SOIL CARBON SEQUESTRATION IN INDIA *

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Abstract. With a large land area and diverse ecoregions, there is a considerable potential of terrestrial/soil carbon sequestration in India. Of the total land area of 329 million hectares (Mha), 297 Mha is the land area comprising 162 Mha of arable land, 69 Mha of forest and woodland, 11 Mha of permanent pasture, 8 Mha of permanent crops and 58 Mha is other land uses. The soil organic carbon (SOC) pool is estimated at 21 Pg (petagram = Pg = 1×10^{15} g = billion ton) to 30-cm depth and 63 Pg to 150-cm depth. The soil inorganic carbon (SIC) pool is estimated at 196 Pg to 1-m depth. The SOC concentration in most cultivated soils is less than 5 g/kg compared with 15 to 20 g/kg in uncultivated soils. Low SOC concentration is attributed to plowing, removal of crop residue and other biosolids, and mining of soil fertility. Accelerated soil erosion by water leads to emission of 6 Tg C/y. Important strategies of soil C sequestration include restoration of degraded soils, and adoption of recommended management practices (RMPs) of agricultural and forestry soils. Potential of soil C sequestration in India is estimated at 7 to 10 Tg C/y for restoration of degraded soils and ecosystems, 5 to 7 Tg C/y for erosion control, 6 to 7 Tg C/y for adoption of RMPs on agricultural soils, and 22 to 26 Tg C/y for secondary carbonates. Thus, total potential of soil C sequestration is 39 to 49 (44 ± 5) Tg C/y.

1. Introduction

Despite impressive gains in cereal production by India, from 50 million tonnes in 1947 to more than 219 million tonnes in 2000 (Swaminathan, 2000; FAO, 2001), there remain two serious but inter-related problems. One, expected food demand by 2050 is 300 million tonnes of cereals and must be met from the shrinking land resource base. Two, there are severe problems of degradation of soil and water resources leading to reduction in use efficiency of inputs (e.g., fertilizer, irrigation, tillage), pollution of surface and ground waters, and emission of greenhouse gases (GHGs) from soil/terrestrial/aquatic ecosystems into the atmosphere. Thus, the objective of sustainable development is to increase production per unit area, time and input; enhance quality of soil and water resources; and sequester carbon (C) in terrestrial and aquatic ecosystems leading to improvements in quality of natural resources (soil, water and atmosphere).

Climate change is among the major global issues of the 21st century. Anthropogenic activities have led to notable changes in the earth's climate including

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increase in the global temperature over the 20th century by 0.6 ± 0.2 °C at an average rate of increase of 0.17 °C/decade since 1950, sea level rise over the 20th century of 0.1 to 0.2 m, increase in precipitation of 0.5 to 1.0%/decade, and increase in frequency of extreme events and heavy precipitation by 2 to 4% (IPCC, 2001). Climate change is attributed to increase in atmospheric concentration of several GHGs by fossil fuel combustion, land use change and deforestation, and human-induced soil degradation. Whereas the contributions of fossil fuel combustion to increase in atmospheric concentration of GHGs are known, those of terrestrial ecosystems are not widely recognized either in relation to emissions (by deforestation and soil cultivation) or C sequestration by ecosystem restoration, conversion to judicious land use and adoption of RMPs in managed ecosystems.

This manuscript reviews the status of soil resources of India, specifically addresses the issue of soil C sequestration through restoration of degraded soils and ecosystems and adoption of recommended practices (RMPs) on managed ecosystems, establishes a link between soil quality and soil organic carbon (SOC) concentration, and identifies policies towards sustainable management of natural resources for achieving food security and mitigating climate change.

2. Land Use and Soil Resources of India

The total geographical area of India is 328.7 million hectares (Mha) or about 2.5% of the total land area of the world (Table I). It is home to 1.1 billion or 16% of the world population. India is the second most populous and densely populated country in the world. Principal land uses include 161.8 Mha of arable land (11.8% of the world) of which 57.0 Mha (21.3% of the world) is irrigated, 68.5 Mha of forest and woodland (1.6% of the world), 11.05 Mha of permanent pasture (0.3% of the world) and 7.95 Mha of permanent crops (6.0% of the world). The large land base, similar to that of the U.S.A. and China or Australia, has a potential to sequester C and enhance productivity while improving environment quality. The Green Revolution of the 1970s needs to be revisited to enhance production once again and to address environment issues of the 21st century including climate change.

