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Impact of agricultural land management practices on soil carbon sequestration

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ABSTRACT

The soil carbon sequestration is a cost effective strategy to mitigate climate change during first 2 to 3 decades of the 21st Century. The greenhouse gases (GHGs) in atmosphere are increasing at the rate of 0.5%, 0.6% and 0.25 ppbv yr⁻¹ for CO₂, CH₄ and N₂O, respectively. Contribution of these three GHGs to global warming is to an extent of 20% due to agricultural activities and 14% due to in land use changes and attendant deforestation. Major agricultural activities that contribute to emission of GHGs include ploughing, application of manures and fertilizers, soil drainage, biomass burning and crop residue removal. The loss of soil C is accentuated by soil degradation factors such as erosion, compaction, salinization etc. and the attendant decline in soil quality. Historic global C loss due to agriculture 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 enhanced in soil organic carbon (SOC) storage and aggregation, and restoration of soil quality. Improved agricultural practices include mulching and conservation tillage, growing cover crops and eliminating summer fallow, using judicious fertilizer inputs including precision farming and use of biosolids, adopting improved cropping systems, managing soil-water through drainage and irrigation, and restoring degraded soils. 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.

1. INTRODUCTION

Climate change involve in alternation of climatic parameters such as temperature, precipitation, increase in sea level and increase in ultraviolet radiation in the atmosphere of Earth as a result degrading environment, changing the growing rate of extinction of species, declining availability of water, loss of fertile land and so on (Basu, 2008). Since 1950, sea level rise over the 20th Century of 0.1 to 0.2 m, increase in rainfall of 0.5 to 1.0% per decade, and the increase in frequency of extreme events and heavy precipitation by 2 to 4% (IPCC, 2007). Tropical and subtropical ecosystems have great impact on global C cycle, environmental concern and socio-economic issues. The numerous experiments from around the world have demonstrated that conversion of tropical ecosystems to agricultural, pastoral and silvicultural land uses substantially enhanced soil carbon pools. The magnitude of this variation, however, depends on the method of removing the natural vegetation, agronomic practices, soil and nutrient management, and cropping systems. In this paper,

the consequences of different land use management practices on earth terrestrial ecosystem and carbon sequestration have been reviewed.

Global Warming

The energy budget for the global annual mean is determined by the net radiant flow of energy at different wavelengths through the top of the atmosphere and at the earth's surface. Approximately, 5×10^6 gigwatt imbalance in our planet's energy budget come from greenhouse gases, water vapour, methane, carbon-dioxide, nitrous oxide, tropospheric ozone, the freons (or chlorofluorocarbons or CFCs) and some of the substances which have now largely replaced them (like the HCFCs). The greenhouse gases are able to catch' infrared or radiation before it escapes back to space from the surface of our planet. Several factors such as anthropogenic activities, black aerosols, small soot particles, burning tar balls leads to increased the concentrations of greenhouse gases in to the atmosphere. They do not stay in the atmosphere for a very long time, but they absorb sunlight efficiently. Most scientists think that

between 0.1 and 0.2°C of the 0.8° warming which has already taken place, this far, has probably happened because the Sun has been a little bit more active than what is its long-term average (Isomaki, 2008).

The world's rice crop is very vulnerable to climate change. If temperature stays above 35°C for more than one hour while the rice is flowering, the heat sterilizes the pollen so that no grains will be produced. According to the International Rice Research Institute (IRRI), we might lose 15% of the world's rice crop with every degree of global warming. Global warming should increase rainfall because more water will evaporate from the oceans. However, the evaporation of water from the soils and from the freshwater lakes and rivers is likely to increase even more. Thus most of the tropical and subtropical regions may become much drier than now. The Intergovernmental Panel on Climate Change (IPCC, 2007) has said that up to five billion people might soon suffer from an acute lack of irrigation water, partly because of the global warming.

James Hasen, the leading Climate Scientist in the USA has said that sea level rise will most probably become the most important single issue of the 21st Century. In the 19th Century, the sea level was rising by only 0.1 mm yr⁻¹. In 1950's, the speed started to accelerate and was approximately 2 mm in the 1990's. The present rate of sea level rise might be 3.7 mm yr⁻¹, even though there is some variation in the results. This rate corresponds to 37 cm in a Century (Chambers, 2003).

