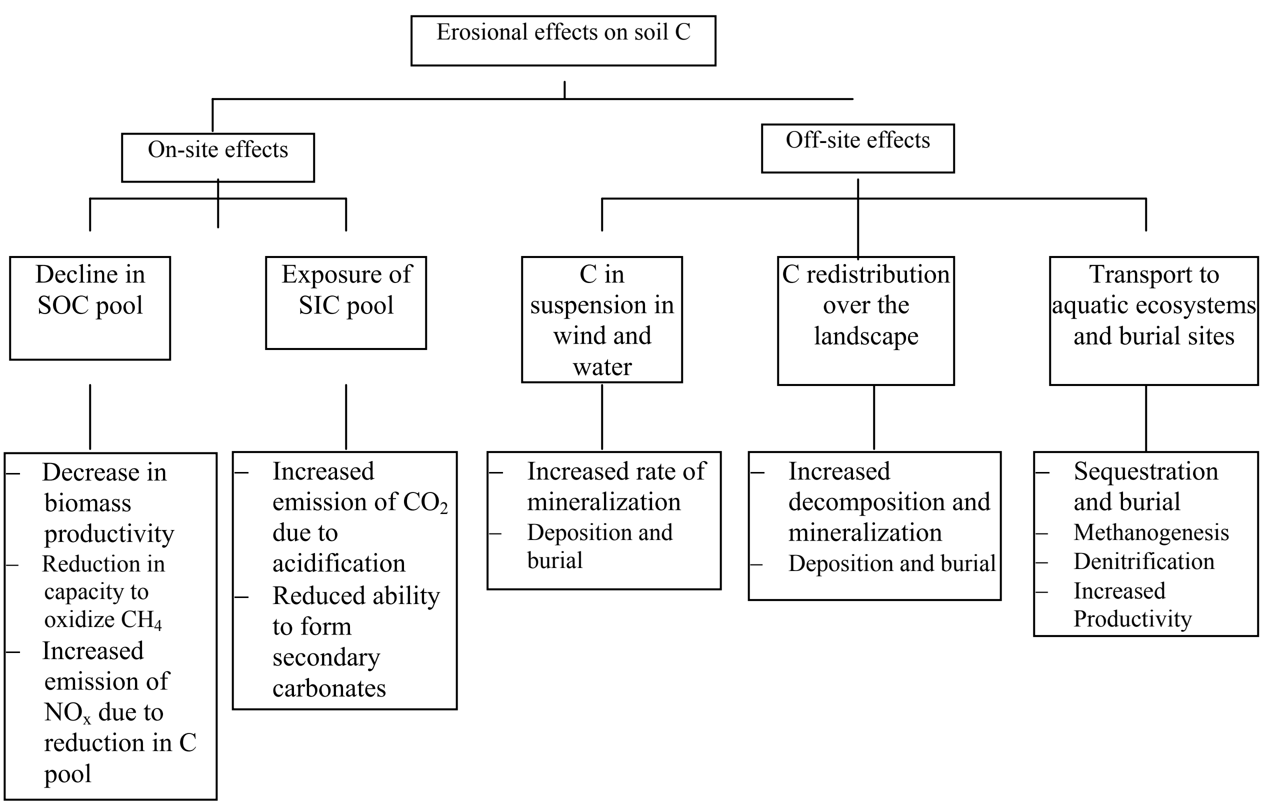

Figure 1. Soil and fluvial processes influencing the fate of C impacted by soil erosion.

Table 1. Erosional effect on SOC pool of a Fragipan soil to 1-m depth in Tennessee, USA (recalculated from Rhoton and Tyler, 1990).

Erosion phase	SOC pool to 1-m Depth (Mg C ha^{-1})	SOC loss due to erosion
Virgin	61.2	--
Slightly eroded	31.8	--
Moderately eroded	19.4	12.4
Severely eroded	18.7	13.1

SOC = SOM ÷ 1.75

Table 2. Soil management effects on loss of soil organic C with erosion for two soils cultivated to cassava in Cali, Colombia (recalculated from Ruppenthal, 1995).