3. Soils of India and their Soil Carbon Pool

In accord with a wide range of ecoregions (Sehgal et al., 1990), India is also endowed with diverse soils of varying characteristics (Table II). Out of the total land area of 297.3 Mha, the principal soil types include 81.1 Mha of Alfisols (27.3%), 60.4 Mha of Vertisols (20.3%), 51.7 Mha of Inceptisols (17.4%), 36.6 Mha of Ultisols (12.3%), 24.8 Mha of Entisols (8.3%), 18.3 Mha of Aridisols (6.2%), 1.8 Mha of Mollisols (0.6%), and 0.8 Mha of Gelisols (0.27%). These diverse soils

Table I
Land use in India and the world in 1999 (FAO, 2001)

Land use	World (Mha)	India (Mha)
Total area	13,414.2	328.7
Land area	13,050.5	297.3
Permanent crops	132.4	7.95
Permanent pasture	3,489.8	11.05
Forest and woodland	4,172.4	68.5
Agricultural area	4,961.3	180.8
Arable land	1,369.1	161.8
Irrigated land	267.7	57.0

are also characterized by a wide range of SOC concentration, which is generally related to clay content (Ali et al., 1966) and climate (Jenny and Raychaudhary, 1960). In general, SOC concentration increases with increase in clay content and rainfall, and decreases with increase in mean annual temperature. Some of these soils have been cultivated for centuries, and often with low off-farm input, based on systems that involve removal of crop residue and dung for fuel and other purposes. Consequently, SOC concentration of most soils is low. The data in Table II show that SOC concentration of most soils is less than 10 g/kg, and is generally less than 5 g/kg. Because of the low clay contents, the SOC concentration is especially low in alluvial soils of the Indo-Gangetic Plains, coarse-textured soils of southern India, and arid zone soils of northwestern India (Dhir et al., 1991).

The prevalent low levels of SOC concentrations are attributed to soil-mining practices of excessive tillage, imbalance in fertilizer use, little or no crop residue returned to the soil, and severe soil degradation. Consequently, even the well-established relationship between climate (temperature and precipitation) (Jenny and Raychaudhary, 1960) and SOC concentration does not exist. The data in Table III show consistently low SOC concentration in soils with rainfall regime of 500 to 1000 mm/y. Under native system and undisturbed soils, however, the SOC concentration of most soils is high (Jenny and Raychaudhuri, 1960). Total SOC pool in soils of India is estimated at 21 Pg to 30 cm depth and 63 Pg to 150 cm depth (Table IV). The SOC pool in soils of India is 2.2% of the world pool for 1 m depth and 2.6% to 2 m depth. The data in Table V shows a decline in SOC concentration of cultivated soils by 30 to 60% compared with the antecedent level in undisturbed ecosystems even by 1960.

The total soil C pool also comprises the soil inorganic carbon (SIC), which is generally high in calcareous soils of arid and semi-arid regions. Calcareous soils are widely distributed covering 54% of the geographical area of India, but

Table II
Soil organic carbon (SOC) concentration of some soils in India (adapted from Nambiar, 1994)

Location	Soil type	Texture	SOC content (g/kg)
Bangalore, KT	Haplustalf	Sandy loam	5.5
Barrackpore, WB	Eutrochrept	Sandy loam	7.1
Bhubaneswar, O	Haplaquept	Sandy	2.7
Coimbatore	Vertic Ustochrept	Clay loam	3.0
Delhi	Ustochrept	Sandy loam	4.4
Hydrabad, AP	Tropaquept	Sandy clay loam	5.1
Jabalpur, MP	Chromustert	Clayey	5.7
Ludhiana, Pb	Ustochrept	Loamy sand	2.1
Palampur, HP	Hapludalf	Silty clay loam	7.9
Pantnagar, UP	Hapludoll	Silty clay loam	14.8
Rauchi, B	Haplustalf	Silty clay	4.5

