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Invited Article

Soil Carbon Sequestration in Agroecosystems of India

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Soils of agroecosystems of India are degraded, depleted and severely devoid of the soil organic carbon (SOC) pool which is often <1 g kg^{-1} or barely 10 to 15 Mg C ha^{-1} to 40 cm depth. Thus, crop yields are low, water and air resources are polluted, and the overall environment is degraded. Indeed, environmental sustainability in India remains a major issue to be addressed. Concentration of SOC is a strong determinant of soil quality. Furthermore, quality of soil also impacts those of plants and animals, and thus, health of human population. Restoration of SOC pool to above the threshold level of 10 to 15 g kg^{-1} in the root zone is essential to advancing food and nutritional security, achieving climate change adaptation and mitigation, improving water quality and renewability, increasing biodiversity, and alleviating poverty by increasing productivity. Among causes of the severe depletion of SOC pool are extractive farming practices of residue removal, indiscriminate plowing, excessive irrigation by flooding, none or unbalanced application of fertilizers, and use of dung as a household fuel rather than manure. Uncontrolled grazing and shifting cultivation also contribute to soil degradation. The extent and severity of degradation are exacerbated by accelerated erosion by water and wind, salinization, acidification, elemental imbalance, and anerobiosis. Thus, soil degradation trends must be reversed by improving SOC concentration through creation of a positive soil/ecosystem C budget. Among best management practices (BMPs) are afforestation and reforestation of hill slopes and agriculturally marginal lands. Establishment of plantations and agroforestry systems is another option. Some BMPs for cropland, essential to improving SOC pool and advancing food security, are conservation agriculture, integrated nutrient management, and crop diversification especially of the rice-wheat system in the Indo-Gangetic Plains. Policy interventions are needed to promote the adoption of BMPs through payments for ecosystems services. Improved governance and strong political will power are essential to revolutionizing the stagnating Indian agriculture.

Key words: Sustainable intensification, soil quality, soil degradation, food security, forestry and agroforestry systems, shifting cultivation

The soil carbon (C) pool consists of organic and inorganic components. The soil organic C (SOC) pool is derived from the remains of plants and animals. The soil inorganic C (SIC) pool is derived from the parent material as primary carbonates (lithogenic) and from sequestration of atmospheric CO_2 as secondary carbonates (pedogenic). The SOC pool is more reactive, highly dynamic and a strong determinant of soil quality. Perpetual use of extractive farming practices (*i.e.* residue removal, biomass burning, use of animal dung as cooking fuel, indiscriminate plowing, minimal or unbalanced use of chemical fertilizers) in India for centuries to millennia has resulted in severe depletion of SOC pool and extreme degradation of soils of agroecosystems. Thus, soils of agroecosystems, especially of croplands, are prone to physical degradation including reduction in structural aggregation, crusting, compaction, water runoff, accelerated erosion by water and wind, and hydrological imbalance including waterlogging (anaerobiosis) and drought, which are accelerated by mismanagement of soil fertility. Degradation of soil physical quality sets-in-motion processes of chemical degradation. Important among these are reduction in cation exchange capacity (CEC), salt imbalance and salinization, acidification, nutrient depletion and elemental imbalance (toxicity and/or deficiency). Processes of physical and chemical degradation are exacerbated by biological degradation. The latter involves decline in quantity and quality of SOC or organic matter content, reduction in microbial biomass carbon (MBC), decline in activity and species

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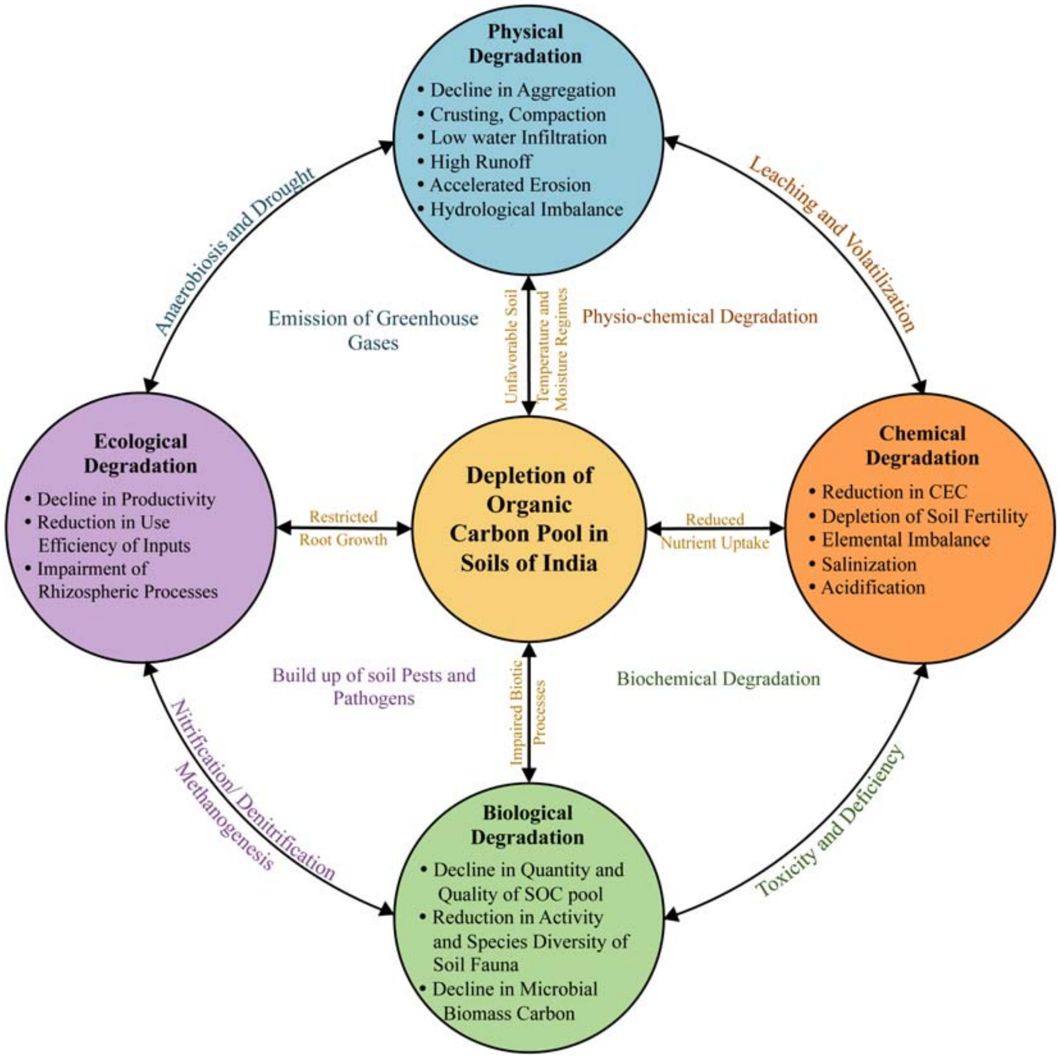

Fig. 1. Soil degradation caused by severe depletion of organic carbon pool in soils of India (SOC= soil organic carbon, CEC= cation exchange capacity)

diversity of macro (*e.g.* earthworms, termites, centipedes, millipedes) and micro fauna (microbes, protozoa, fungi, *etc*.) (Fig.1). Thus, soils of arable lands often contain low SOC concentration of 1 to 10 g kg^{-1} in the root zone (Manna *et al.* 2003), and often much lower. Cropland soils of the Indo-Gangetic Plains (IGP) hardly contain SOC pool of 8.5 to 15.2 Mg C ha^{-1} to 40 cm depth and 12.4 to 22.6 MgC ha^{-1} to 1 m depth (Singh *et al.* 2011a). Such low levels of SOC concentration and pool in the root zone are partly responsible for low agronomic productivity and large yield gaps. Severe environmental problems in India and elsewhere in South Asia (water pollution, sedimentation, air pollution) are partly related to soils which are severely depleted of their SOC pool. Indeed, low SOC concentration in the surface layer may strongly curtail critical rhizospheric processes, limit the use efficiency of inputs, reduce agronomic productivity and degrade the environment. Among factors affecting SOC pool and its functions are land misuse, soil mismanagement, and accelerated soil erosion (Sharma and Rai 2007; Saha *et al.* 2011).