Treatment	Quilichao 1990-91	Quilichao 1991-92	Mondomo 1990-91	Mondomo 1991-92
	----------------- kg ha^{-1} -----------------			
Bare fallow	4750	7190	6459	4287
Flat cropping	283	189	447	63
Intercropping	734	54	183	44
Grass barriers	116	121	118	17

Soil carbon was computed by dividing organic matter content with 1.75

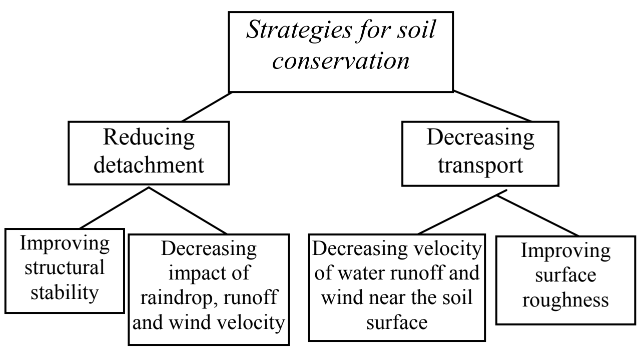

Figure 2. Soil management strategies for soil conservation.

Table 4. Soil organic carbon loss from farmland in Zimbabwe (Tagwira, 1992).

Management system	SOC loss (kg ha^{-1} yr^{-1})
I. Traditional farming	
(i) Predominant practice	534
(ii) Tied ridging	21
II. Commercial farming	
(i) Cotton	1154
(ii) Cotton with tied ridging	77
(iii) Corn	231
(iv) Corn with tied ridging	15

Table 5. Estimate of C emission to the atmosphere by accelerated soil erosion.

Region	C loss due to erosion (Pg C yr^{-1})	Reference
USA	0.015	Lal et al. (1998)
Drylands	0.23-0.29	Lal et al. (1999)
World	1.14	Lal (1995)

Table 6. Tillage effects on SOC pool and residence time for duroc loam, Sidney, NE for 0-20 cm depth. Recalculated from Six et al. (1998)

Treatment	SOC (kg/m^2)	Bulk density (Mg/m^3)	Mean residence time (yr)
Native sod	4.1a	1.05	--
No till	3.4ab	1.18	73
Conventional till	2.9b	1.26	44

Table 7. Reduced CO_2 emission by conservation tillage for a loamy silt soil at Legrand, NE Italy for a 7-year period. Borin et al. (1997)

Parameter	Conventional tillage	Ridge tillage	No tillage
SOC pool (Mg/ha)	48.3	52.5	50.6
?C (kg/ha/yr)	--	593	770
Stored CO_2 in soil (kg/ha/yr)	--	2174	2823
Fuel consumption (kg/ha/yr)	116	64	43
Saved CO_2 in fuel (kg/ha/yr)	--	162	227
Saved CO_2 total (kg/ha/yr)	--	2336	3050

Table 3. Erosion and cultivation effects on losses of soil organic carbon from an Alfisol in western Nigeria (recalculated from Lal, 1976).

Treatment	1% 1972	1% 1973	5% 1972	5% 1973	10% 1972	10% 1973	15% 1972	15% 1973
	---------- kg ha^{-1} ----------							
Bare fallow	14.5	16.0	184.3	145.3	200.0	280.0	510.2	230.6
Maize-maize (mulch)	0	0	0.0	0	1.2	0	1.1	0
Maize-maize (plow till)	12.1	1.3	27.5	2.4	52.9	16.6	99.1	36.1
Maize-cowpea (no till)	3.5	0	16.2	0	57.4	0	78.7	0
Cowpea-maize (plow till)	1.1	5.0	7.1	23.0	18.6	19.7	16.6	113.1

Table 8. Soil fertility management and SOC content of soils in India (1971-1989). Adapted from Nambiar and Meelu (1996). NPKSM refers to nitrogen, phosphorus, potassium, sulfur and manure, respectively.

Treatment	Soil Type					
	Alluvial	Vertisol	Redloam	Laterite	Sub-montane	Foothill
	----%					
Initial (1971)	0.21	0.59	0.45	0.27	0.79	1.48
Unmanured	0.27	0.63	0.30	0.43	0.74	0.54
NPK	0.30	0.56	0.35	0.56	0.96	0.86
NPKSM	0.40	1.11	0.38	0.80	1.57	1.45
CD (.05)	0.03	0.06	0.01	0.12	0.23	0.08
	Ludhiana	Jabalpur	Ranchi	Bhub	Palampur	Pantnagar

Table 9. Fallow elimination and SOC pool for 0-15 cm depth in a weld loam in Akron, CO.Recalculated from Bowman et al. (1995)