Table III
Soil organic carbon (SOC) concentration of soils of India in relation to the rainfall regime and temperature (Sekhon and Meelu, 1994)

Rainfall (mm/y)	Mean annual temperature (°C)	SOC content (g/kg)	
		Surface	Sub-soil
<500	25.9–26.7	1.2–8.0	1.2–4.0
500–1000	23.6–27.9	1.8–12.5	0.7–11.7
>1000	24.4–27.2	2.6–9.0	2.3–8.4

especially occur in Rajsthan, Gujrat, Punjab, Haryana, Uttar Pradesh, Maharashtra, Karnatka, Tamil Nadu, Andhra Pradesh and parts of Madhya Pradesh and Bihar (Pal et al., 2000). Total SIC pool in soils of India is estimated at 196 Pg to 1-m depth (Pal et al., 2000). The SIC pool in world soils is estimated at 722 Pg to 1-m depth (Batjes, 1996). Therefore, the SIC pool in soils of India comprises about 27% of the world total. Pedogenic or secondary carbonates play a significant role in C sequestration through formation of $CaCO_3$ or $MgCO_3$ and leaching of $Ca(HCO_3)_2$ especially in irrigated systems. The rate of formation of secondary carbonates may range from 30 to 130 kg/ha/y (Pal et al., 2000).

Table IV

Organic carbon pool in soils of India and the world (adapted from Velayuthan et al., 2000; Eswaran et al., 1993, 1995)

Soil order	India		World	
	0–30 cm (Pg)	0–150 cm (Pg)	0–25 cm (Pg)	0–100 cm (Pg)
Alfisols	4.22	13.54	73	136
Andisols	–	–	38	69
Aridisols	7.67	20.30	57	110
Entisols	1.36	4.17	37	106
Histosols	–	–	26	390
Inceptisols	4.67	15.07	162	267
Mollisols	0.12	0.50	41	72
Oxisols	0.19	0.49	88	150
Spodosols	–	–	39	98
Ultisols	0.14	0.34	74	101
Vertisols	2.62	8.78	17	38
Total	20.99	63.19	652	1555

Table V

Depletion of soil organic carbon concentration of cultivated compared with that in undisturbed soils (adapted from Jenny and Raychaudhary, 1960; Swarup et al., 2000)

Region	SOC content		Percent reduction
	Cultivated (g/kg)	Native (g/kg)	
1. Northwest India			
Indo-Gangetic Plains	4.2 ± 0.9	104. ± 3.6	59.6
Northwest Himalaya	24.3 ± 8.7	34.5 ± 11.6	29.6
2. Northeast India	23.2 ± 10.4	38.3 ± 23.3	39.4
3. Southeast India	29.6 ± 30.1	43.7 ± 23.4	32.3
4. West coast	13.2 ± 8.1	18.6 ± 2.1	29.1
5. Deccan Plateau	7.7 ± 4.1	17.9 ± 7.6	57.0

Table VI
Estimates of soil degradation in India (FAO, 1994; Yadav, 1996; Karale et al., 1991)

Process	GLASOD (Mha)	Others (Mha)
Water erosion	32.8	74–177
Wind erosion	10.8	13–39
Soil fertility decline	29.4	26
Waterlogging	3.1	7–9
Salinization	4.1	7–26
Lowering of watertable	0.2	NA
Total area	45.1	175

Table VII
Estimate of desertification in India (recalculated from Dregne and Chou, 1994)

Land use	Desertified area (Mha)	Total area in the dry season (Mha)
Irrigated cropland	8.1	23.3
Rainfed cropland	60.0	100.4
Rangeland	34.2	38.1
Total	102.3	161.8

4. Soil Degradation and Soil Organic Carbon Pool

Soil degradation, decline in soil quality with an attendant reduction in biomass productivity and environment moderating capacity, has severe adverse impacts on the SOC pool. In other words, the low SOC pool in soils of India is partly due to the severe problem of soil degradation. Estimates of soil degradation by different processes vary widely (Biswas et al., 1991; Table VI). The GLASOD estimate (FAO, 1994) show that land area affected is 32.8 Mha by water erosion, 10.8 Mha by wind erosion, 29.4 Mha by fertility decline, 4.1 Mha by salinization and 3.1 Mha by inundation. The total area affected by diverse degradative processes is 45 Mha. There is also a severe problem of desertification because 102 Mha out of the 162 Mha or 63% of the dryland area is prone to some degree of desertification (Table VII).