Martin *et al*. (2010) observed that the SOC pool in the Himalayan regions is strongly affected by the climate, and the projected changes in temperature and precipitation may reduce the SOC pool even more. Rainfall and temperature data between 1960 and 2010 indicate decline in rainfall by 46% and shift in period of the maximum rainfall from June-July to August – September. Further, the mean annual temperature also increased by 1.6 °C and the mean monthly temperature by 1.3 °C over this period. Along with the glacial retreat, climatic changes may also reduce the SOC pool in highlands of the Himalayas because of the

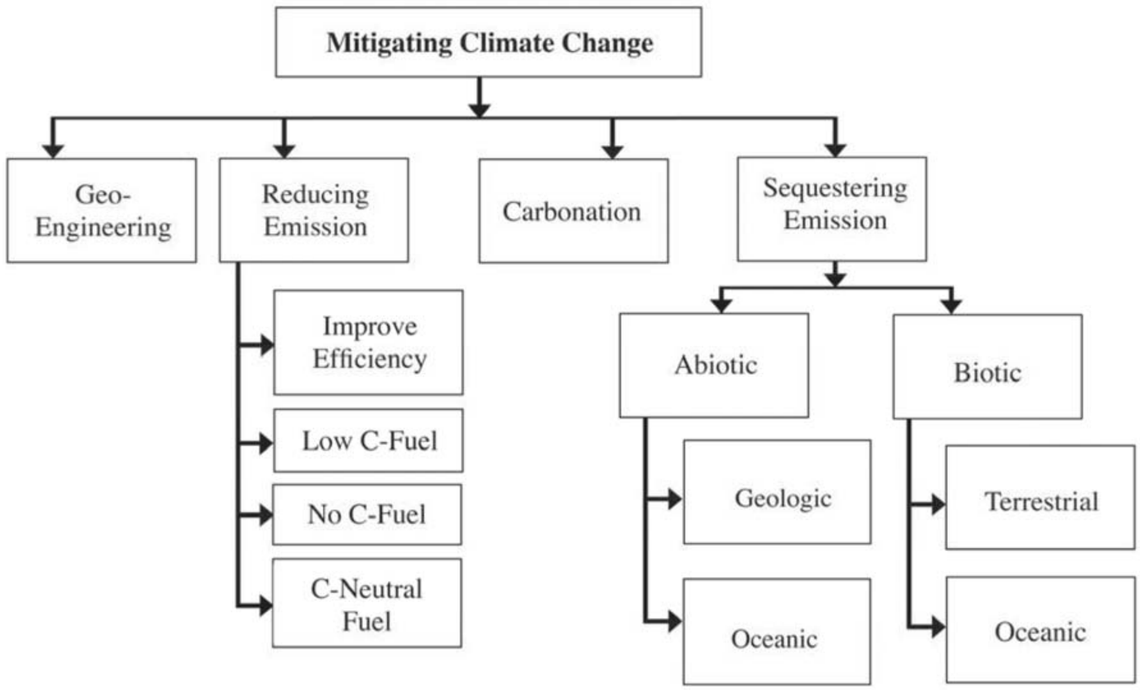

Fig. 2. Strategies of mitigating climate change in India

short supply of water. Information on trends in climate change may be useful to the identification of some "bright spots" of ecosystem C sequestration, and for developing long-term national strategies of mitigating climate change. Among numerous options of mitigating climate change, biotic strategies of sequestering atmospheric CO_2 in the terrestrial biosphere (soil, vegetation) are among important options for India (Fig. 2, 3). Thus, conversion to a restorative land use (afforestation) in temperate regions may be a prudent strategy to harness the potential SOC sink capacity. Identification of the best management practices (BMPs) for recarbonization of soils of India must be based on thorough understanding of the cause-effect relationships affecting SOC pool and its dynamics (Pretty *et al.* 2002). Therefore, the objectives of this article are: i) to review the state of the SOC pool in soils of agroecosystems of India, ii) identify BMPs which can restore the SOC pool, and iii) outline strategies and policies to promote the adoption of BMPs to restore SOC pool, increase productivity and improve the environment. The focus of this manuscript is on the management of SOC pool. Readers are referred to other literature for the characteristics and dynamics of SIC pool in soils of India (Pal *et al.* 1999). The strategy is to cite a few examples of the research done in India rather than to compile a thorough review of the literature.

Organic Carbon Pool in Soils of Agroecosystems in India

Assessing the impact of land use conversion, soil management and cropping/farming systems on SOC pool at a range of spatial scales (10^{-9} to 10^{6} m) is essential to understand the magnitude of the depletion of SOC pool, establish the cause-effect relationship, and identify BMPs for recarbonization of soil and the ecosystem by following a specific protocol (Fig. 4) There exists a wide variation in estimates of SOC pool in soils of India ranging from 24 Pg (Pg = petagram = 10^{15} g = 1 billion metric tonne) to 63 Pg to 1.5 m depth (Bhattacharyya *et al.* 2000). The SOC pool has also been estimated on regional basis. Regional and national estimates of SOC pool are often based on detailed geo-referenced datasets of soils, climate, landuse and management information (Milne *et al.* 2007). Using the GEFSOC Modeling System and compare it with the mapping technology, Bhattacharyya *et al.* (2007b) estimated SOC pool of the Indo-Gangetic Plains (IGP) at 1.27-1.32 Pg for 0-20 cm depth. Other estimates of SOC pool for IGP range from 0.57-1.44 Pg. For the central Western Ghats, covering an area of 8.8 million hectare (Mha), and stretching between Goa and the Palghat Gap, SOC pool has been mapped for forests at varying levels of degradation (Krishnan *et al.* 2007). Wani *et al.* (2010) estimated SOC pool to 0.3 m depth for the state of Madhya Pradesh (M.P.) for the year 2005-2006. These

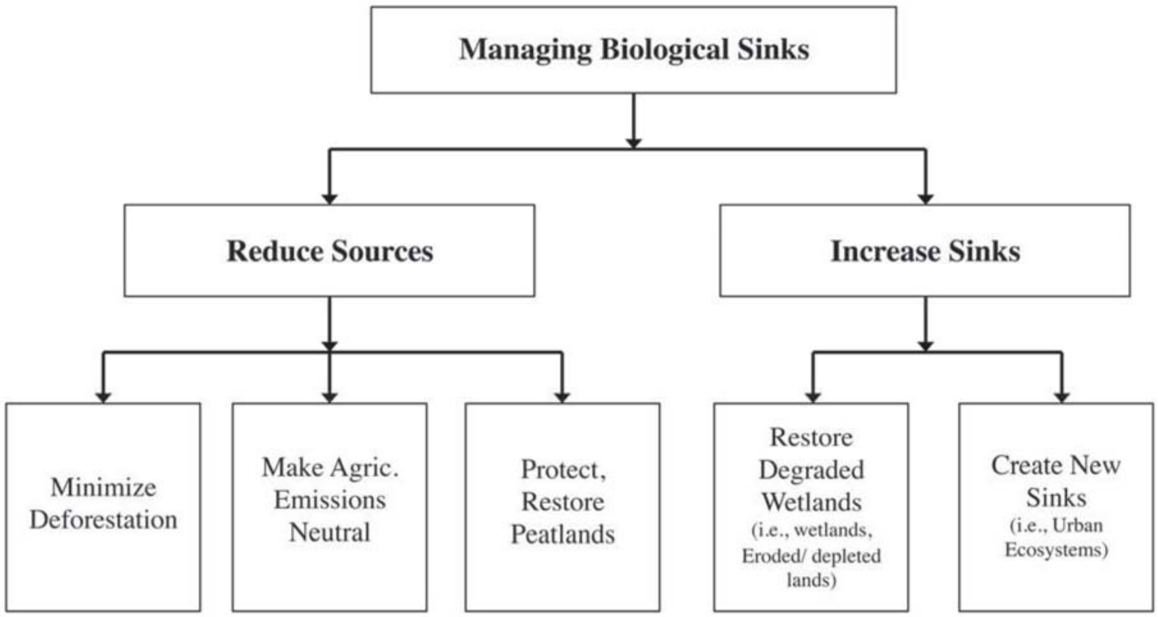

Fig. 3. Strategies of managing biological and terrestrial C sinks

estimates were based on the remote sensing data, district boundaries, the agro-ecological sub-regions and the geographic information system (GIS) using the FAO/UNESCO soil map. Total biomass and SOC pool of M.P. were 34.9 and 790.6 Tg C (Tg= teragram = 10^{12} g = 1 million metric tonne), respectively. The ecosystem C pool of the Kolli Hills, parts of the eastern Ghats of Tamil Nadu, were estimated by Ramachandran *et al*. (2007) at 2.74 Tg and 3.48 Tg for biomass and SOC pool, respectively. Similarly, C pool for soils of Rajasthan has been estimated at 1.23 Pg for SOC and 0.90 Pg for SIC to 1 m depth (Singh *et al.* 2007). Of these, the surface 0-25 cm layer stored 31% of the total C pool. In general, soils of the arid and semi-arid regions contain more SIC (both lithogenic and pedogenic carbonates, and also bicarbonates) than those of sub-humid and humid climates.

The available literature on estimates of SOC and SIC pools indicate the strong need for systematic study of C pool for soils of India on the basis of agro-ecoregions using standardized methodology. Credible data must be obtained to about 2 m depth using the schematic protocol outlined in fig. 4. These measurements must be repeated every 10 to 20 years. Periodic evaluation of the depth distribution of SOC/SIC pools to 2 m depth, in relation to land use and soil/crop management, is critically essential to land use planning and sustainable management of soil resources.