Treatment	1993	1997	?SOC
	--------Mg ha^{-1}-------		Mg ha^{-1} yr^{-1}
With fallow	14.7	15.4	
W/o fallow	15.4	16.6*	+0.3

Table 10. Cropping intensity and SOC pool for 0-15 cm depth in a weld loam in Akron, CO. Adapted from Bowman et al. (1995)

Cropping intensity	SOC pool (Mg ha^{-1})
0.50	15.0b
0.67	15.8ab
0.75	15.8ab
1.0	17.0a

Table 11. Biomass production on degraded lands in Jhansi, India with sylvopastoral system. Rai (1999)

Treatment	1990	1991	1992	1993	1994	1995	1996
	---- Mg ha^{-1} ----						
Natural/Traditional	3.5	3.6	3.5	3.0	3.1	2.1	3.3
Improved	2.0	7.6	7.5	10.4	5.5	7.2	6.8

estimated at 21.2 Pg by water erosion and 3.7 Pg by wind erosion (Lal, 1999). The total historic C loss of 24.9 Pg due to accelerated erosion is 45% of the estimated 55 Pg of C lost from world soils (IPCC, 1995).

Soil Conservation and SOC Pool

Soil conservation implies reducing risks of soil erosion to the tolerable limit, which in most soils of the tropics and sub-tropics may be as low as 1 to 2 Mg ha^{-1} yr^{-1} (Lal, 1998). In a broader context, soil conservation may also imply improving soil quality through controlling erosion, enhancing SOC content, improving soil structure, accentuating activity of soil fauna etc. Soil conservation may be achieved through reduction of soil detachment and its transport by agents of erosion (Fig. 2). Improving soil's resistance to forces causing detachment and transport involves enhancing soil structure. Some agricultural practices with favorable impact on soil structure include growing cover crops, sowing crops with conservation tillage, maintaining required level of soil fertility, and converting marginal and degraded lands to restorative land uses. All these practices lead to C sequestration through improvement of soil structure and enhancement of soil quality.

I. Cover crops: Through formation of a quick and protective ground cover, cover crops improve SOC content, enhance soil biodiversity, improve soil structure and minimize risks of soil erosion. In addition to erosion control, several experiments around the world have also documented increase in SOC content. In Nigeria, Lal et al., 1978; 1979 observed improvements in SOC content by growing cover crops. In Ohio, Lal et al. (1998d) observed significant increases in SOC content after 5 years of growing tall fescue and smooth bromegrass. In Auburn, Alabama, Mitchell et al. (1996) observed an increase in SOC content with incorporation of legume cover crops in continuous corn, and in a 2-year or 3-year rotation. Appropriate cover crops differ among soil types and ecoregions. Further, integrating cover crops in agripastoral systems may improve soil structure and enhance SOC content.

II. Conservation tillage: Beneficial impacts of conservation tillage in decreasing runoff and soil erosion are widely recognized (Lal, 1989; Shipitalo and Edwards, 1998). When used in conjunction with crop residue mulch and cover crops, conservation tillage improves soil structure and enhances SOC pool (Paustian et al., 1997; Dick et al., 1998). The data in Table 6 from Sydney, Nebraska show that use of no-till system increased SOC content and the residence time of carbon in soil (Six et al., 1998) probability due to encapsulation of SOC within stable aggregates and alteration in soil quality. The benefits of conservation tillage in C sequestration are due both to increase in SOC content (Dick et al., 1998; Riezebo and Loerts, 1998), decrease in CO_2 emissions caused by plowing (Reicosky et al., 1998), and to reduction in fuel consumption. The data in Table 7 from Italy by Borin et al. (1997) show the cumulative benefits of conservation tillage in reducing CO_2 emissions. In comparison with conventional tillage, the cumulative reduction in CO_2 emissions was 2336 kg ha^{-1} yr^{-1} with ridge tillage and 3050 kg ha^{-1} yr^{-1} with no tillage (Table 7). Additional savings in energy use with conservation tillage can be achieved through adoption of integrated pest and nutrient management technologies.

Using crop residue and other biomass as mulch is an integral component of a conservation tillage system. Merely reducing the frequency of plowing or totally eliminating tillage are not enough to avail full ecological benefits of conservation tillage. It is the presence of crop residue mulch on the soil surface that increases infiltration rate, decreases runoff and soil erosion, improves soil structure (Lal et al., 1980) and sequesters C in the pedosphere.