The principal cause of decline in SOC pool in degraded soils is a reduction in biomass productivity and the low amount of crop residue and roots returned to the soil. A typical example of the low SOC pool is in salt-affected soils of Haryana, Andhra Pradesh and West Bengal. Even in the surface 0 to 10 cm layer, the SOC pool may be lower than 5 g/kg (Singh and Bandyopadhyay, 1996).

Accelerated soil erosion depletes the SOC pool severely and rapidly. The SOC fraction is preferentially removed by surface runoff and wind because it is concentrated in the vicinity of the soil surface and has low density (1.2 to 1.5 Mg/m^3 compared with 2.5 to 2.7 Mg/m^3 for the mineral fraction). Consequently, eroded sediments are enriched with SOC pool compared with the field soil with an enrichment ratio of 1.5 to 5.0 (Lal, 1999). The SOC loss by erosion and runoff can be high even on gentle slopes of 0.5 to 3.0% (Banerjee et al., 1991).

Soil erosion is a four-step process. It involves detachment, breakdown, transport and deposition of soil particles. Soil detachment and breakdown are caused by soil slaking or disruption of aggregates by raindrop impact, shearing force of flowing water or blowing wind, and collision among particles. Breakdown of aggregates exposes SOC hitherto encapsulated and physically protected to microbial processes. Although the fate of SOC displaced along with eroded sediments is governed by a series of complex and interacting processes, a considerable part of it is mineralized leading to release of CO_2 under aerobic conditions and CH_4 under anaerobic environments. Lal (1995) assumed that 20% of the SOC displaced by erosion is mineralized.

Soil erosion in India, soil moved and redistributed over the landscape and transported to aquatic ecosystems and depositional sites, is estimated at about 3 Pg of sediments per year (Table VIII). Of the total loss, 1.2 Pg (40%) of erosion occurs at a rate of 10 to 20 Mg/ha/y, 0.5 Pg (16%) at 20 to 40 Mg/ha/y and an additional 5 Pg (16%) at 40 to 80 Mg/ha/y (Table VIII). Assuming SOC concentration of 8 to 12 g/kg (1%) in eroded sediments, total C displaced by erosional process is 29.8 Tg C/y. Assuming that 20% of the eroded SOC is mineralized, erosion-induced emission of C in India is estimated at 6 Tg C/y (Table IX). This compares with erosion-induced emission of 15 Tg C/y in the U.S. (Lal et al., 1998) and 1.1 Pg C/y in the world (Lal, 1995). Therefore, adoption of conservation-effective measures that reduce erosion may lead to reduction of carbon emissions from erosion-prone ecosystems.

5. Soil Quality and Soil Organic Carbon Concentration

Soil organic matter is an important component necessary to the formation of both micro- and macro-aggregates. The SOC thus encapsulated is protected from the microbial processes, and is sequestered until aggregates are broken or disrupted by plowing and other disruptive processes such as raindrop impact and shearing force of running water. The degree of aggregation and the stability of aggregates

Table VIII
Total soil erosion in India (recalculated from Yadav, 1996)

Soil erosion rate (Mg/ha)	Area affected (Mha)	Total soil erosion (Tg/y)
0–5	80.1	200
5–10	40.6	305
10–20	80.5	1208
20–40	16.0	480
40–80	8.3	498
>80	3.2	288
Total	228.7	2979

Table IX
Soil erosion and C emission in India

Process	Flux
Total soil erosion	2.98 Pg sediments/yr (2979 Tg sediments/yr)
Total C loss at 8–12 g/kg	23.8–35.8 Tg C/yr
C emission at 20% of displaced C	4.8–7.2 Tg C/yr

is directly proportional to SOC concentration. Because of high aggregation, soils with high SOC concentration have high available water holding capacity, low susceptibility to soil erosion, and have low losses of plant nutrients into the ground water. Use efficiency of fertilizer, irrigation and other input is high in soils with high SOC concentration. All other factors remaining the same, soils with high SOC concentration have more agronomic/biomass productivity than those with low SOC concentration (Sandhu et al., 1996). High crop yields in coarse-textured soils of Punjab are due to high input of water and fertilizers. Therefore, enhancement and management of SOC concentration are important to sustainable management of soil and water resources.