Soil Quality Index and Agronomic Productivity

The SOC pool, its amount and quality, is a defining property and a strong determinant of soil quality and its four components (*i.e.*, physical, chemical, biological and ecological). Using principal components analysis (PCA) and linear discriminant analysis for eroded soils of southern Karnatka, Rajan *et al*. (2010) observed that SOC was the most discriminating parameter for soil quality index (SQI) with the maximum loadings. In addition, other parameters of SQI were electrical conductivity (EC), available water capacity (AWC), micro-aggregates and dehydrogenase activity. However, all these parameters are not necessarily independent and are also affected by SOC concentration. Thus, SOC concentration and different fractions have been used in assessing SQI in relation to specific land use function and cropping/farming system for soils of India. On regional basis, SQI based on SOC in relation to land use has been computed for soils of North-East India (Ghosh *et al.* 2009), and for dryland of semi-arid tropical Alfisols (Sharma *et al.* 2005). Rather than total C, soil quality is strongly affected by the concentration and dynamics of the labile fraction (Majumder *et al.* 2008a,b). Examples of developing SQI shown in table 1 indicate the significance of SOC to agronomic productivity. However, SOC pool has numerous other ecosystem services including water quality and renewability, elemental cycling, biodiversity, climate change and adaptation and mitigation, *etc*.

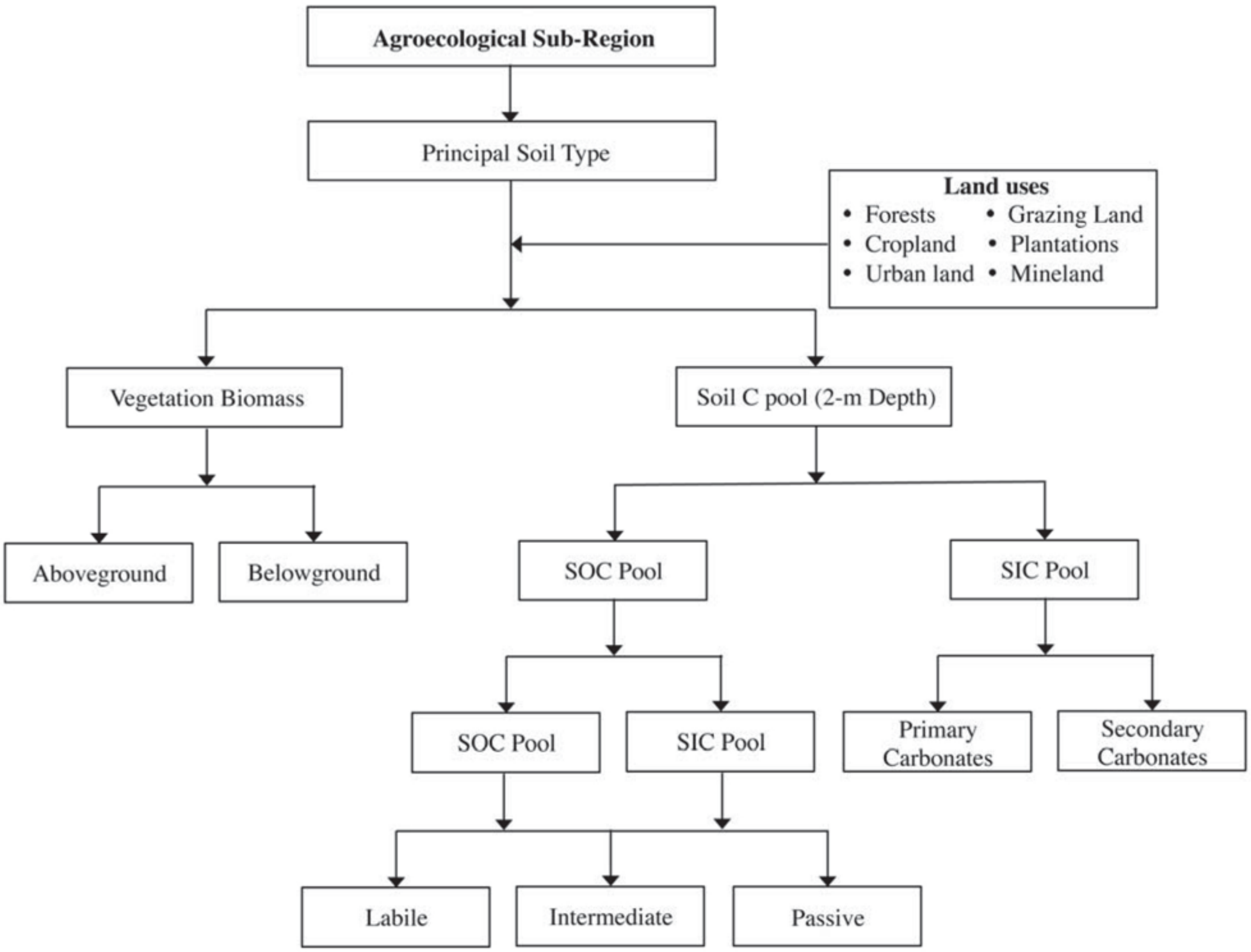

Fig. 4. A Protocol for estimation of C pool in soils of India. These estimates must be made every 10-20 years

Table 1. Effects of soil organic carbon on soil quality index

Location	Ecosystem	Soil quality indicators	Reference
Karnatka	Degraded soils	SOC concentration	Rajan *et al*. (2010)
Meghalaya	Hilly (perennial grasses)	Restore SOC	Ghosh *et al*. (2009)
Eastern	Rice-berseem	Labile SOC	Majumder *et al*. (2008a,b)
Central	Sorghum-castor (*Gliricidia*)	Biological parameters (MBS)	Sharma *et al*. (2005)
Semi-arid region	Maize-wheat-cowpea	SOC and MBC	Manjaiah and Singh (2001)

Concentration of SOC in the root zone affects soil quality through moderation of numerous chemical, physical and biological properties (Lal 2014), especially the AWC and nutrient dynamics. Sub-optimal levels of SOC concentration in the root zone adversely affect the use efficiency of inputs (*i.e.*, fertilizer, irrigation, improved varieties). Thus, there is a strong impact of SOC on agronomic yield and total productivity (Table 2). Increasing SOC concentration by 1 Mg C ha^{-1} in the root zone can increase crop yield by 15-33 kg ha^{-1} for wheat (Benbi and Chand 2007); 170 kg ha^{-1} for pearl millet, 140 kg ha^{-1} for cluster bean and 150 kg ha^{-1} for castor (Srinivasarao *et al.* 2014b); 145 kg ha^{-1} for soybean (Srinivasarao *et al.* 2012c) and 160 kg ha^{-1} for rice (Srinivasarao *et al.* 2012d) (Table 2).

Data from long-term experiments, especially from those which have the baseline information on antecedent SOC concentration and pool, should be used to develop appropriate SQI for principal soils and cropping/farming systems of India. Thus, strengthening databank on soil properties, agronomic productivity and temporal changes in SOC concentration and pool under BMPs for principal soils of major agro-ecoregions is a high national priority.

Table 2. Effects of soil carbon concentration on agronomic yield and productivity

Region	Soil	Crop	Productivity increase (kg Mg^{-1} SOC)	Reference
Sub-Tropical	-	Wheat	15-30	Benbi and Chand (2007)
Western India	-	Pear millet	170 Pearl millet 140 Cluster bean 150 Castor	Srinivasarao *et al.* (2014b)
Tropics	Inceptisols	A wide range	SOC affect sustainable yield index	Wanjari *et al.* (2004)
Central India	Vertisols	Sorghum	90	Srinivasarao *et al.* (2012a)
Southern India	Alfisols	Groundnut-based	13	Srinivasarao *et al.* (2012b)
Central India	Vertisols	Soybean Safflower	145 Soybean 59 Safflower	Srinivasarao *et al.* (2012c)
North-central	-	Rice-lentil	160 Rice 180 Lentil	Srinivasarao *et al.* (2012d)

Causes of Depletion of Organic Carbon Pool in Soils of India

Soil and crop management practices which create a negative soil/ecosystem C budget lead to depletion of the SOC pool. Conversion of natural to managed ecosystems, perpetual use of extractive farming practices, and prevalence of soil degradation processes (erosion) can rapidly deplete the SOC pool. Using satellite imagery from 1988 to 2001 in Sikkim, Sharma and Rai (2007) observed that the total area of forest was decreased by 28% and that of cropland was increased by 100%, and the land use conversion resulted in a strong decline in SOC pool. Jhum (shifting) cultivation, practiced widely in the hilly regions of North-East India, also depletes the SOC pool especially on sloping lands prone to accelerated erosion (Arunachalam and Pandey 2003). Lenka *et al.* (2012) reported that SOC pool in traditional jhum cultivation to 30 cm depth was 21 Mg ha^{-1} compared with 30-40 Mg ha^{-1} for plots managed by the BMPs for 6 years. Thus, it is important to develop viable alternatives to jhum cultivation, those alternatives which enhance and sustain productivity from existing land and minimize the need for any new deforestation through jhum cultivation in these fragile ecosystems.