Soil Carbon Pools

Sink of carbon from atmosphere to either plant into soil or from atmosphere into soil is called as soil carbon sequestration. Excluding carbonate rocks (inorganic carbon path), a soil represents the largest terrestrial stock of carbon, holding 1500 Pg (1Pg = 10¹⁵ g), which is approximately twice the amount held in the atmosphere and three times the amount held in terrestrial vegetation (Rice, 2002). Soil inorganic carbon (SIC) pool contains 750-950 Pg C and terrestrial vegetation is reported to contain 600 Pg C (Rice, 2002). The majority of carbon is held in the form of soil organic carbon, having a major influence on soil structure, water holding capacity, cation exchange capacity, the soils ability to form complexes with metal ions to store nutrients, improve productivity, minimize soil erosion *etc.* This organic carbon is highly sensitive to changes in land use and management practices such as increased tillage, cropping systems, fertilization *etc.* leading to soil organic carbon decline. The objective of this paper is to conceptualize erosion impacts on soil C dynamics, land use and management practices, cropping systems and the effects of soil conservation measures on enhancement of soil carbon sequestration and management effects on mitigating the potential greenhouse effect.

Consequences of Soil Erosion on C-sequestration

Soil erosion indeed can cause a rapid depletion of the soil organic carbon (SOC) pool. Accelerated soil erosion, affecting 1094 million ha (M ha) by water erosion and 549 M ha by wind erosion (Oldeman, 1994), has local,

regional and global impacts (Lal, 1998a). 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 from elsewhere (Lal, 1994; Walling, 1987). In addition to effects on crop productivity, soil erosion also profoundly impacts the environment. Two principal impacts of erosion on the environment include reduction in quality of water and air through pollution and eutrophication of surface water, and emissions of green house gases (e.g., CO₂, CH₄ and N₂O) to the atmosphere. Increasing atmospheric concentration of radioactively-active gases (0.5% yr⁻¹ for CO₂, 0.6% yr⁻¹ for CH₄, 0.25% yr⁻¹ for N₂O) (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.*, 1995 a, b; Janzen *et al.*, 1998) that of soil erosion on C dynamics is not properly understood.

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. Soil carbon transported in water runoff may include particulate organic material, and dissolved organic and inorganic carbon.

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 Canada, Gregorich *et al.* (1995) observed a rapid decline in SOC on an eroded compared to an uneroded cropland. The SOC content in the top 30-cm layer decreased by 20% in an uneroded soil and by 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 (Gregorich and Anderson, 1985; Gregorich *et al.*, 1998). In Ohio, USA, Fahnestock *et al.* (1996) observed that SOC pool in the top 0-10 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. The drastic reductions were observed 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. Taking into

consideration the land area affected, the historic C loss is 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 degradation is a widespread problem in India. It is estimated that the land areas affected by different degradative processes include 33 Mha by water erosion, 11 Mha by wind erosion, 3 Mha by fertility decline, 3 Mha by water logging and 4 Mha by salinization (Lal, 2004). Many factors contribute to loss of SOM levels such as lower application of carbon to the soil, removal or burning of crop residues, tillage induced aggregates disruption, more favorable condition for decomposition and greater losses of surface soil by water erosion. Factors that increase organic matter under arable agriculture include a decreasing proportion of fallow in rotation, an increase in the proportion of cereal as compared to root crops, an increasing proportion of perennial crops in rotation, return of crop residues rather than burning or removal, improved root biomass and crop growth with better fertilizer and irrigation conditions, and addition of organic manure or other organic wastes.