6. Technological Options for Soil Carbon Sequestration

The overall strategy is to increase SOC density, distribution of SOC in the subsoil, aggregation, and formation of secondary carbonates. The SOC density can be enhanced by increasing C input into the soil and decreasing losses by erosion, mineralization and leaching. The depth distribution of SOC can be achieved by planting deep-rooted species with high below- ground biomass production. Using

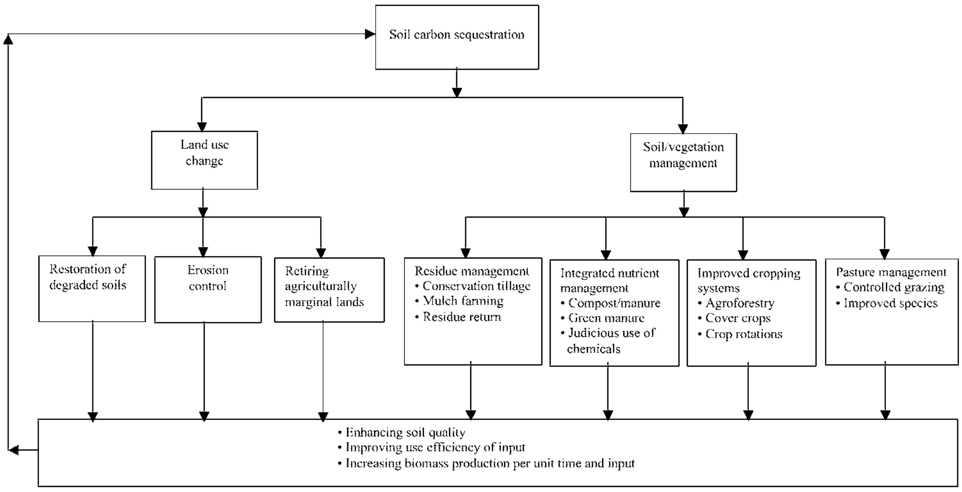

Figure 1. Strategies of soil carbon sequestration.

biosolids and improving earthworm activity can enhance aggregation (Singh and Singh, 1996; Sharma et al., 1995). These strategies can be achieved through a wide range of land use and soil/vegetation management options (Figure 1). Restoration of degraded soils and ecosystems, erosion control and conversion of agriculturally marginal soils to a restorative land use are important options of SOC sequestration (Moench, 1991; Aggarwal et al., 1997; Singh, 1996; Kaur et al., 2000, 2002a,b). Restoring eroded soils can enhance biomass production and improve SOC concentration. Similarly, restoration of salt-affected soils can lead to a drastic increase in SOC pool. Garg (1998) observed a drastic increase in SOC pool of a sodic soil planted to perennials (e.g., mesquite). The SOC pool increased from about 10 Mg/ha to 30–45 Mg/ha over an 8-year period of establishing tree species. Bhojvaid and Timmer (1998) also reported a substantial increase in SOC pool by restoration of salt-affected soils. A similar potential exists in restoring vast tracts of wastelands throughout India (Gupta and Rao, 1994).

Potential of restoration of degraded soils of India, upon conversion to a restorative land use, is shown by the calculations in Table X. Even at modest rates of 40 to 150 kg/ha/y, the potential of SOC sequestration is 2.6 to 3.9 Tg C/y for restoring soils prone to water erosion, 0.4 to 0.7 Tg C/y for wind erosion, 3.5 to 4.4 Tg C/y for soil fertility decline, 0.1 to 0.2 Tg C/y for waterlogged soils, and 0.5 to 0.6 Tg C/y for salinized soils. The total potential of restoring degraded soils in India is 7 to 10 Tg C/y. Similarly, a large potential of SOC sequestration exists for desertification control (Lal, 2001, 2002a).