Off-setting CO_2 Emissions and Mitigating Climate Change by Harnessing Land-based C Sinks through Afforestation

There are several techniques of removing excessive CO_2 from the atmosphere (Fig. 5). Of these, biotic fixation through plants is an important option in the Indian context. Land-based biological C sinks can be judiciously managed to reduce sources and enhance sinks of C (Fig. 3). In terms of land use and land use conversion, reducing sources implies minimizing or avoiding deforestation, and increasing emphasis on afforestation. Restoration of degraded lands by afforestation and reforestation, and of wetlands by management of the hydrologic regime (water table, inundation), and of depleted soils of agroecosystems by adoption of BMPs can create new and strengthen exisiting soil/ecosystem C sinks.

Forested biomass have a high SOC pool ranging from 37.5 Mg ha^{-1} in tropical dry deciduous forest to 92.1 Mg ha^{-1} in littoral and swamp forests to 0.5 m depth. The mean SOC pool ranges from 70 Mg ha^{-1} to 162 Mg ha^{-1} to 1 m depth (Chhabra *et al.* 2003). Therefore, afforestation of degraded soils has multiple benefits, including C sequestration in biomass in soil. Swamy *et al.* (2003) estimated the biomass C in 6-year old plantation of *Gmelina arborea* in three degraded red lateritic soils. Stand biomass ranged from 3.9 (one-year old) to 53.7 Mg ha^{-1} (six-year old), and stand C in six-year old plantation from 24.1 to 31.1 Mg ha^{-1}. Furthermore, SOC pool increased from 8.5 to 14.0 Mg ha^{-1} in the surface layer with an average rate of C sequestration of ~1.25 Mg ha^{-1} yr^{-1} (Swamy *et al.* 2003). Devi *et al.* (2013) compared the impact of eight different tree species on ecosystem C pool in the Western Himalayas. There were strong differences in C pool and sequestration among species. The aboveground (185.6±49.0 Mg ha^{-1}) and the belowground biomass (42.5±10.4 Mg ha^{-1}) were the maximum under *Ulmus villosa*. The SOC pool was the maximum (219.9±10.3 Mg ha^{-1}) under *Alnus nitida* and the minimum (170.8±20.6 Mg ha^{-1}) under *Pinus roxburghii* (Devi *et al.* 2013). The vegetation C pool was the maximum for *Albizia precera* (118.4±1.5 Mg ha^{-1}) and the minimum for *Acacia catechu* (36.5±9.9 Mg ha^{-1}). In comparison, soil C pool was the maximum (219.9±10.3 Mg ha^{-1}) under *Alnus nitida* and the minimum (170.8±20.6 Mg ha^{-1}) under *Pinus roxburghii* (Devi *et al.* 2013).

Establishing plantation of *Prosopis juliflora* can reclaim salinized soils and restore their quality. In

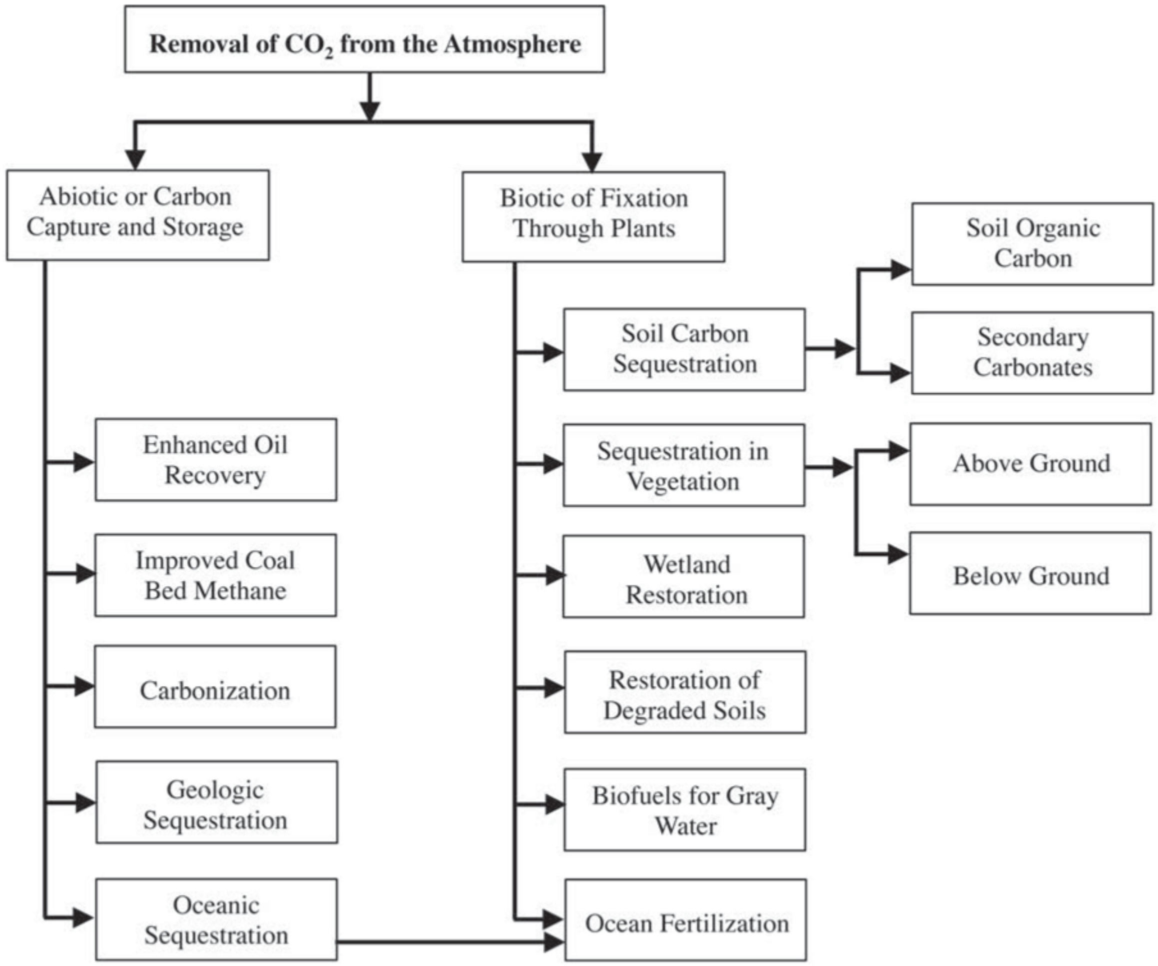

Fig. 5. Techniques of removing excessive CO_2 from the atmosphere.

Haryana, Bhojvard and Timmer (1998) observed evolution of soil quality of salinized soils over 30-year. Furthermore, tree growth altered microclimate, enhanced SOC concentration and improved soil fertility. Establishment of mixed native species can enhance SOC pool even more than that under monoculture of forest plantations as was observed in Jharkhand (Roy *et al.* 2010).

Agroforestry systems, growing trees in association with crops and pastures, is also important to enhancing SOC sequestration in India's agroecosystems (croplands and grazing lands). Agroforestry systems have also the potential to reclaim alkaline/sodic soils. In Karnal, Haryana, Kaur *et al.* (2000) observed that agrisilvicultural systems of *Acacia*, *Eucalyptus* and poplar along with rice-berseem rotation improved SOC and N pools. In Punjab, Gupta *et al.* (2009) assessed SOC pool and aggregation under poplar-based agroforestry systems, and observed that the SOC pool to 0.3 m increased by 2.9-4.8 Mg ha^{-1} over 6 year period compared with the sole crop system. However, the increase in SOC pool may primarily occur in the labile C pool (Benbi *et al.* 2012). In Kerala, Saha *et al*. (2010a) assessed the potential of tree-based systems on C sequestration in home gardens and observed high C storage in soils under tree-based than seasonal land use systems.

Jatropha has the potential to produce biodiesel, and can also be grown on agriculturally marginal lands. Wani *et al*. (2012) estimated the biodiesel C replacement potential of 230 kg ha^{-1} yr^{-1}, and SOC sequestration potential of 2500 kg ha^{-1} over a 3-5 year period. Improvement in SOC concentration also enhanced soil quality of marginal lands. Therefore, establishment of biofuel plantations on marginal lands can meet the local fuel needs and spare animal dung for use as an amendment for improving soil quality.