Depletion of Organic C Fraction in Soil

Perturbations to the soil system such as conversion of native vegetation to arable agriculture cause large changes in SOM content in soil. The large pool of POM maintains soil structure and macro-aggregation. These are reflected in labile and stabilized SOM fractions in soil. In addition, labile fraction has a disproportionately large effect on nutrient supplying capacity and structural stability of soil. In agricultural soil, the light fraction typically contain 20-30% C and 5-20% N and 18-22% of total C and 1-16% of total N in the whole soil (Manna *et al.*, 2013). Particulate organic matter contains 20-45% of TOC and 13-40% of TN in the whole soil. Particulate organic carbon is the precursor for formation of soil microbial biomass carbon, soluble fraction of carbon, humic and non-humic fraction of carbon in soil and thus it is a key attribute of soil quality. It is the major source of cellular C and energy for the heterotrophic microorganisms. The POM accumulation is also the major pathway by which nutrients are recycled from crop residues back to the soil and release nutrients by mineralization of decomposing POM. The large amount of microbial community associated with the decomposing POM produces binding agent such as exocellular mucilaginous polysaccharides. It acts as a major food and energy for endogenic soil fauna. Thus, POM is associated with a multitude of soil processes and functions and is therefore, a key attribute of soil quality. Acid hydrolysable carbohydrate (AHC) (32-37% of TOC) is a labile C fraction and has been found to change more rapidly in response to changes in management than TOC contents. The KMnO_4 oxidizable C fraction accounts for 5-30% of organic C. This oxidizable fraction usually is more sensitive to soil management than TOC. Simple measurement of soil aggregate stability,

POM, light fraction of carbon, acid hydrolysable carbohydrates have been evaluated for their sensitivity to change in different soils and crop management systems.

Impact of Land Use Practices on SOC Pool

In general, soils with high SOC pool have more biomass productivity than those with low SOC pool. High biomass productivity from soils of high SOC pool is attributed to high soil aggregation and better soil tilth, high plant-available water retention capacity, more resistance to erosive forces of water and wind, and lower compaction ability. Enhancement of SOC pool reduces leaching losses of fertilizers and pesticides, and losses of chemicals in surface runoff also decrease with increase in SOC pool. Thus, increasing SOC pool improves quality of both soil and water resources. Land use and soil management systems, which enhance the amount of biomass returned to the soil, also accentuate the terrestrial C pool. Different technological options for biotic and soil C sequestration include afforestation, restoration of degraded ecosystem, establishment of bio-energy plantations with a large potential for biomass production, establishing perennials with a deep and prolific root system, growing species containing high cellulose and other resistant species containing high cellulose, and developing appropriate land use systems. Similarly, strategies for soil C sequestration include adoption of conservation tillage and mulch farming techniques, maintenance of soil fertility, soil and water conservation, and adoption of complex rotations. The total potential of SOC sequestration through restoration of degraded soils in India is 10-14 Tg C yr⁻¹ (Lal, 1994).

Major changes in land use occurred in the forests and grassland with 39.9 and 37.5% of total land use change (Lal *et al.*, 1998c, 1999). Change in land use contributes C to the atmosphere in two principal ways: (i) release of C in the biomass which is either burnt or decomposed, and (ii) release of SOC following cultivation enhanced mineralization brought about by change in soil moisture and temperature regimes and low rate of return of biomass to the soil. Carbon contained in the biomass of the climax vegetation is in the order: tropical rainforest > temperate forest > temperate deciduous > boreal forest > tropical woodland > temperate woodland > tropical grassland > temperate grassland > desert scrub > tundra and alpine meadow (Lal *et al.*, 1999). After forest, introduction of improved pasture in natural savanna (grassland) ecosystem is another major option of carbon sequestration in soil.

Adoption of recommended soil and crop management is another option for SOC sequestration. Soil and crop management practices, which enhance biomass production, add high belowground biomass to the soil, improve soil fertility and effectively conserve soil and water also, lead to SOC sequestration. Returning crop residues, animal wastes, and other biomass to soils is important to SOC sequestration but not a practical option because of alternate uses for these