III. Soil fertility management: Nutrient management isessential to increasing crop yield, improving soil quality, decreasing risks of soil erosion (through protective ground cover establishment) and improving SOC content. Subsistence agricultural practices, followed in sub-Saharan Africa and elsewhere in the tropics, lead to depletion of soil fertility (Smaling and Oenema, 1998) and reduction in SOC content. The data in Table 8 from long-term soil fertility management experiments in India show that application of nutrients and manure maintained or increased SOC content even in harsh (hot and dry) climates. The long-term experiment at Rothamsted, U.K. have documented continuous increase in SOC content even after 150 years of manure application at the rate of 35 Mg ha^{-1} yr^{-1} (Powlson et al., 1998).

IV. Agricultural intensification: Adopting "good" or recommended farming practices is an important and effective strategy for soil conservation (Lal, 1989). Recommended farming practices involve agricultural intensification on prime agricultural land through use of improved varieties, adoption of appropriate cropping systems that enhance cropping intensity, and elimination of summer fallow. Soil erosion risks are extremely high on plowed uncropped land, and accelerated soil erosion accentuates the depletion of SOC pool. Experiments conducted in Akron, Colorado have shown an increase in SOC pool at the rate of 0.3 Mg C ha^{-1} yr^{-1} in 0 to 15-cm depth by elimination of summer fallow (Table 9). In fact, the SOC pool in 0 to 15-cm depth increased linearly with increase in cropping intensity. Doubling of cropping intensity from 0.5 to 1.0 y elimination of summer fallow significantly increased SOC pool from 15 to 17 Mg ha^{-1} (Table 10). Improvements in crop yield through adoption of recommended technology enhance SOC pool and improve soil quality (Flach et al., 1997; Bowman et al., 1999).

V. Conservation Reserve Program and Conservation Buffers: Conversion of marginal agricultural land, to restorative land use (e.g. natural regrowth, establishing grasses, shrubs or trees) reduces soil erosion and increases SOC pool. Follett (1993) estimated that CRP sequesters SOC at the rate of about 1 Mg C ha^{-1} yr^{-1}. The data on SOC dynamics in the top 0-5 cm depth for a set-aside steep land in U.K. show increase in SOC content at the rate of 0.2% yr^{-1} and drastically low rates of water runoff and soil erosion. The rate of sequestration may differ among soil types, management, and ecoregional factors. Establishing grasses and trees on set aside land, and developing a rotational grazing system may further enhance the SOC pool. The data in Table 11 from a degraded soil in central India show 1.8 to 3.5 times increase in SOC pool due to adoption of an agripastoral system in a highly degraded soil. Similar observations on set-aside land have been reported from U.K. by Fullen (1998).

Global Potential of Soil Conservation for C Sequestration

Accelerated soil erosion is a serious economic and environmental issue of modern era. It is a biophysical process driven by socio-economic, cultural, and political factors. Consequently, effective soil conservation strategies have to be based on integrated approaches that combine biophysical techniques with socio-economic and cultural considerations. In addition to erosion control, acceptable soil conservation technologies must have numerous ancillary benefits such as improvement in water quality, enhancement of biodiversity, and soil C sequestration for mitigating the greenhouse effect. Restoration of eroded soils enhances C sequestration (Izaurralde et al., 1997), and improves soil quality (Reeves, 1997). There are at least three opportunities for C sequestration through soil conservation:

I. Historic C lost from eroded soils estimated at 24.9 Pg can be resequestered through soil restorative measures including afforestation and establishment of appropriate vegetative cover, land application of biosolids, nutrient management etc.
II. Effective soil conservation, if adopted on a global scale, can reduce erosion-related emissions of 1.1 Pg C yr^{-1}.
III. Adoption of conservation effective farming practices can lead to reduction in soil erosion, improvement in soil quality, and enhancement of SOC pool. Important agricultural practices with potential for C sequestration include conservation tillage, crop residue mulch, CRP and conservation buffers including management of riparian zone, elimination of summer fallow, soil fertility management and adoption of recommended (improved) cropping systems.

The maximum potential of SOC sequestration in soil, terrestrial and associated aquatic ecosystems are about 3 Pg C yr^{-1}. In practice, realization of 30 to 50% of this potential would be an excellent achievement. In addition to being finite, the soil C sink is also transient. While being highly labile, this sink can be filled over a 25 to 50 year period. Thus, soil C sink is a short-term solution to the serious problem of greenhouse effect. The long-term solution of the potential global warming threat lies in finding alternatives to fossil fuel. Nonetheless, soil C sequestration buys us the much-needed time during which other energy-related alternatives take effect. Soil C sequestration is a win-win-

win strategy. While enhancing soil productivity, it improves water quality and mitigates the greenhouse effect.