Forest plantations in temperate climate have a large potential of enhancing the ecosystem C pool in India (Singh *et al*. 2011b). With a large C sink capacity, restoring 40 Mha of surplus degraded land in India by afforestation, at 5.5 Mg C ha^{-1} yr^{-1} in forest productivity, could sequester 3.32 Pg C over 50 year (Singh and Lal 2000). Thus, identification of surplus degraded lands and choice of appropriate species for afforestation by site-specific species is a high priority. Afforestation of lower and middle Himalayas may also alleviate the flood-drought syndrome which has plagued the nation for decades and even centuries. This long-term initiative or reforestation of the Himalayas, from northwest to northeast, will create jobs and business opportunities, alleviate poverty, bring peace and prosperity while mitigating climate change and improving the environment.

Adoption of Best Management Practices in Agroecosystems

Site-specific BMPs depend on soil type, climate, farming/cropping systems and socio-economic conditions. Some generic BMPs outlined in fig. 6 must be validated and fine-tuned under site-specific conditions for each cropping/farming system and land use. Examples of some BMPs for SOC sequestration and sustainable production are explained below:

1. *The Rice-Wheat System:* The rice-wheat system (RWS) is practiced on about 13.5 Mha in the IGP including India, Pakistan, Nepal and Bangladesh. In addition, RWS is also practiced on 10.3 Mha in China (Benbi and Senapati 2010). However, the yield of both rice and wheat in India has stagnated or even declined, probably because of the depletion of SOC concentration, decline in soil structure, and nutrient imbalance in soil (Bhandari *et al.* 2002; Ladha *et al.* 2003). The decline in SOC pool is exacerbated by continuous cropping (Shibu *et al.* 2010) with disregard to residue management. The SOC pool and its dynamics are strongly affected by soil texture or the silt+clay content (Gami *et al.* 2009), and the decline is more severe in sandy or coarse-textured than in clayey or fine-textured soils. Therefore, enhancing SOC concentration and improving soil quality is a

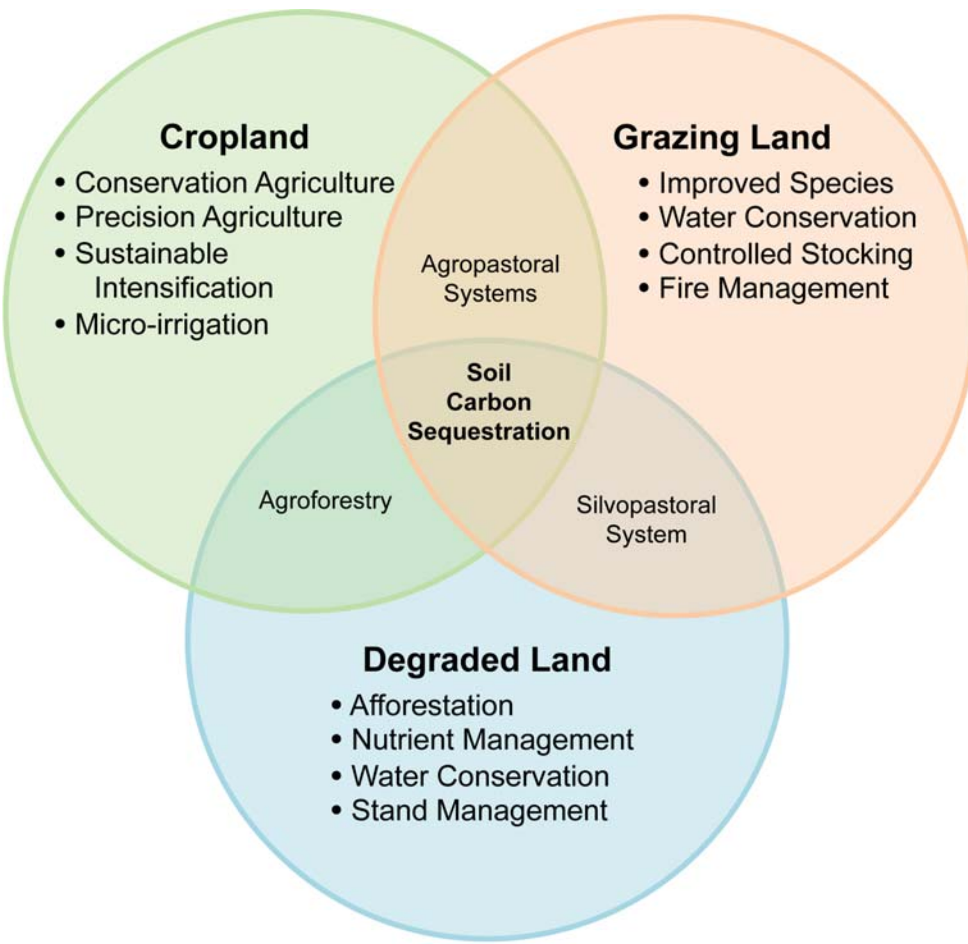

Fig. 6. Principles and practices of soil carbon sequestration by creating a positive soil/ecosystem carbon exchange in terrestrial ecosystems of India

Table 3. Soil carbon dynamics in the rice-wheat system in the IGP

Region	Site	SOC Sequestration	Reference
Northern India	IGP	Decline in SOC and crop yield with cultivation	Shibu *et al*. (2010)
Nepal, Bangladesh	IGP	Silt+clay content affect SOC pool	Gami *et al*. (2009)
Tropical Region	Irrigated	Agroforestry system increased SOC	Purakayastha *et al*. (2007)
Wheat Belt	-	44.1 Tg C over 20 years	Grace *et al*. (2012)
Eastern India	Humid Subtropics	INM improved SOC	Bandyopadhyay *et al*. (2010)
Western	Upper IGP	Crop diversion (pigeon pea) increased SOC	Singh *et al*. (2005)
Eastern	IGP	6-26% of biomass-C was sequestered	Ghosh *et al*. (2012)
Northcentral	IGP (Rice-lentil)	0.31 Mg ha^{-1} yr^{-1} to 1 m depth	Srinvasarao *et al*. (2012d)
Northwestern	IGP	More particulate organic C by CA	Kumari *et al*. (2011)
Punjab	IGP	0.22 Mg ha^{-1} yr^{-1}	Brar *et al*. (2013)
Punjab	IGP	SOC pool increased with input of FYM	Kukal *et al*. (2009)
Punjab	IGP	INM increased SOC	Singh *et al*. (2007)
Northeastern	IGP	22% of biomass-C was stabilized	Majumder *et al*. (2007)
Northcentral	IGP	0.39 to 0.62 Mg ha^{-1} yr^{-1}	Nayak *et al*. (2012)
Northcentral	IGP	Green manure+fertilizer enhanced SOC at location with low intial level	Yadav *et al*. (2000)
Central	IGP	+22.5 to 56.3% after 28 crop cycles by INM	Hati *et al*. (2007)
Sub-tropical	IGP	+24.3% over 19 years	Majumder *et al*. (2008a)

prudent strategy. In this context, importance of creating a positive C budget and of enhancing soil quality (physical, chemical and biological) cannot be over-emphasized. The data from several long-term experiments (Table 3) conducted in IGP indicate that retention of rice straw, addition of farmyard manure (FYM) and use of integrated nutrient management (INM) can enhance SOC pool (Tirol-Padre *et al.* 2007; Bhattacharyya *et al.* 2007a; Majumder *et al.* 2008a,b; Nayak *et al.* 2012; Brar *et al.* 2013). Application of organic amendments also enhances soil aggregation, especially when used in conjunction with no-till (NT) or conservation agriculture (CA) (Benbi and Senapati 2010; Kumari *et al.* 2011). In general macro-aggregates (>250 µm) have higher SOC concentration than micro-aggregates (<250 µm). The rate of SOC sequestration by residue management and application of FYM varies widely in the IGP and may range from 0.1 to 1 Mg C ha^{-1} yr^{-1} (Table 3).

Improvements in SOC pool, soil quality and agronomic productivity can also be brought about by crop diversification. Growing pigeon pea rather than rice during the summer can improve soil quality and also enhance the productivity of the following wheat crop (Singh *et al.* 2005). Rice-berseem system with balanced fertilization system can also maintain SOC pool, and retain 62% of the C applied with FYM (Majumder *et al.* 2008a). Application of FYM and mineral fertilizers to rice-lentil system can increase SOC concentration and pool (Srinivasarao *et al.* 2012c).

Adoption of BMPs to RWS in the IGP has a large potential of SOC sequestration and for climate change adaptation and mitigation. Grace *et al.* (2012) estimated the C sequestration potential of RWS system in India upon adoption of NT/CA at 44.1 Tg C over 20-year period. Indeed, the potential is much higher because doubling the productivity of RWS, which is feasible with restoration of soil quality, will increase the input of biomass-C into soil and set-in-motion the much-needed restorative trend.