by-products as fodder, fuel, construction material and numerous other economic uses particularly in India. Adoption of appropriate farming systems and use of cover crops provide another option of C-sequestration with in terrestrial ecosystems. Mixed crop rotations and use of cover crops improve SOC contents and enhance aggregation. Diversified cropping systems with better management substantially improved SOC in semiarid-tropic soils of India (Manna *et al.*, 2008). Adoption of conservation tillage increases C-sequestration in soil (Karlen, 1994). Lal (1989) estimated that widespread adoption of conservation tillage on soil in 400 million ha cropland by the year 2020 may lead to C-sequestration of 1481 to 4913 Tg (1 Tera gram = 10^{12} g). It is estimated that agricultural intensification in India results in C-sequestration of about 12.7 to 16.5 Tg yr⁻¹. Researchers reported that there was also a potential of sequestration of secondary carbonates; especially in irrigated soils, at about 21.8 to 25.6 Tg C yr⁻¹. The total potential of a SOC sequestration in India of 77.9 to 106.4 Tg yr⁻¹ (92.2 ± 20.2 Tg yr⁻¹). Of this potential, 12.9% is through restoration of degraded soils and 45.6% through erosion prevention and management, 15.8% through agricultural intensification and 25.7% through secondary carbonates (Bhattacharya *et al.*, 2007).

Advantages of Conventional Agricultural Practices on C-sequestration

Cropping system

In India, the major cropping systems are cereal-cereal (rice-rice, cereal-cereal-cereal (rice-wheat-maize), cereal-cereal-legume (rice-wheat-green gram), legume-cereal (pulse-wheat) and oilseed-cereal (oilseed-wheat). Conventional agriculture normally reduces the SOC of the

surface or plough layer. Conservation tillage systems increase SOC level. Under intensive cultivation two or three crops are grown per year and the grain yield at the rate of 10 Mg ha⁻¹ yr⁻¹ was achieved (Sinha and Swaminathan, 1979, Prasad, 1983). The data in Table 1 indicated that rice-wheat-green gram crop sequence has greater SOC restoration than rice-wheat followed by rice-green gram and rice-mustard possibly due to inclusion of legume in cereal-cereal cropping system.

Residue management

The usual practice of Indian farmers is to either remove the residue from field, or burning them in field and thereby SOC maintenance is difficult. Residue management as surface mulch provides a congenial environment for biodiversity, which significantly improves on SOC (Tomar *et al.*, 1992).

Nutrient management

Among Asian countries, India has the lowest average concentration of SOC in agricultural soils especially in the Indo-Gangetic Plains (Koshal, 2014). These alluvial soils are inherently fertile and high in K. However, removal of crop residue in intensive rice cropping system has contributed to the decline in SOC. This decline appears to be continuing at present in many areas, and in places where SOC is 3.0 to 4.0 g kg⁻¹, a near equilibrium at these low levels has been reached. On the other hand, applications of manure with NPK improves the content of SOC or results in relatively higher SOC levels (Swarup *et al.*, 2000).

Alternate land use management

Management practices for agro-forestry are more complex because multiple species are having varied phenological, physiological and agronomic requirements. The conversion of long-term arable crop land to agro-horticulture resulted in a significant increase in SOC. In this study, it was observed that the cultivation of fruit trees, coconut (*Cocos nucifera* L.) intercropped with guava (*Psidium guajava* L.) increased SOC from 3.4 to 7.8 and 2.4 to 6.2 g kg⁻¹ or C-sequestered 877 kg C ha⁻¹ yr⁻¹ and 325 kg C ha⁻¹ yr⁻¹ after 38 and 10 years of cultivation under same agro-ecosystem (Singh *et al.*, 2012). In a 20-years study, the cultivation of *Prosopis juliflora*, *Acacia nilotica*, *Eucalyptus tereticornis*, *Terminalis arjuna* and *Albizia lebbek* increased about 6-10 fold greater SOC as compared to control (Table 2). In this study, it was observed that C-sequestration was relatively low under *E. tereticornis* (168 kg C ha⁻¹ yr⁻¹).

