THE POTENTIAL OF CARBON SEQUESTRATION IN SOILS OF SOUTH ASIA

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Abstract
Assessment of the potential of carbon (C) sequestration in soils of 8 countries in South Asia (Afghanistan, Bangladesh, Bhutan, India, Iran, Nepal, Pakistan and Sri Lanka) is made on the basis of the available information on the area and soil C dynamics for different land use and soil management practices. Out of a total land area of 642 million hectares (Mha), 218 Mha is cropland including 89 Mha of irrigated cropland, 85 Mha is forest and woodland, 13 Mha is permanent crops and 94 Mha is permanent pasture. Estimates of area affected by soil degradation processes include 82 Mha by water erosion, 11 Mha by wind erosion, 11 Mha by fertility decline, 13 Mha by waterlogging, 33 Mha by salinization, and 83 Mha by desertification. The soil organic C (SOC) concentration in most agricultural soils is <10 g/kg. Technological options of SOC sequestration include afforestation and restoration of degraded soils with fast growing perennials, and using recommended management practices on agricultural soils including integrated nutrient management with manuring and cover cropping, mulch farming and conservation tillage, water harvesting and recycling, and improving pastures and using controlled grazing at low stocking rate. The rate of SOC sequestration is low (<200 kg/ha/y) with a total potential of 25 to 50 Tg C/yr for several decades.

Keywords: Climate change, soil organic matter, soil degradation, carbon trading, land use, Asia

Introduction
South Asia covers a large land area (Table 1) with diverse ecoregions, land uses and management practices. Over 22% of the world's population lives on less than 5% of the world's land area (FAO, 1994). The cropland area represents 34% of the total land area, and the high proportion is a reflection of the high population density. In accord with the land and population statistics, the per capita land area in some countries is <0.1 ha and decreasing. There is no possibility of expansion of cropland area, and the potential of expanding irrigated land area is also limited. The region is undergoing rapid industrialization and economic growth, leading to increase in emission of CO_2 and other greenhouse gases (GHGs) into the atmosphere. Furthermore, urgency of meeting increased demand for agricultural produce (food, feed, fiber, fuel) is rapidly degrading soil quality and exacerbating degradation. Most agricultural soils have low soil organic matter (SOM) reserves due to fertility- mining practices (residue removal, uncontrolled and excessive grazing, imbalance in application of plant nutrients), and widespread problem of soil degradation. Therefore, the objective of this report is to assess the potential of soil C sequestration in the region through restoration of degraded soils and ecosystems, and adoption of recommended management practices (RMPs) on agricultural soils.

Table 1. Land use in South Asia (adapted from FAO 2001).

Country	Total area	Land area	Agricultural area	Arable land	Permanent crops	Permanent pasture	Forest and woodland	Irrigated cropland
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Afghanistan	65.2	65.2	38.1	7.9	0.14	30.0	1.4	2.4
Bangladesh	14.4	13.0	9.1	8.1	0.4	0.6	1.3	4.4
Bhutan	4.5	4.7	0.6	0.15	0.02	0.4	3.0	0.04
India	328.7	297.3	180.8	161.8	8.1	10.9	64.1	54.8
Iran	164.8	163.6	60.5	14.3	2.2	44.0	7.3	7.5
Nepal	14.7	14.3	4.9	3.1	0.09	1.8	3.9	1.1
Pakistan	79.6	77.1	27.2	21.5	0.7	5.0	2.5	17.8
Sri Lanka	6.6	6.5	2.4	0.9	1.0	0.4	1.9	0.6
Total	**678.5**	**641.7**	**323.6**	**217.8**	**12.7**	**93.8**	**85.4**	**88.6**

Soil Degradation in South Asia
Soil degradation is a serious problem throughout South Asia (Table 2). Principal degradative processes include accelerated erosion by water and wind, and encompassing desertification, salinization, waterlogging, and fertility depletion. Soil erosion by water is a serious problem in the Himalayan region and other sloping lands where removal of vegetation cover and tillage make soils susceptible to erosional processes. Wind erosion and desertification occur in dry regions, and desertification involves decline in quality of both soils and vegetation by

degradation processes. Secondary salinization, caused by excessive irrigation and lack of adequate drainage, is a problem in regions irrigated by canal water, and is often accompanied by rise of water table and seasonal or permanent waterlogging. In contrast, ground water depletion is occurring in regions intensively irrigated by tubewells (Table 2).

Table 2. Extent of soil degradation in South Asia (adapted from FAO, 1994; Dregne and Chou, 1992).