Table X
Soil organic carbon sequestration through restoration of degraded soils

Degradation process	Area (Mha)	SOC sequestration rate (kg/ha/y)	Total SOC sequestration potential (Tg C/y)
Water erosion	32.8	80–120	2.62–3.94
Wind erosion	10.8	40–60	0.43–0.65
Soil fertility decline	29.4	120–150	3.53–4.41
Waterlogging	3.1	40–60	0.12–0.19
Salinization	4.1	120–150	0.49–0.62
Lowering of watertable	0.2	40–60	0.01–0.012
Total			7.20–9.82

7. Soil Organic Matter in Rice Soils of India

Rice is an important crop in India. Out of a total area of 99.5 Mha under cereal cultivation, 42.3 Mha or 42.5% is under rice cultivation (FAO, 2001). Of this, 10 Mha is grown as a rice-wheat system in the Indo-Gangetic plains (Ladha et al., 2000). Out of a total cereal production of 219 million Mg, rice constitutes 122 million Mg or 56% of the total production. Rice cultivation differs from upland crops. It is grown under flooded conditions and the seedbed preparation involves puddling or plowing when the soil is wet to destroy aggregates and reduce the infiltration rate of water. Anaerobic conditions thus created lead to emission of methane (CH_4) and possibly nitrous oxide (N_20) through inefficient fertilizer use (Bronson and Singh, 1994). Emission of CH_4 from rice paddies in India is estimated at 2.4 to 6 Tg out of the world total emission of 25.4 to 54 Tg from all sources and 16 to 34 Tg from rice cultivation (Sass, 1994). The average CH_4 flux from rice paddies ranges from 9 to 46 g/m^2 over a 120 to 150 day growing season (Prashar et al., 1994). Because of a favorable water regime during the rice season, the SOC concentration in rice soils is more than in upland soils. However, rice straw, similar to those of other crops, is removed for fodder and other uses, and it reduces the input of C into the system. Swarup (1998) reported that integrated nutrient management enhanced SOC concentration of rice soils from <5 g/kg in 1973 to about 8 g/kg in 1994. Research is being done to find ways of growing rice without puddling so that emission of greenhouse gases can be minimized and use of fossil fuel reduced (Duxbury et al., 2003). Conservation tillage, rapidly being adopted in the Indo-Gangetic plains (Hobbs and Gupta, 2003; Malik et al., 2003) may enhance SOC concentration in these soils. In addition, it will also reduce fossil fuel use for plowing and puddling.

8. Agricultural Intensification and Soil Carbon Sequestration

Agricultural intensification implies use of RMPs on prime agricultural land to enhance food production per unit area and unit time so that marginal land can be taken out of production and converted to a restorative land use. Some technologies for agricultural intensification are outlined in Figure 1. Extensive literature exists on SOC dynamics in soils of India (Mohan-Rao and Shantaram, 1978). Use of crop residues and manure to enhance soil biodiversity, especially earthworm activity, is an important strategy for increasing SOC concentration and soil quality (Lavelle et al., 1998; Bhadauria and Ramakrishnan, 1996). The effectiveness of several techniques for SOC sequestration has been discussed by Sekhon and Meelu (1994), Swarup (1998) and Swarup et al. (2000), and is outlined in Table XI. Manuring and application of biosolids, as crop residue or compost, also enhances soil aggregation (Table XII). Nambiar (1994) reported an increase in mean weight diameter (MWD) of aggregates by application of manure for 14 years. The most drastic increase occurred in soils of Palampur in which case the mean weight diameter increased from 1.78 mm to 3.93 mm, an increase of 121%. Swarup (1998) reported the impact of integrated nutrient management, including application of NPK and manuring (8 to 10 Mg/ha/y), on SOC concentration in surface layer of soils from long-term experiments established in different ecoregions of India. Assuming a plow depth of 20 cm and soil bulk density of 1.4 Mg/m^3, the rate of SOC sequestration was calculated for NPK + manuring over that of the control. The results showed low rates of 15 to 120 kg C/ha/y. The low rates are attributed to low soil water, high soil temperature and high rate of oxidation.