Table: 1
Soil organic carbon status as influenced by different cropping systems (after 6 years)

Cropping systems	Organic C (g kg ⁻¹)
Rice-wheat-fallow	5.8
Rice-wheat-fodder	6.1
Rice-wheat-green gram	6.8
Rice- mustard-fallow	5.6
Rice-mustard-fodder	6.0
Rice-mustard-green gram	6.5
Uncultivated soil	5.1
Initial soil status	5.2
LSD at 5 %	0.5

Source: Sharma and Bali (2000)

Table: 2
Long-term effect (1970-1989) of cropping systems on C- sequestration in an alkaline soil of India

Location	Soil type	Tree species	Sampling depth (cm)	Initial SOC (mg ha ⁻¹)	SOC (mg ha ⁻¹)	C-sequestration (kg ha ⁻¹ yr ⁻¹)
Haryana CSSRI, Karnal	Alkaline soil	<i>Acacia nilotica</i>	0-120	4.03	12.3	413
		<i>Eucalyptus tereticornis</i>	0-120	4.03	7.4	168
		<i>Prosopis juliflora</i>	0-120	4.03	13.0	448
		<i>Terminalis arjuna</i>	0-120	4.03	12.9	443
		<i>Albizia lebbek</i>	0-120	4.03	10.5	323

Source: Singh (1994). After 20 years of tree plantation in alkaline soils at CSSRI, Karnal, C- sequestration was least under *Eucalyptus* plantation (168 kg ha⁻¹ yr⁻¹).

Alternate land use systems, viz., agro-forestry, agro-horticulture, and agro-silviculture, are more remunerative for SOC restoration as compared to sole cropping system (Table 3). In northeast hill regions of India, the above three land use systems practice reduce soil erosion and loss of SOC considerably. In a 6 year study, organic carbon content was about double in agro-horticultural and agro-forestry systems as compared to sole cropping (Table 3). In long-term study in Indo-Gangetic alluvial soils with rice based cropping system C-sequestration was maximum in rice-wheat-jute system ($535 \text{ kg ha}^{-1}\text{yr}^{-1}$) at Barrackpore followed by Rice-mustard-sesame ($414 \text{ kg ha}^{-1}\text{yr}^{-1}$) than rice-fallow-rice ($402 \text{ kg ha}^{-1}\text{yr}^{-1}$) at CRRI, Cuttack (Table 4).

Soil organisms regulate SOC turnover

Soil microorganisms are believed to play a major regulatory role in organic carbon dynamics. The abiotic factors (temperature, moisture, soil type, nature, and quantity of residues) may have a large impact on soil organic carbon dynamics by virtue of their effect on microbial activities. In sub-humid and semi-arid tropical ecosystems involving different cropping systems, the turnover rate of SOC decreased by 3.8 fold compared to forest land (Table 5). The rate of mineralization depends on tillage, residues management, cropping practices, and

erosion. Materials having wide C:N ratio are resistant to decomposition thereby restricting the supply of nitrogen for organisms and eventually resulting in increased immobilization and reduced supply of nitrogen to plant.

Tillage and residue management

The SOC losses can be reduced by several tillage options such as zero tillage, reduced tillage, stubble mulching and conventional ploughing. In a 3-year field experiment, the effect of types of tillage operations and continuous addition of organic matter through use of naturally occurring wild sage (*Lantana camara* L.) was tested. It was observed that application of *Lantana camara* L. @ $10 \text{ Mg ha}^{-1}\text{yr}^{-1}$ improved soil physical properties and organic carbon content (Sharma et al., 2010). Mulch conservation tillage treatments favorably moderated the hydrothermal regimes for growing of crops. In a 45 years long-term study, use of FYM, and, organic carbon content and crop productivity was studied in cotton sorghum system (Table 6). It was observed that seed yield of cotton failed to improve because of tap root system of cotton, which reduced the extraction of nutrients from deeper layer. In another study, residue management as surface mulch and reduced tillage provide a congenial environment for native micro flora and fauna which significantly improved SOC. In alluvial soil, application of residue mulches or compost often improves organic carbon.