Country	Soil erosion		Desertification		Salinization	Waterlogging	Nutrient depletion	Ground water depletion
	Water	Wind	Dryland	Irrigated land				
	Mha							
Afghanistan	11.2	2.1	1.5	0.7	3.1	0	0	0
Bangladesh	1.5	0	0	0	3.0	0	6.4	0
Bhutan	0.04	0	0	0	0	0	0	0
India	32.8	10.8	60.0	8.1	7.0	8.5	3.2	--
Iran	26.4	35.4	2.0	1.2	16.0	0.6	0	19.5
Nepal	1.6	0	0	--	0	0	0	0
Pakistan	7.2	10.7	3.4	6.1	4.2	3.7	0	0
Sri Lanka	1.1	0	0.1	0	0	0	1.4	0
Total	81.8	59.0	67.0	16.1	33.0	12.8	10.9	19.5

Soil Organic Matter Dynamics

The SOM concentration differs among climate, soil type and land uses. Depletion of SOM, a widespread problem on croplands and grazing lands in the region, is exacerbated by soil degradation. Most soils have extremely low levels of soil organic carbon (SOC) contents, ranging from 8 to 10 g/kg. Depletion of SOC pool is caused by fertility-exploitative practices and soil degradation processes (Table 3). Low external input of chemical fertilizers and organic amendment causes depletion of SOC pool because nutrients harvested in agricultural products are not replaced, and are made available through mineralization of SOM. In some cases, soil is burnt to release nutrients contained in SOM. Fuel for household use is limited, and crop residue and animal dung are used as fuel. Crop residues are also used as fodder for livestock. It is estimated that SOC loss due to agricultural activities in Bangladesh between 1967 and 1995 was 16.2 Mg C/ha, with a range of 3.8 to 30.5 Mg C/ha. For a land area of 3 Mha under this study, the total SOC loss was 42.8 Tg C within a 27-year period. This decline was attributed to removal of crop residue, and changes in cropping systems etc. Reduction in SOC pool sets-in-motion other degradation processes including decline in soil structure and aggregation, reduction in exchangeable bases, decrease in plant available nutrients, and reduction in plant-available water capacity. Indeed, some argue that the sustainability of the rice-wheat system is threatened by continuous decline in SOC pool. Crop yield and use efficiency of input are also adversely affected by low levels of SOC pool (Anandacoomaraswamy et al., 2001). In Sri Lanka, yield of rubber increased by 75 kg for every 0.1% increase in SOC content. Depletion of SOC pool in soils of Bangladesh, most of which have SOC between 6 and 10 g /kg, is the main cause of low productivity.

Table 3. Land use, management practices, and degradation processes leading to decline in soil organic matter content.

Country	Fertility/mining soil degrading processes and practices
Bangladesh	Soil degradation and nutrient depletion Intensive tillage, puddling Accelerated erosion
Bhutan	Soil burning Deforestation
India	Residue removal for fodder and fuel Excessive grazing, and using dung for fuel Unbalanced fertilizer use Accelerated erosion, desertification, and soil degradation
Nepal	Deforestation
Pakistan	Accelerated erosion Monoculture
Sri Lanka	Accelerated erosion Deforestation and shifting cultivation

A strong inter-dependence between SOC content and productivity on the one hand, and environment quality (including runoff, erosion and non-point source pollution and emission of GHGs into the atmosphere) on the other, warrant the need for a coordinated effort to restore SOC pool in degraded and depleted soils of South Asia.

Land Use and Management Practices for Enhancing Organic Matter in Soils of South Asia

Table 4 lists soil and crop management practices with beneficial impact on soil C sequestration. Important among these are restoration of degraded soils and ecosystems, agroforestry and afforestation, grazing management and adoption of RMPs on cropland. The latter includes integrated nutrient management such as use of manure, compost, green manuring and other biosolids including city sludge, mulch farming, conservation tillage, and diverse crop rotations based on legumes and cover crops in the rotation cycle. Soil conservation and water management, water harvesting and recycling, are important strategies of minimizing losses and restoring soil quality. Afforestation of degraded soils by fast-growing tress is a useful strategy. Commonly grown fast-growing species for the humid regions include *Flamingia macrophyle, Leucaena leucocephala, Gliricidia sepium, Tephrosia candida, Ipomea fistulosa* etc. used as living fences, green manuring and fodder. In Bangladesh, SOC content in cropland was only 7.4 g/kg, and it increased to 12.6 g/kg in grassland and 12.8 g/kg in reforested land. Therefore, afforestation and establishment of grasses and other cover crops are important to enhancing the SOC pool.