9. Potential of Soil Carbon Sequestration in India

Using ecoregions as the basis of extrapolation and the rates of SOC sequestration from data of long-term experiments reported in the literature (Table XII), the potential of SOC sequestration in soils of India is shown by the data in Table XIII. The total potential ranges from 12.7 to 16.5 Tg C/y. Included in this potential is also that of the restoration of degraded soils and ecosystems estimated at 7.2 to 9.8 Tg C/y (Table X). Therefore, potential of agricultural intensification for SOC sequestration is 5.5 to 6.7 Tg C/y. In addition, there is also a potential of SIC sequestration estimated at 21.8 to 25.6 Tg C/y (Table XIV). With reduction in erosion-induced emission of 4.3 to 7.2 Tg C/y, total potential of soil C sequestration in India is 39.3 to 49.3 Tg C/y (44.3 $\pm$ 7.1) (Table XV).

There are numerous agricultural sources of GHG emissions (Duxbury, 1994) with hidden C costs of tillage, fertilizer, pesticide use and irrigation. In general, net C sequestration must take into account these costs. It is assumed, however, that these inputs are needed for enhancing agricultural production to meet food demands of increasing population. Therefore, soil C sequestration is a by-product of adopting RMPs on agricultural land and restoring degraded soils.

10. Achieving Food Security and Mitigating Climate Change

Enhancing soil quality is important to increasing use efficiency of inputs (e.g., fertilizers, irrigation), increasing biomass/agronomic yields, and improving the environment. Improving quality and quantity of SOC concentration are important to enhancing soil quality. In fact, there is a strong linkage between low SOC concentration in soils of India and the widespread problem of soil degradation. Therefore, reversing soil degradation trends necessitates increasing SOC concentration through adoption of no-till farming, use of crop residue mulch and compost on soil, and legume-based rotations. A major constraint in adopting conservation tillage and mulch farming in India is the non-availability of crop residue for returning to the soil. Most of the crop residues are removed from the fields for use as fodder and fuel. Dung is also used as fuel for cooking. Thus, adoption of mulch farming techniques is possible only if economic sources of fuel and alternative sources of fodder are identified.

Emissions from fossil fuel combustion in India are increasing. The soil C sequestration potential of 39.3 to 49.3 Tg C/y (mean of 43.3 Tg C/y) can be significant towards reducing the net emission from fossil fuel combustion. Further, there is an additional potential of C sequestration in biomass especially by forest and other biota. This potential is considerable in terms of the negotiation under the provision of Clean Development Mechanisms under IPCC, and for trading C in the national and international markets.

Biosequestration of C, both by soil and biota, is a truly win-win situation. While improving agronomic/biomass productivity, these options also improve water quality and mitigate climate change by decreasing the rate of enrichment of atmospheric CO_2. Realization of this vast potential, which is in interest of India, requires adoption of recommended management practices including the use of mulch farming and conservation tillage, integrated nutrient management and manuring, agroforestry systems, restoration of eroded and salinized soils, and conversion of agriculturally marginal lands into restorative land uses.

Table XI
Technological options for soil carbon sequestration

Technology	Cropping system	Region	Reference
1. Green manuring	Sugarcane	Tropical	Yadav (1995)
	Rice-wheat	Northwestern	Aulakh et al. (2001)
	Rice	Tropical	Singh et al. (1991)
	Rice	Tropical	Kumar et al. (1999)
	Rice-wheat	Northern	Joshi et al. (1994)
	Rice-wheat	Punjab	Boparai et al. (1992)
2. Mulch farming/ conservation tillage	Rice-wheat	Punjab	Aulakh et al. (2001)
	Pearl millet	Arid	Aggarwal et al. (1997)
	Soybean-wheat	Central	Kundu et al. (2001)
	Arable land	Northern	Srivastava and Prakash (1982)
	Arable land	Northern	Biswas and Narayanasamy (1998)
	Sugarcane	Tropics	Yadav and Verma (1995)
	Surgarcane	Tropics	Yadav and Prasad (1992)
3. Afforestation/ agroforestry	Silviculture	Northern	Singhal et al. (1975)
	Acacia nilotica	Central	Pandey et al. (2000)
	Agroforestry	Tropical	Chander et al. (1998)
4. Grazing management/ ley farming	Grassland	U.P.	Pandey (1982)
	Grassland	M.P.	Chaubey et al. (1986)
	Mixed farming	Arid	Rao et al. (1997)
5. Integrated nutrient management/ manuring	Arable land	Tamil Nadu	Jayaraman and Perumal (1984)
	Rice-wheat	Northwest	Duxbury (2001)
	Cotton	Central India	Venugopalan et al. (1999)
	Arable land	Northeast	Chakrabarti et al. (2000)
	Rice-rice	Northern	Dinesh et al. (1998)
	Maize-wheat-cowpea	Semi-arid	Kanchikerimath and Singh (2001)
	Rice-wheat	Northern	Yadav et al. (1998, 2000)
	Arable	Northern	Benbi et al. (1998)
	Wetland rice-wheat	Northern	Singh et al. (1996)
	Maize-wheat	Northern	Singh et al. (1995)
6. Cropping systems	Pearl millet	Arid	Kumar et al. (1997)
	Fallowing/ecological approach	Humid/sub-humid	Szott et al. (1999)
	Mint-mustard	U.P.	Patra et al. (2000)