2. *Conservation Agriculture:* Excessive tillage depletes SOC pool by exacerbating the rate of decomposition, and also increasing the risks of soil erosion by water on sloping lands, and wind in arid and semi-arid regions. Thus, adoption of CA (in conjunction with residue retention, cover cropping, INM, and diverse rotation) can create a positive soil/ecosystem C budget and enhance SOC concentration and pool (Table 4; Lal 2015a,b). A six-year CA study conducted on a sandy clay loam soil of central Himalayas indicated increase in SOC concentration and soil aggregation in the rainfed lentil-finger millet cropping system in the Himalayas. Properly implemented, CA can improve agronomic productivity, soil structure (aggregation) and enhance SOC concentration and quality (Table 4). Grace *et al.* (2012) estimated that implementing CA system in maize-wheat and cotton-wheat production systems would sequester 6.6 Tg C, in addition to 44.1 Tg sequestered by adopting CA in the RWS. Together, sequestration of 50.7 Tg C in wheat-based systems in

Table 4. Impact of conservation agriculture on soil carbon sequestration.

Region	Soil Type	Cropping System	SOC Sequestration	Reference
IGP	Sandy loam	Cotton-wheatMaize-wheat-green grain	+26-28% high SOC stock	Das *et al.* (2013)
Himalayas	Sandy clay loam	Rice-wheat	+11-12% more SOC	Bhattacharyya *et al.* (2012a)
Northeastern	-	Rice-based	+70-75%	Ghosh *et al.* (2010b)
Northwestern	-	Direct seeding rice	More POM fraction	Kumari *et al.* (2011)
Southern	Alfisols	Cover cropping (horse gram)	Restored soil quality	Vekateswarlu *et al.* (2007)
Himalayas	-	Legume-based cropping	+10.12 -17.2%	Bhattacharyya *et al.* (2009)

India could offset 9.6% of India's annual 519 Tg greenhouse gas (GHG) emissions in 2010 (Grace *et al.* 2012).

In the context of perennial culture, management of crop residues (bagasse and leaf litter) in multi-ratooning sugarcane can also be beneficial to SOC sequestration. For example, Yadav *et al.* (1994) observed that recycling of sugarcane trash, constituting 10-20% of the total biomass can be extremely beneficial. Retention of trash as mulch, rather than burning, increased SOC concentration by 0.13% over a three-year period, while also improving soil fertility. Suman *et al.* (2009) documented that adoption of BMPs in sugarcane (grown on an Inceptisol under sub-tropical conditions) strongly increased SOC pool in 0-30 cm layer over five-year period.

When combined with SOC sequestration potential of forestry, agroforestry, plantations and other systems, the potential of CA as a land-based C sink in India must be integral to any agenda of mitigating climate change, improving the environment, and creating climate-resilient agroecosystems, and advancing the Sustainable Development Goals of the United Nations (Lal 2015a,b)

3. *Soil Fertility Management:* A severe depletion of SOC pool in soils of India and elsewhere in developing countries (*e.g.* South Asia, Sub-Saharan Africa, the Caribbean, Andean region) is attributed to the widespread use of extractive farming practices whereby the plant nutrients removed in harvests (crops, fruits, animal products, timber, *etc*.) are not replaced. Nutrient mining, creating a negative nutrient budget, is a serious problem in South Asia, as is also in Sub-Saharan Africa. Indeed, nutrients removed by harvest must be replaced by adding/recycling biomass and/or applying inorganic fertilizers. The strategy of INM is the best option to create nutritional balance in the soil-plant-animal continuum. Improving soil fertility also enhances nutritional security of the population because health of the soil-plant-animal-human is a continuum and indivisible. Examples of impacts of INM and soil fertility management on SOC sequestration in soils of India are illustrated by examples listed in table 5. The rates of SOC sequestration vary widely, and depend on soil type, climate, cropping system and the site-specific management. Measured rates of increase in SOC pool range from 0.1 to 1.4 Mg C ha^{-1} yr^{-1} (Table 5). Stability and the mean residence time (MRT) of the SOC sequestered depend on the degree and strength of soil aggregates, and use of any organic amendments also enhances aggregation and their strength (Biswas *et al.* 2009). There is a strong need to strengthen the databank with regards to the judicious management of soil fertility for increasing productivity, improving SOC pool, and enhancing nutritional security.

4. *Forestry, Agroforestry and Perennial Culture:* Afforestation and reforestation of degraded soils can reverse the degradation trends and restore soil quality. Continuous ground cover and lack of soil disturbance under a perennial landuse minimize the risks of soil erosion, optimize recycling of nutrients in the detritus material, and increase addition of biomass C into the soil. Therefore, conversion of degraded agricultural soils (croplands, grazing lands) to forestlands and perennial land use can enhance SOC sequestration (Table 6).

Afforestation and establishment of forest plantations on degraded and marginal croplands can increase both the biomass and soil C pools. Thus, establishment of forest plantation is the most appropriate land use for the fragile hill ecosystems of the Himalayas and elsewhere on the highlands (see Section 5). Agroforestry systems, combining perennials with crops and livestock, is another viable option for sustainable intensification of agro-ecosystems. On a 6-year study in eastern India, Lenka *et al.* (2012) observed that agroforestry systems increased SOC pool in 0-30 cm depth while reducing risks of surface runoff and accelerated erosion. The best system involved a mixture of guava with stylosnathese and establishment of trenches for runoff

Table 5. Effects of manuring, fertilization and amendments of soil carbon dynamics

Region	Soils	Amendment	Cropping System	Soil C Sequestration	Reference
Central India	Vertisols	Distillary effluent	Soybean-wheat	Increased SOC and aggregation	Biswas *et al.* (2009)
Sub-Tropics	Inceptisols	Organic manure	Sugarcane	+0.46-3.42 Mg C ha^{-1} yr^{-1}	Suman *et al.* (2009)
Himalayas	-	Fertilizers/ FYM	Soybean-wheat	+16% of applied C was stabilized	Bhattacharyya *et al.* (2011)
IGP	-	Organics+ Fertilizers	Rice-wheat	+83.5% SOC	Benbi *et al.* (2012)
Sub-Tropics	Inceptisols	INM	Pearl millet-wheat	FYM increased SOC	Moharana *et al.* (2012)
Eastern India	Alluvial	INM	Diverse crops	+59 Mg C ha^{-1}	Ghosh *et al.* (2010a)
Northeast	Acidic	INM	Soybean-wheat	Increased	Saha *et al.* (2010b)
Central India	Vertisol	INM	Sugarcane	+139-888 kg ha^{-1} yr^{-1}	Kundu *et al.* (2001)
U.P.	-	Mulch	Long-term/ diverse	+0.08%	Yadav *et al.* (1994)
Across India	-	INM	Rice-rice	+0.12 to 0.28 Mg ha^{-1} yr^{-1}	Pathak *et al.* (2011)
North Central	Endoaquept	INM	Rice-wheat	+1.3 to 3.2 g kg^{-1} over 20 years	Nayak *et al.* (2012)
Northwestern	-	INM	Rice-legume	+0.44 to 1.53 Mg ha^{-1} yr^{-1}	Benbi and Senapati (2010)
Central India	-	Vermi-compost	Wheat-soybean	+4.6 to 6.8%	Jeyabal and Kuppaswamy (2001)
Himalayas	Silty clay loam	INM	Diverse	+1.4 to 1.74 Mg ha^{-1} yr^{-1}	Bhattacharyya *et al.* (2007a)
Northwestern	Sandy loam	Intensive agriculture	Diverse	Intensification increased SOC pool	Benbi and Brar (2009)
Northeastern	Alfisol	INM	Rice-rice	Improved soil quality	Hati *et al.* (2008)
IGP	-	Rice straw	Soybean-wheat	+1.39 Mg ha^{-1}	Bhattacharyya *et al.* (2012b)
Sub-Himalayas	-	Fertilizer	Sorghum-wheat	+0.57 Mg ha^{-1} yr^{-1} over 30 years	Bhattacharyya *et al.* (2010)
Tropics (SAT)	-	INM	Sorghum-wheat	Yeild decline with decline of SOC	Manna *et al.* (2005)
Tropics (SAT)	Haplustept	INM	Maize-wheat-cowpea	+0.73 Mg ha^{-1} yr^{-1}	Rudrappa *et al.* (2006)
Northwestern	Inceptisol	INM	Maize-wheat-cowpea	+4.5 to 7.5 g kg^{-1}	Masto *et al.* (2006)
Sub-Tropics	Haplustept	INM	Maize-wheat-cowpea	+1 Mg ha^{-1} yr^{-1}	Purakayastha *et al.* (2008)
Himalayas	-	INM	Soybean-wheat	+900 kg ha^{-1} yr^{-1}	Kundu *et al.* (2007)
Central	Rainfed	INM	Sorghum-millet-groundnut	+902 kg ha^{-1} yr^{-1}	Srinivasarao *et al.* (2014a)