Benefits of Soil Carbon Sequestration

There are numerous benefits of soil carbon sequestration. Important among these are reduced risks of water pollution and eutrophication, increased biodiversity, and enhanced soil quality with the attendant increase in productivity. Soil organic matter is an important attribute of soil quality. It influences soil physical, chemical and biological properties and processes. It regulates energy and

Table: 3

Organic carbon in soil after six years of plantation with different land use options

System	Organic C (g kg^{-1})	
	0-15 cm	15-30 cm
Sole cropping	4.2	3.7
Agro-forestry	7.1	7.3
Agro-horticulture	7.3	7.4
Agro-silviculture	3.8	5.6

Source: Das and Itnal (1994)

Table: 4

Long-term effect of Rice-based cropping system on C-sequestration in an Alluvial soils of India

Location	Cropping system	Cropping period	Sampling depth (cm)	Initial SOC (mg ha^{-1})	SOC (mg ha^{-1})		C-sequestration ($\text{kg ha}^{-1} \text{y}^{-1}$)	
					NPK	NPK+FYM/ compost	NPK	NPK+FYM/ compost
Gayeshpur (WB)	Rice-mustard-sesame	1998-2004	0-20	37.3	39.1	40.2	257	414
Mohanpur (WB)	Rice-wheat-fallow	1986-2004	0-20	34.0	35.2	37.2	63	168
Barrackpur (WB)	Rice-wheat-jute	1971-2004	0-20	27.9	30.1	46.09	64	535
CRRI, Cuttack (Orissa)	Rice-fallow-rice	1969-2004	0-20	31.6	39.7	46.10	225	402

Source: Mandal et al. (2008)

Table: 5

Carbon pool of sub humid, semiarid tropical and arid ecosystems under different land management practices

	Sal forest ^a	Mixed forest ^a	Pearl millet-Wheat fallow ^b	Pearl millet-Mustard-Sunflower ^b	Soybean-Wheat ^c -Fallow land
Soils organic C (g m^{-2})	2854	2530	1063	1104	1144
Carbon input ($\text{g Cm}^{-2} \text{yr}^{-1}$)	250	250	281	365	265
Carbon Turnover (yr^{-1})	11.41	10.12	3.78	3.02	4.47
Soils microbial biomass C (g m^{-2})	87	90	42.30	31.70	50.8
C input/soil microbial biomass C	2.87	2.78	6.64	11.51	15.74

Source: ^aSrivastava and Singh, 1989; ^bChander et al., 1997; ^cManna et al., 1996.

nutrients for soil biota, aggregate stability, water retention, hydraulic properties, resistance or resilience to compaction, buffering capacity, cation exchange capacity, and formation of soluble and insoluble complexes with metals. The most important biological properties of organic matter are i) its role as a reservoir of metabolizable energy for soil microbial and faunal activities, ii) its effects in stabilizing enzyme activities and iii) its values as a source of plant nutrition through mineralization. Soil organic matter attributes (microbial biomass C and N) are very sensitive to changes in total soil organic matter and could be utilized, based on their relative simple and straightforward methodology, as indicators of change. More recently, a greater range of labile soil organic matter attributes such as light fraction of organic matter (LF), particulate organic matter (POM, <53 μ m), water soluble carbon, acid hydrolysable carbohydrates and potentially mineralizable fraction of carbon are more sensitive to changes in management. Little attention has been paid towards labile pools of carbon as compared to total organic carbon in most agricultural soils.

Typically, organic matter levels decline rapidly when soil under native vegetation is converted to arable agriculture in the first 10-25 years and then stabilize at a new equilibrium level (Table 7 and Table 8).

Cropping Systems for C-sequestration in Semi-arid Tropic (SAT) Regions of India

In Vertisol, C-sequestration was maximum in cotton/greengram+pigeonpea cropping system (885 kg ha⁻¹yr⁻¹) followed by paddy-paddy system (861 kg ha⁻¹yr⁻¹) then horticulture crop (citrus, 745 kg ha⁻¹yr⁻¹) (Table 9). In red soil, C-sequestration was maximum in intercropping system (castor + pigeon pea, 936 kg ha⁻¹yr⁻¹) than monocrop finger millet (130 kg ha⁻¹yr⁻¹). From different studies, it was observed that to maintain SOC storage equilibrium C input in soybeanwheat system was required 888 kg C ha⁻¹yr⁻¹, in rice-wheat-jute system was required 5562 Kg C ha⁻¹yr⁻¹ in Inceptisol, 4269 kg C ha⁻¹yr⁻¹ for soybean-wheat system in Ranchi and 321 kg C ha⁻¹yr⁻¹ was required for soybean-wheat system in Inceptisol at Almora (Table 10).