Table XII

Effect of soil fertility management on SOC concentration in a long-term manuring experiment (recalculated from Swarup, 1998) (assuming plow depth of 20 cm and bulk density of 1.4 Mg/m^3)

Location	Soil	Initial (g/kg)	Control (g/kg)	NPK (g/kg)	NPK + FYM (g/kg)	Period (yrs) (g/kg)	Rate of change over control (kg C/ha/y) (g/kg)
Bangalore	Haplustalf	4.5	4.8	5.9	8.4	10	101
Barrackpore	Eutrochrept	7.0	4.1	5.0	5.4	24	15
Bhubaneswar	Haplaquept	2.6	3.7	5.7	8.1	21	59
Coimbatore	Vertic Ustochrept	3.0	4.3	4.9	6.2	23	23
Delhi	Ustochrept	4.3	4.4	5.5	6.7	25	25
Hyderabad	Tropaquept	5.0	4.6	5.3	8.0	23	41
Jabalpur	Chrmustert	5.8	5.3	6.0	9.8	25	48
Ludhiana	Ustochrept	2.0	2.5	3.3	3.8	25	15
Palampur	Hapludalf	7.8	7.3	10.0	12.0	22	60
Pantnagar	Hapludoll	13.0	5.0	8.3	15.0	24	117
Rauchi	Haplustalf	4.5	3.0	3.5	4.8	23	22

Table XIII

The potential of soil organic carbon sequestration in different ecoregions

Region	Temperature	Area [a] (Mha)	Rate of SOC sequestration kg/ha/y	Total potential of SOC sequestration (Tg C/y)
Arid	Cold	15.2	20–40	0.30–0.60
	Hot	36.8	10–20	0.37–0.74
Semi-arid	Hot	116.4	20–40	2.33–4.66
Sub-humid	Hot	86.4	40–60	3.46–5.18
Sub-humid/humid	Warm	21.2	40–60	0.85–1.27
	Moist	12.1	100–120	1.21–1.45
Perhumid	Moist	20.2	120–150	2.42–0.30
Sub-humid/semi-arid	Hot	8.5	40–60	0.34–0.51
Humid/perhumid	Hot	11.9	120–150	1.43–1.79
Total		328.7		12.71–16.50

[a] Pal et al. (2000), and Nordt et al. (2000).

Table XIV

Potential of sequestration of secondary carbonates

Soil	Area (Mha)	Rate of SIC sequestration (kg/ha/y) [a]	Total potential (Tg C/y)
Vertisols	60.4	35–40	2.11–2.42
Alluvial	94.8	125–133	11.85–12.61
Ferriginous	116.5	28–32	3.26–3.73
Irrigated	57.0	80–120	4.56–6.84
Total	328.7		21.78–25.60

[a] Pal et al. (2000), and Nordt et al. (2000).

Table XV

Total potential of carbon sequestration in soils of India

Process	Potential (Tg C/y)
A. Soil organic carbon (SOC)	
– Restoration of degraded soils	7.2–9.8
– Agricultural intensification	5.5–6.7
B. Secondary carbonates	21.8–25.6
C. Erosion control	4.8–7.2
Total	39.3–49.3

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