Increase in SOC pool also increases aggregate stability and the available water holding capacity. In India, use of NPK and farmyard manure maintained the SOC at 15 g/kg for a 25-year period compared with decline to 8.0 g/kg with NPK alone and 5.0 g/kg with no fertilizer use. The data in Table 5 from India shows increase in SOC content by application of NPK and manure in 6 out of 9 soils, and increase in 3 out of 9 soils by use of chemical fertilizers. There was a drastic decrease in SOC content in all soils, which received neither fertilizer nor manure (Table 5). The SOC pool of soils is primarily regulated via the formation of stable aggregates, which depends on clay content and

Table 4. Recommended management practices for soil carbon sequestration.

Country	Recommended management practice
Bangladesh	Ground cover crops, forages and fallowing Manure and compost Applying biofertilizers using azolla, bluegreen algae, Adding crop residue Liming and fertilizer use Green manuring Afforestation Agroforestry
India	Green manuring Mulch farming/conservation tillage Afforestation/agroforestry Grazing management/ley farming Integrated nutrient management/manuring Diverse cropping systems
Iran	Conservation tillage
Nepal	Manuring and green manuring Legume-based rotations Agroforestry and afforestation Fertilizer use
Pakistan	Sludge application Biocompost and manure Crop residues and green manures Agroforestry Chemical fertilizers and integrated nutrient management Legume-based rotations
Sri Lanka	Agroforestry/alley cropping, afforestation Chemical fertilizers Mulch farming and residue management Green manuring Manures and organic materials

Table 5. Soil C sequestration through integrated nutrient management for 20 years in some soils of India (adapted from Nambiar, 1995; Swarup et al., 1998).

Location	Soil	Cropping system	Initial SOC (g/kg)	SOC after 20 years (g/kg) Control	NPK	NPK+FYM
Bhubneshwar	Inceptisol	Rice-rice	2.7	4.1	5.9	7.6
Pantnagar	Mollisol	Rice-wheat	14.8	5.0	9.5	15.1
Pantnagar	Mollisol	Rice-wheat-cowpea	14.8	6.0	9.0	14.4
Faizabad	Inceptisol	Rice-wheat	3.7	1.9	4.0	5.0
Barrackpore	Inceptisol	Rice-wheat-jute	7.1	4.2	4.5	5.2
Palampur	Alfisol	Maize-wheat	7.9	6.2	8.3	12.0
Karnal	Alkali soil	Fallow-rice-wheat	2.3	3.0	3.2	3.5
Nagpur	Vertisol	Cotton-cotton	4.1	--	--	5.5
Trivandrum	Ultisol	Cassava	7.0	2.6	6.0	9.8

mineralogical composition. Puddling and intensive tillage destroys aggregates and lead to drastic losses in SOC. In contrast, SOC pool can be increased by addition of crop residue, maintenance of soil fertility through application of fertilizers, cattle manure and compost. Experiments conducted at Bhairahawa, Nepal, showed that addition of 30 Mg/ha/yr of farmyard manure (dry weight) increased SOC level from 1.03 to 1.78%.

Potential of Soil Carbon Sequestration in South Asia

There are two principal strategies of SOC sequestration: restoration of degraded soils and adoption of RMPs on agricultural soils. Restoration of degraded soils involves afforestation and establishment of pastures and planted fallow on severely and extremely degraded lands or the so-called waste lands. The potential of restoration of degraded soils in India is 7 to 10 Tg C/y (Lal, 2004). The data in Table 6 show that potential of restoration of degraded soils in South Asia is 18 to 35 Tg C/yr. These estimates are of attainable potentials providing that regional governments adopt appropriate policies and implement plans to restore degraded soils through afforestation, establishing planted fallows, and improving grazing lands. It is a major challenge that must be addressed in a coordinated and planned manner.

Table 6. Soil carbon sequestration through restoration of degraded soils.