Table 6. Soil carbon sequestration in forest and perennial ecosystems

Regions	Forest Species/ Vegetation	SOC Sequestration	Reference
Tropical Forest	Plantations of native species	Mixed native species	Roy *et al.* (2010)
Northwestern Himalayas	Plantations	Alnus nitida	Devi *et al.* (2013)
Sub-Tropical	Fruit trees (coconut, guava)	Increase from 3.4-7.8 g kg^{-1} over 38 year	Manna and Singh (2001)
Northeast	Bamboos	SOC stock of 57 Mg ha^{-1} to 30-cm	Nath *et al.* (2009)
Central India	Jatropha	305 kg ha^{-1} yr^{-1}	Wani *et al.* (2012)
Northwest	Tree-based systems	Higher SOC storage	Saha *et al.* (2010a)
Central India	*Gmelina arborea*	0.93 Mg ha^{-1} yr^{-1}	Swamy *et al.* (2003)
Western India	Poplar-based	0.48-0.8 Mg ha^{-1}	Gupta *et al.* (2009)
Northwestern	*A. nilotica*, *D. sissoo*, *P. juliflora* plus grasses	Silvopastoral systems improved SOC	Kaur *et al.* (2002)
Southwestern	Home gardens (Kerala)	102 to 127 Mg ha^{-1} to 1 m depth	Saha *et al.* (2009)
Northwestern	Jatropha	Improved SOC	Bhojvald and Toimmer (1998)
Northwestern	Agrisilvicultural	Increased MBC	Kaur *et al.* (2000)

management. Long-term experiments conducted on some Inceptisols in sub-tropical regions of India showed that conversion of croplands to agro-forestry systems for more than two decades strongly increased the SOC pool (Purakayastha *et al.* 2007). Poplar-based agroforestry systems have been widely used in Punjab and Haryana, without severe adverse impacts on wheat and other crops for the first four to six years of establishing trees. In Punjab, Benbi *et al*. (2012a) reported that use of poplar-based agroforestry in maize-wheat system increased the labile fraction of the SOC pool. Gupta *et al.* (2009) also observed that poplar-based agroforestry systems improved soil aggregation and enhanced SOC pool. Establishment of jatropha on degraded lands for biodiesel production can also restore soil quality and reduce dependence on fossil fuel (Wani *et al.* 2012). A site-specific adoption of silvo-pastoral systems can also improve SOC pool (Kaur *et al.* 2002). Indeed, agroforestry systems are among the BMPs for restoration of degraded soils and increasing C pool in the land-based sinks.

Therefore, forestry and agroforestry systems are important to restoration of soil quality and increasing SOC pool of degraded cropland soils and desertified agroecosystems. The overall strategy is to improve plant diversity which can enhance C and elemental recycling and enhance SOC pool (Saha *et al*. 2009). Similarly, crop diversification, as in case of RWS, is also important to sustainable management of soil (Singh *et al.* 2005), especially of rainfed cropland soils.

5. *Viable Alterative to Jhum or Shifting Cultivation:* Shifting cultivation is practiced in North East and elsewhere by tribal population in India. Deforestation and biomass burning in jhum cultivation can aggravate the soil erosion hazards on sloping lands. Thus, identifying viable alternatives to shifting cultivation is a high priority. Sustainable management of bamboos can increase ecosystem C pool in the biomass (Table 7), and soil (Nath *et al.* 2009; Nath *et al*. 2015a,b). Creating another income stream for farmers, through trading C credits and payments for ecosystems services (Nath *et al.* 2015b) may be another strategy that deserves to be objectively considered for reducing deforestation and promoting eco-friendly landuse systems in the fragile hilly ecoregions. Trading surplus grains for the north-western region for preserving the forests in the north-east is a win-win strategy, and worthy of serious consideration.

Sustainable Intensification of Agroecosystems in India

Agronomic productivity (yield per unit time and energy-based inputs) in India is low in both irrigated and rainfed production systems. Crop yields of irrigated systems can be doubled and those of rainfed systems quadrupled through the adoption of proven BMPs. The overall strategy is to adopt techniques of sustainable intensification. The latter implies producing more from less—less land, fertilizers, irrigation, pesticides and inherent resources by reducing losses and improving efficiency. For examples, an experiment of intensive cropping for 25 years (1981/82 to 2005/06) in Punjab indicated increase in SOC pool and the overall soil quality along with increase in productivity (Benbi and Brar 2009). Increased productivity by intensification also enhanced SOC pool by 0.8 Mg C ha^{-1} per Mg of grains produced over this period. Similar results have been reported from the North China Plains (Kong *et al*. 2014). Thus, sustainable intensification is a strategy for an objective consideration at national level.

Similar to the irrigated agriculture, sustainable intensification is also urgently needed for improving the low productivity of rainfed systems in India. Several long-term experiments on diverse crops and cropping systems conducted in the semi-arid tropics have indicated that increase in production also increases SOC pool and improves soil quality provided that positive soil C and nutrient budgets are maintained (Kundu *et al.* 2001; Srinivasarao *et al.* 2009; 2012a,b,c,d; 2014a,b; Srinivasarao and Lal 2015). Increase in SOC pool along with improvement

Table 7. Viable alternative to shifting cultivation through soil carbon sequestration

Region	Land/Soil	Improved Systems	Δ SOC Stock Mg yr^{-1}	Reference
Eastern India	Degrading hillslopes	Hedgerows of *Indiofera teysmani*	1.5-3.2	Lenka *et al*. (2012)
North Eastern India	Sloping hilly land	Length of the fallowing	SOC increased with succession	Arunachalam and Pandey (2003)
North Eastern	Sloping land	Bamboo	Increase SOC pool	Nath *et al*. (2009; 2015a,b)

in soil quality, also enhances agronomic productivity and efficiency of resource use (Tables 1, 2). In Punjab, Benbi and Chand (2007) reported that increase in SOC pool by 1 Mg C ha^{-1} increased yield of wheat by 15 to 33 kg ha^{-1} for low SOC concentration of 3 to 9 g kg^{-1} (Table 2). Threshold level of SOC concentration for soils of the tropics being 10 to 15 g kg^{-1} (Aune and Lal 1998), additional improvements in productivity are only achievable through restoration of SOC pool and the attendant increase in soil quality. Similarly, a study conducted in eastern cereal belt in India showed that use of fertilizers and manure (INM) has a large potential to increase SOC pool (Ghosh *et al.* 2010a), while enhancing productivity and the environment.

With limited soil and water resources, and declining per capita cropland area because of urbanization and other competing land uses, India must adopt techniques of sustainable intensification. This is a win-win-win option of increasing productivity, improving environment, and alleviating poverty. Appropriate policy interventions are needed to promote adoption of proven BMPs.

Conclusions

There is a need for research, education, outreach and policy interventions to restore SOC pool, improve quality of soils of agroecosystems, increase productivity, and improve environment quality.

1. *Researchable Issues:* There are several knowledge gaps in SOC dynamics and pool. Important among these include the following:

i. The SOC pool must be monitored for soils of India to 2 m depth following a standardized protocol. Temporal changes in pool at national scale must be assessed at decadal scale.
ii. Critical levels of total SOC pool and labile fraction in the root zone must be established in relation to productivity and use efficiency of inputs, for diverse farming systems in a wide range of agroecosystems.
iii. Impacts of SOC pool on agronomic productivity (kg grain/ Mg of SOC pool) must be established for major soils and principal crops for a wide range of SOC pool in the root zone.
iv. Net rates of SOC sequestration, keeping into consideration the hidden C costs of inputs, must be assessed for different soils, farming/cropping systems and agro-ecoregions. Life cycle analysis must be done to assess the net gains in soil C from techniques such as biochar, and other off-farm inputs.
v. The amount of biomass-C needed, to maintain the SOC pool and to enhance it, must be determined for different agroecoregions (climate, soil, landuse).
vi. Nutrient management (N, P and S) must be determined for conversion of the biomass-C into humus. Thus, fertilizer rates may need to be revised, in view of the nutrients input for both crop requirements and humification of biomass-C.
vii. It is pertinent to assess the mean residence time of SOC sequestered, by modern analytical techniques.
viii. The BMPs must be identified for site-specific situations.
ix. Depth-distribution of SOC pool must be determined to 2 m depth on decadal scale.
x. Relationship must be established between SOC pool and secondary (pedogenic) carbonates. Secondary carbonates are important in arid and semi-arid regions, and are created by biogenic processes. Leaching of bicarbonates must be assessed in irrigated systems, and of dissolved organic C in humid climates.
xi. Soil properties (clay+silt contents, mineralogy, depth, soil temperature, and moisture regimes) and profile characteristics must be identified in relation to the C sink capacity, MRT, and rate of SOC sequestration.
xii. The rate and magnitude of SOC sequestration must be linked to aggregate size and stability, and particle size fractions.
xiii. Societal and economic values of SOC must be determined.
xiv. Scaling procedures to extrapolate data from point source to regional, watershed and national scale need to be developed.
xv. Development of non-destructive and in-situ measurements of SOC pool at landscape scale (Mg C ha^{-1} to 1 m depth) is a high priority.