REFERENCES

Borin, M., C. Menini and L. Saratori. 1997. Effects of tillage systems on energy and C balance in north-eastern Italy. Soil & Tillage Res. 40: 209-226.

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

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

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

Fahnestock, P., R. Lal and G.F. Hall. 1996. Land use and erosional effects on two Ohio Alfisols. I. Soil Properties. J. Sust. Agric. 7: 63-84.

Flach, K.W., T.O. Barnwell, R. and P. Crosson. 1997. Impacts of agriculture on atmospheric CO_2. In: E. Paul, K. Paustian, E.T. Elliott and C.V. Cole (eds) "Soil Organic Matter in Temperate Agroecosystems: Long-Term Experiments in North America. CRC Press, Boca Raton, FL: 3-13.

Follett, R.F. 1993. Global climate change, U.S. agriculture and carbon dioxide. J. Prod. Agric.6: 181-190.

Fullen, M.A. 1998. Effects of grass ley set-aside on runoff erosion and organic matter levels on sandy soils in east Shropshire, U.K. Soil & Tillage Res. 46: 41-49.

Gachene, C.K.K., N.J. Jarvis, H. Liner and J.P. Mbari. 1997. Soil erosion effects on soil properties in highland areas of central Kenya. Soil Sci. Soc. Am. J. 61: 559-564.

Geng, G.-Q and D.R. Coote. 1991. The residual effect of soil loss on the chemical and physical quality of three soils. Geoderma 48: 415-429.

Gregorich, E.G. and Anderson, D.W. 1985. Effects of cultivation and erosion on soils of four toposequences in the Canadian prairies. Geoderma 36: 343-354.

Gregorich, E.G., D.A. Angers, C.A. Campbell, M.R. Carter, C.F. Drury, B.H. Ellert, P.H. Groenevelt, D.A. Holmstrom, C.M. Monreal, H.W. Rees, R.P. Voroney and T.J. Vyn. 1995. Changes in soil organic matter. In: D.F. Acton and L.J. Gregorich (eds) "The Health of Our Soils: Towards Sustainable Agriculture in Canada." Agric. & Agri-Food Canada, Ottawa, Canada: 41-50.

Gregorich, E.G., K.J. Greer, D.W. Anderson and B.C. Liang. 1998. Carbon distribution and losses: erosion and deposition effects. Soil Till. Res. 47: 291-302.

IPCC 1995. Climate Change 1995, Working Group I. IPCC, Cambridge Univ. Press, Cambridge, 1996.

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

Janzen, H.H., C.A. Campbell, R.C. Izaurralde, B.H. Ellert, N. Juma, W.B. McGill and R.P. Zentner. 1998. Management effects on soil C storage on the Canadian prairies. Soil & Tillage Res. 47: 181-195.

Kreznor, W.R., K.R. Olson, W.L. Banwart and D.L. Johnson. 1989. Soil, landscape, and erosion relationships in a northwest Illinois watershed. Soil Sci. Soc. Am. J. 53: 1763-1771.

Lal, R. 1976. Soil erosion problems on Alfisols in western Nigeria and their control. IITA Monograph 1, IITA, Ibadan, Nigeria, 208pp.

Lal, R. 1980. Losses of plant nutrients in runoff and eroded soil. T. Rosswall. Nitrogen Cycling in West African Ecosystems: 31-38.

Lal, R. 1989. Conservation tillage for sustainable agriculture. Adv. Agron. 42: 85-197.

Lal, R. 1994. Global overview of soil erosion. In: R.S. Baker (ed) "Soil and Water Science: Key to Understanding Our Global Environment." Soil Sci. Soc. Amer. Special Publication No. 41, Madison, WI: 39-51.

Lal, R. 1995. Global soil erosion by water and carbon dynamics. In: R. Lal, J. Kimble, E. Levine and B.A. Stewart (eds) "Soil Management and Greenhouse Effect," Lewis Pub., Boca Raton, FL.

Lal, R. 1998. Soil erosion impact on agronomic productivity and environment quality. Critical Review in Plant Sciences 17: 319-464.