Table: 6

Physico-chemical properties of the soil (0-20 cm depth) and mean yield of cotton and sorghum grown in rotation under rainfed condition for 45 years

Treatments	Organic Matter (%)	Total Nitrogen (%)	Available nutrients (kg ha ⁻¹)			Mean yield of seed cotton (mg ha ⁻¹)	Mean grain yield of sorghum (mg ha ⁻¹)
			N	P	K		
HM	1.16	0.061	93.8	13.76	320	3.28	9.37
PM	1.13	0.059	90.7	15.24	345	2.98	12.30
H	0.59	0.047	77.8	10.48	283	1.44	7.15
P	0.52	0.045	72.8	11.68	267	1.66	9.73
LSD at 5% Tillage	0.05	0.017	2.7	0.80	6.66	0.50	3.07
Harrowing	0.9	0.054	85.4	12.12	321	2.36	8.26
Ploughing	0.8	0.052	81.8	13.40	321	2.26	11.01
LSD at 5% Manuring	NS	NS	2.2	0.56	4.7	NS	2.18
Manuring with FYM	1.14	0.060	92.3	14.50	333	3.09	10.84
No manure	0.56	0.046	75.0	11.08	290	1.53	8.44
LSD at 5%	0.04	0.012	2.26	0.56	4.7	0.35	2.18

Source: Khiani and More (1984), HM= Shallow tillage, harrowing up to 8-10 cm depth by Deccan blade harrow and manuring @ 6.2 Mg ha⁻¹ of FYM; PM= Deep tilling, ploughing up to 18-20 cm by iron plough (Kirkoskar) and application of FYM at 6.2 Mg ha⁻¹; H= Shallow tillage, harrowing only up to 8-10 cm depth with Deccan blade harrow and P= Deep tillage ploughing to 18-20 cm with iron plough, NS= Not significant.

Table: 7

Initial status of organic C and equilibrium values for different treatments after 14 years of cultivation at 0-15 cm depth at Akola, India

Treatment	Initial SOC (g kg ⁻¹)	SOC _o mean (g kg ⁻¹)	Steady state (SOC _e) (g kg ⁻¹)	Loss rate (k yr ⁻¹)	t _{1/2} (yr)	R ²
Control	4.6	4.8 ± 0.502	2.3 ± 1.94	0.098	7.1	0.5
N	4.6	4.6 ± 0.0329	3.54 ± 1.798	-0.027	25.7	0.93*
NP	4.6	4.7 ± 0.067	4.4 ± 0.429	-0.086	8.1	0.86*
NPK	4.6	4.8 ± 0.093	4.6 ± 0.267	-0.138	5.02	0.84*
NPK+FYM	4.6	5.4 ± 0.147	5.3 ± 0.374	-0.291	2.4	0.42

SOC= Soil organic carbon; * Value is significant at P<0.05, ± Indicates standard error.

Table: 8

Initial status of organic C and equilibrium values for different treatments after 30 years of cultivation (Barrackpore)

Treatment	Initial SOC (g kg ⁻¹)	SOC _o mean (g kg ⁻¹)	Steady state (SOC _e) (g kg ⁻¹)	Loss rate (yr ⁻¹)	t _{1/2} (yr)	R ²
N	7.12	4.9 ± 0.025	4.8 ± 0.018	-0.020	50.3	0.10
NP	7.12	4.9 ± 0.065	5.0 ± 0.022	-0.067	14.9	0.22
NPK	7.12	5.0 ± 0.038	5.1 ± 0.04	-0.095	10.7	0.39
NPK+FYM	7.12	5.4 ± 0.022	5.6 ± 0.017	-0.129	7.7	0.62**

** Value is significant at P≤ 0.05; ± Standard error.

Table: 9**Initial status of organic C and equilibrium values for different treatments after 30 years of cultivation (Barrackpore)**