Degradation process	Area (Mha)	Rate of SOC sequestration[b] (kg C/ha/yr)	Total potential (Tg C/yr)
Erosion by water	81.2	100-150	8.1-12.2
Erosion by wind	10.8	20-50	0.2-0.5
Desertification control			
(i) Irrigated land	16.1	100-150	1.6-2.4
(ii) Rainfed	67.0	20-50	1.3-3.4
Salinization	33.0	200-500	6.6-16.5
Waterlogging[a]	12.8	(-50)-(-100)	-0.6-(-1.3)
Fertility depletion	10.9	100-150	1.1-1.6
Total			**18.3-35.0**

[a]Drainage of waterlogged soils may reduce SOC pool.
[b]Rates of SOC sequestration are from Lal (1999; 2001a)

Potential of SOC sequestration on cropland of South Asia, based on the assumptions made, is estimated at 11 to 22 Tg C/yr (Table 7) of which 6 to 8 Tg C/yr is in cropland of India (Lal, 2004). This potential is attainable providing that appropriate policies are in place to facilitate adoption of RMPs including conservation tillage, mulch farming and cover crops, integrated nutrient management including manuring and biological nitrogen fixation, and water conservation and harvesting.

There is also a potential of sequestration of secondary carbonates. This potential exists in arid regions including Iran (164 Mha), Afghanistan (65 Mha), Pakistan (77 Ma) and about 25% of India (80 Mha). Total area of arid regions is 386 Mha. The average rate of sequestration of secondary carbonates in most of these soils can be as much as 50 to 70 kg C/ha/yr. In addition, there is a potential of carbonate leaching in irrigated soils at 80 to 120 kg C/ha/yr (Lal, 2001b). Thus, potential of SIC sequestration in South Asia is:
(a) Secondary carbonates in 386 Mha @ 50 to 70 kg C/ha/yr = 19-27 Tg C/yr

(b) Leaching of carbonates in 89 Mha @ 80 to 120 kg C/ha/yr = 7-11 Tg C/yr
Total 26-38 Tg C/yr

Whereas SOC sequestration can be achieved through management, there is little control on formation of secondary carbonates. Therefore, the potential of SIC sequestration is not achievable through targeted management, although adoption of biofertilizers and manuring can accentuate formation of secondary carbonates.

Table 7. Carbon sequestration potential through adoption of recommended management practices on croplands in south Asia.

Country	Land area (Mha)	Adoption of RMPs by 2020 (Mha)	Rate of SOC[a] sequestration (kg/C/ha/yr)	Total potential (Tg C)
Afghanistan	7.9	1.5 (20%)	50-100	0.1-0.2
Bangladesh	8.1	6.0 (75%)	200-300	1.2-1.8
India	161.8	80.9 (50%)	100-200	8.1-16.2
Iran	14.3	7.1 (50%)	50-100	0.4-0.8
Nepal	3.1	2.3 (75%)	300-500	0.7-1.2
Pakistan	21.5	10.7 (50%)	50-100	0.5-1.0
Sri Lanka	0.9	0.7 (80%)	300-500	0.2-0.4
Total				**11.2-21.6**

[a]Rates of SOC sequestration are from Lal (2003, 2004), Duxbury (2001), Katyal et al. (2001).

Challenges in Achieving Potential of Soil Carbon Sequestration in South Asia

Despite the potential, and the dire need for enhancing soil quality, enhancing SOC pool in soils of South Asia (and that of sub-Saharan Africa) remains a challenge for agricultural scientists, land managers, policy makers and industrial planners. Major impediments to SOC sequestration are social and economic conditions which lead to (i) removal of crop residue for fodder, fuel, fencing and other purposes, (ii) excessive and uncontrolled grazing, (iii) use of animal waste for household cooking rather than a soil amendment, and (iv) a widespread use of the top 1-m of soil for brick making to meet the demands of rapid urbanization. A necessary prerequisite for a successful adoption of no-till farming or conservation tillage is the use of crop residue mulch and frequent incorporation of cover crops and forages in the rotation cycle. Thus, there has to be a paradigm shift in soil management philosophy that leads to conversion from plow till to no-till, residue removal to mulch farming, removal of livestock waste for cooking fuel to use as soil amendment, and removal of residue to grow fodder on dedicated land for feeding cattle. It is a question of stewardship of the land so that cash-strapped farmers do not sell the top 1-m of soil, which took millions of years to form, for making bricks. Long-term sustainable management of soil must be given priority over the short-term gains.

These are difficult challenges, which manifest vividly in densely populated South Asia with predominantly resource-poor farmers. Similar conditions exist in sub-Saharan Africa.

Conclusions

Total SOC sequestration potential of 25 to 50 Tg C/yr can be achieved through conversion to restorative land use and adoption of RMPs on agricultural soils. In addition, there is some potential of formation of secondary carbonates but there is little or no management control. The SOC sequestration has numerous economic and ecologic implications in terms of trading C credits, improving quality of soil and water resources, and achieving food security. The positive impact of enhancing SOC pool on crop yield and food security cannot be over-emphasized.

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