Lal, R. 1999. Soil erosion control for C sequestration and greenhouse effect mitigation. Prepared for ISCO Background Paper "Sustaining the Global Farm," 10th ISCO Conference, 23-28 May 1999, Purdue University, West Lafayette, IN.

Lal, R., G.F. Wilson and B.N. Okigbo. 1978. No tillage farming after various grasses and leguminous cover crops in tropical Alfisols. I. Crop performance. Field Crops. Res. 1: 71-84.

Lal, R., G.F. Wilson and B.N. Okigbo. 1979. Changes in properties of an Alfisol by various cover crops. Soil Sci. 127: 377-382.

Lal, R., D. De Vleeschauwer and R.M. Nganje. 1980. Changes in properties of a newly cleared tropical Alfisol as affected by mulching. Soil Sci. Soc. Am. J. 44: 827-833.

Lal, R., J. Kimble, E. Levine and B.A. Stewart (eds). 1995a. Soils and Global Change. Adv. in Soil Sci., Lewis Pub., Chelsea, MI, 440pp.

Lal, R., J. Kimble, E. Levine and B.A. Stewart (eds). 1995b. Soil Management and Greenhouse Effect. Adv. in Soil Sci., Lewis Pub., Chelsea, MI, 385pp.

Lal, R., J.M. Kimble, R.F. Follett and B.A. Stewart (eds). 1998a. Soil Processes and the Carbon Cycle. CRC Press, Boca Raton, FL: 609pp.

Lal, R., J.M. Kimble, R.F. Follett and B.A. Stewart (eds). 1998b. Management of Carbon Sequestration in Soils. CRC Press, Boca Raton, FL: 457pp.

Lal, R., J.M. Kimble, R.F. Follett and C.V. Cole (eds). 1998c. Potential of U.S. Cropland to Sequester C and Mitigate the Greenhouse Effect. Ann Arbor Press, Chelsea, MI, 128pp.

Lal, R., P. Henderlong and M. Flowers. 1998d. Forages and row cropping effects on soil organic carbon and N contents. In: R. Lal, J.M. Kimble, R.F. Follett and B.A. Stewart (eds) "Management of C Sequestration in Soil," CRC Press, Boca Raton, FL: 365-379.

Lal, R., J.M. Kimble and B.A. Stewart (eds). 1999a. Pedogenic Carbonates and Global Change. Ann Arbor Press, Chelsea, MI (in press).

Lal, R., J.M. Kimble and B.A. Stewart (eds). 1999b. Carbon Pools and Dynamics In Tropical Ecosystems. Ann Arbor Press, Chelsea, MI (in press).

Lal, R., J.M. Kimble and B.A. Stewart (eds). 1999c. Carbon Pools and Dynamics In Cold Ecoregions. Ann Arbor Press, Chelsea, MI (in press).

Lal, R., H.M. Hasson and J. Dumanski. 1999. Desertification control to sequester C and mitigate the greenhouse effect. In: N.J. Rosenberg, R.C. Izaurralde and E.L. Malone (eds) Conf. Proc., St. Michael Conference, 3-5 December 1998, MD: 83-137.

Leys, J. and G. McTainsh. 1994. Soil loss and nutrient decline by wind erosion - cause for concern. Aust. J. Soil Water Cons. 7:

30-35.
Ludwig, W., J.L. Probst and S. Kempe. 1996. Predicting the oceanic input of organic carbon in continental erosion. Global Biogeochemical Cycles 10: 23-41.
Massey, H.F. and M.L. Jackson. 1952. Selective erosion of soil fertility constituents. Soil Sci. Soc. Am. Proc. 16: 353-356.
Mitchell, C.C. and J.A. Entry. 1998. Soil C, N and crop yields in Alabama's long-term old rotation cotton experiment. Soil & Tillage Res. 47: 331-338.
Mitchell, C.C., F.J. Arriaga, J.A. Entry, W.R. Goodman, J.L. Novak, D.W. Reeves, M.W. Runge and G.J. Traxler. 1996. 100 years of sustainable cropping research. Alabama Agric. Exp. Stn. Bulll., Auburn Univ., AL, 26pp.
Moore, T.R. 1998. Dissolved organic carbon: sources, sinks and fluxes and role in the soil C cycle. In: R. Lal, J.M. Kimble, R.F. Follett and B.A. Stewart (eds) "Soil Processes and the Carbon Cycle," CRC Publishers, Boca Raton, FL: 281-292.
Nambiar, K.K.M. and O.P. Meelu. 1996. Chemical degradation leading to soil fertility decline and use of integrated nutrient management system for degraded soils. In: T.D. Viswas and G. Narayanasamy (eds) "Soil Management in Relation to Land Degradation and Environment," Ind. Soc. Sci., New Delhi, India: 102-113.
Oldeman, L.R. 1994. The global extent of soil degradation. In: D.J. Greenland and I. Szabolcs (eds) "Soil Resilience and Sustainable Use," CAB International, Wallingford, U.K.: 99-118.
Paul, E.A., R.F. Follett, S.W. Leavitt, A. Halvorson, G. Peterson and D. Lyon. 1997. Determination of the pool sizes and dynamics of soil organic matter: use of carbon dating for Great Plains soils. Soil Sci. Soc. Amer. J. 61: 1058-1067.
Paustian, K., .P. Collins and E.A. Paul. 1997. Characterization of soil organic carbon relative to its stability and turnover. In: E. Paul, K. Paustian, E.T. Elliott and C.V. Cole (eds) "Soil Organic Matter in Temperate Agroecosystems: Long-Term Experiments in North America. CC Press, Boca Raton, FL: 51-71.
Powlson, D.S., P. Smith, K. Coleman, J.U. Smith, M.J. Glendining, M. Körschens and U. Franko. 1998. A European network of long-term sites for studies on soil organic matter. Soil & Tillage Res. 47: 263-274.
Rai, P. 1999. Growing greener and increasing the production of wastelands. Wastelands News XIV: 49-50.
Reeves, D.W. 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil & Tillage Res. 43: 131-168.
Rhoton, F.E. and D.D. Tyler. 1990. Erosion-induced changes in the properties of a Fragipan soil. Soil Sci. Soc. Am. J. 54: 223-228.
Riezebo, H. Th. and A.C. Loerts. 1998. Influence of land use change and tillage practice on soil organic matter in southern Brazil and eastern Paraguay. Soil & Tillage Res. 49: 271-275.
Ruppenthal, M. 1995. Soil conservation in Andean cropping systems. Hohenheim Tropical Agricultural Series, Univ. of Hohenheim, Stuttgart, Germany, 110pp.
Scherr, S.J. and S. Yadav. 1995. Land degradation in the developing world: Implications for food, agriculture and the environment to 2020. 2020 Vision for Food, Agriculture and Environment Discussion Paper 14. IFPRI, Washington, D.C.
Scherr, S.J. 1999. Soil Degradation: A Threat to Developing Country Food Security By 2020. IFPRI Food Agric. and Env. Disc. Paper 27, Washington, D.C., 63pp.
Shipitalo, M.J. and W.M. Edwards. 1998. Runoff and erosion control with conservation tillage and reduced-input practices on cropped watersheds. Soil Till. Res. 46: 1-12.
Six, J., E.T. Elliott, K. Paustian and J.W. Doran. 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci. Soc. Am. J. 62: 1367-1377.
Smaling, E.M.A. and O. Oenema. 1998. Estimating nutrient balances in agro-ecosystems at different scales. In: R. Lal, W.H. Blum, C. Valentine and B.A. Stewart (eds) "Methods for Assessment of Soil Degradation," CRC Publishers, Boca Raton, FL: 229-251.
Stallard, R.F. 1998. Terrestrial sedimentation and the C cycle: coupling weathering and erosion to carbon burial. Global Biogeochemical Cycles 12: 231-237.
Tagwira, F. 1992. Soil erosion and conservation techniques for sustainable crop production in Zimbabwe. J. Soil Water Conserv. 47: 370-374.
Walling, D.E. 1987. Rainfall, runoff and erosion of the land: A global review. In: K.J. Gregory (ed) "Energetics of Physical Environment," J. Wiley & Sons, Chichester, U.K.: 89-117.
Yadav, J.S.P. 1996. Extent, nature, intensity and causes of land degradation in India. In: T.D. Viswas and G. Narayanasamy (eds) "Soil Management in Relation to Land Degradation and Environment," Ind. Soc. Sci., New Delhi, India: 1-26.
Zobisch, M.A., C. Richter, B. Heiligtag and R. Schlott. 1995. Nutrient losses from cropland in the central highlands of Kenya due to surface runoff and soil erosion. Soil Till. Res. 33: 109-116.