Location (State)	Soil type	Cropping system	Cropping period	Sampling depth (cm)	Initial SOC (Mg ha ⁻¹)	SOC (Mg ha ⁻¹)	C-sequestration (kg ha ⁻¹ yr ⁻¹)
Madhya Pradesh	<i>Typic Haplusterts</i> (Kheri)	Paddy-Wheat	1982-2002	0-30	19.8	22.5	135
Maharashtra	<i>Typic Haplusterts</i> (Linga)	Citrus	1982-2002	0-30	22.0	36.9	745
Maharashtra	<i>Typic Haplusterts</i> (Asra)	Cotton/ Greengram+ Pigeon pea	1982-2002	0-30	17.3	35.0	885
Gujarat	<i>Typic Haplusterts</i> (Semla)	Groundnut-Wheat	1978-2002	0-30	27.3	31.9	209
Karnataka	<i>Typic Haplusterts</i> (Teligi)	Paddy-paddy	1974-2002	0-30	18.61	43.6	861
Karnataka	<i>Typic Haplustalf</i> (Vijapura)	Finger millet	1982-2002	0-30	19.3	21.9	130
Andhra Pradesh	<i>Typic Halplustalf</i> (Kaukuntala)	Castor+Pigeonpea	1978-2002	0-30	14.5	35.1	936

Source: Manna and Subba Rao (2012)

Table: 10**Change in SOC storage equilibrium (dC/dt = aX-bSOC) in relation to total input required to maintain SOC in different cropping systems**

Cropping System	Equation	R ²	Amount of C input required (kg ha ⁻¹ yr ⁻¹) to maintain SOC	References
Soybean- wheat (IISS, Bhopal)	Y=0.1806x-160.34	0.95	888	Kundu <i>et al.</i> (2001)
Rice-wheat-jute (Barrackpore)	Y= 0.0536x-298.08	0.77	5562	Manna <i>et al.</i> (2005)
Soybean-wheat (Ranchi)	Y=0.0217x-92.637	0.45	4269	Manna <i>et al.</i> (2005)
Sorghum-wheat (Akola)	Y= 0.0871x-53.4	0.73	613	Manna <i>et al.</i> (2005)
Soybean -wheat system (Almora)	Y= 0.191x-61.3	0.98	321	Kundu <i>et al.</i> (2007)

Impact of 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⁻¹yr⁻¹ (Lal, 1998b). 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. 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.

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 brome grass.

Conservation tillage: Beneficial impacts of conservation tillage in decreasing runoff and soil erosion are widely recognized (Lal, 1989). When used in conjunction with crop residue mulch and cover crops, conservation tillage improves soil structure and enhances SOC pool (Paustian *et*

al., 1997). The benefits of conservation tillage in C sequestration are due both to increase in SOC content (Dick *et al.*, 1998); decrease in CO₂ emissions caused by ploughing (Reicosky *et al.*, 1998), and to reduction in fuel consumption. 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.

Soil fertility management: Nutrient management is essential to increasing crop yield, improving soil quality, decreasing risks of soil erosion (through protective ground cover establishment) and improving SOC content. 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⁻¹yr⁻¹ (Powlson *et al.*, 1998).

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 ploughed uncropped land, and accelerated soil erosion accentuates the depletion of SOC pool. Improvements in crop yield through adoption of recommended technology enhance SOC pool and improve soil quality (Manna *et al.*, 2007).

Conservation reserve program and conservation buffers: Conversion of marginal agricultural land, to restorative land use (e.g. natural re-growth, establishing grasses, shrubs or trees) reduces soil erosion and increases SOC pool.

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. There are at least three opportunities for C sequestration through soil conservation as mentioned by Lal (1999):

Historic C lost from eroded soils estimated at 24.9 Pg can be sequestered through soil restorative measures including afforestation and establishment of appropriate vegetative cover, land application of biosolids, nutrient management etc.

Effective soil conservation, if adopted on a global scale, can reduce erosion-related emissions of 1.1 Pg C yr⁻¹.

Adoption of effective conservation 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, conservation research programme (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.

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