2. *Educational and Curricula Issues:* There is a strong need to update the curricula at undergraduate and graduate levels to offer courses which explain the importance of: i) soils in the global C (N, P, S and H_2O) cycle, ii) soil C sink capacity to mitigate climate change, iii) societal and economic values of soil C, iv) processes, factors and causes of soil degradation, v) soil degradation and human nutrition and health, vi) protocol for payments of ecosystem services, vii) soil restoration to environment quality, viii) scaling techniques involving GIS and remote sensing to assess SOC pool at regional and national scales, ix) nano-

technology and other innovation in SOC management, and x) recycling urban and animal wastes in agroecosystems.

3. *Outreach:* Research and education must be closely linked with outreach and extension. Scientific knowledge must be translated into action. Adoption of improved technology must be promoted through on-farm field experiments with full participatory approach. Farmers, especially the women farmers, must be involved in the decision making process. The yield gap, difference between the attainable yield and the national average yield, must be abridged through promotion of site-specific BMPs. Nutrition-sensitive agriculture must be promoted to reduce hidden hunger through improvement in soil quality. Effective outreach is essential to usher the soil-based (rather than seed-based) Green Revolution.

4. *Policy Interventions:* Political will power is essential to promote the adoption of improved technologies and BMPs. Just, transparent, and effective governance is critical to promoting sustainable intensification. Farmers must be compensated for provisioning of ecosystem services on the basis of the true societal value of soil C. Thus, societal and economic values of SOC must be objectively determined. Rather than subsidies, compensation must be paid for ecosystem services (climate mitigation and C sequestration, biodiversity, water quality) through sequestration of SOC pool.

References

Arunachalam, A. and Pandey, H.N. (2003) Ecosystem restoration of jhum fallows in northeast India: Microbial C and N along altitudinal and successional gradients. *Restoration Ecology* **11**, 168-173.

Aune, J.B. and Lal, R. (1997) Agricultural productivity in the tropics and critical limits of properties of Oxisols, Ultisols and Alfisols. *Tropical Agriculture (Trinidad)* **74**, 96-103.

Bandyopadhyay, P.K., Saha, S., Mani, P.K. and Mandal, B. (2010) Effect of organic inputs on aggregate associated organic carbon concentration under long-term rice-wheat cropping system. *Geoderma* **154**, 379-386.

Benbi, D.K. and Brar, J.S. (2009) A 25-year record of carbon sequestration and soil properties in intensive agriculture. *Agronomy for Sustainable Development* **29**, 257-265.

Benbi, D.K., Brar, K., Toor, A.S., Singh, P. and Singh, H. (2012a) Soil carbon pools under poplar-based agroforestry, rice-wheat, and maize-wheat cropping systems in semi-arid India. *Nutrient Cycling in Agroecosystems* **92**, 107-118.

Benbi, D.K. and Chand, M. (2007) Quantifying the effect of soil organic matter on indigenous soil N supply and wheat productivity in semiarid sub-tropical India. *Nutrient Cycling in Agroecosystems* **79**, 103-112.

Benbi, D.K. and Senapati, N. (2010) Soil aggregation and carbon and nitrogen stabilization in relation to residue and manure application in rice-wheat systems in northwest India. *Nutrient Cycling in Agroecosystems* **87**, 233-247.

Benbi, D.K., Toor, A.S. and Kumar, S. (2012b) Management of organic amendments in rice-wheat cropping system determines the pool where carbon is sequestered. *Plant and Soil* **360**, 145-162.

Bhandari, A.L., Ladha, J.K., Pathak, H., Padre, A.T., Dawe, D. and Gupta, R.K. (2002) Yield and soil nutrient changes in a long-term rice-wheat rotation in India. *Soil Science Society of America Journal* **66**, 162-170.

Bhattacharyya, R., Tuti, M.D., Bisht, J.K., Bhatt, J.C. and Gupta, H.S. (2012a) Conservation tillage and fertilization impact on soil aggregation and carbon pools in the Indian Himalayas under an irrigated rice-wheat rotation. *Soil Science* **177**, 218-228.

Bhattacharyya, R., Tuti, M.D., Kundu, S., Bisht, J.K. and Bhatt, J.C. (2012b) Conservation tillage impacts on soil aggregation and carbon pools in a sandy clay loam soil of the Indian Himalayas. *Soil Science Society of America Journal* **76**, 617-627.

Bhattacharyya, R., Kundu, S., Srivastva, A.K., Gupta, H.S., Prakash, V. and Bhatt, J.C. (2011) Long term fertilization effects on soil organic carbon pools in a sandy loam soil of the Indian sub-Himalayas. *Plant and Soil* **341**, 109-124.

Bhattacharyya, R., Prakash, V., Kundu, S., Srivastva, A.K. and Gupta, H.S. (2009) Soil aggregation and organic matter in a sandy clay loam soil of the Indian Himalayas under different tillage and crop regimes. *Agriculture, Ecosystems and Environment* **132**, 126-134.

Bhattacharyya, R., Prakash, V., Kundu, S., Srivastva, A.K., Gupta, H.S. and Mitra, S. (2010) Long term effects of fertilization on carbon and nitrogen sequestration and aggregate associated carbon and nitrogen in the Indian sub-Himalayas. *Nutrient Cycling in Agro-ecosystems* **86**, 1-16.

Bhattacharyya, R., Chandra, S., Singh, R.D., Kundu, S., Srivastva, A.K. and Gupta, H.S. (2007a) Long-term farmyard manure application effects on properties of a silty clay loam soil under irrigated wheat-soybean rotation. *Soil and Tillage Research* **94**, 386-396.

Bhattacharyya, T., Pal, D.K., Easter, M., Batjes, N.H., Milne, E., Gajbhiye, K.S., Chandran, P., Ray, S.K., Mandal, C., Paustian, K., Williams, S., Killian, K., Coleman, K., Falloon, P. andPowlson, D.S. (2007b) Modelled soil organic carbon stocks and changes in the Indo-Gangetic plains, India from 1980 to 2030. *Agriculture, Ecosystems and Environment* **122**, 84-94.

Bhattacharyya, T., Pal, D.K., Mandal, C. and Velayutham, M. (2000). Organic carbon stock in Indian soils and their geographical distribution. *Current Science* **79**, 655-660.

Bhojvaid, P.P. and Timmer, V.R. (1998) Soil dynamics in an age sequence of *Prosopis juliflora* planted for sodic soil restoration in India. *Forest Ecology and Management* **106**, 181-193.

Biswas, A.K., Mohanty, M., Hati, K.M. and Misra, A.K. (2009) Distillery effluents effect on soil organic carbon and aggregate stability of a Vertisol in India. *Soil and Tillage Research* **104**, 241-246.

Brar, B.S., Singh, K., Dheri, G.S. and Balwinder-Kumar (2013) Carbon sequestration and soil carbon pools in a rice-wheat cropping system: Effect of long-term use of inorganic fertilizers and organic manure. *Soil and Tillage Research* **128**, 30-36.

Chhabra, A., Palria, S. and Dadhwal, V.K. (2003) Soil organic carbon pool in Indian forests. *Forest Ecology and Management* **173**, 187-199.

Das, T.K., Bhattacharyya, R., Sharma, A.R., Das, S., Saad, A.A. and Pathak, H. (2013) Impacts of conservation agriculture on total soil organic carbon retention potential under an irrigated agro-ecosystem of the western Indo-Gangetic Plains. *European Journal of Agronomy* **51**, 34-42.

Devi, B., Bhardwaj, D.R., Panwar, P., Pal, S., Gupta, N.K. and Thakur, C.L. (2013) Carbon allocation, sequestration and carbon dioxide mitigation under plantation forests of north western Himalaya, India. *Annals of Forest Research* **56**, 123-135.

Gami, S.K., Lauren, J.G. and Duxbury, J.M. (2009) Influence of soil texture and cultivation on carbon and nitrogen levels in soils of the eastern Indo-Gangetic Plains. *Geoderma* **153**, 304-311.

Ghosh, S., Wilson, B., Ghoshal, S., Senapati, N. and Mandal, B. (2012) Organic amendments influence soil quality and carbon sequestration in the Indo-Gangetic plains of India. *Agriculture, Ecosystems and Environment* **156**, 134-141.

Ghosh, S., Wilson, B.R., Mandal, B., Ghoshal, S.K. and Growns, I. (2010a) Changes in soil organic carbon pool in three long-term fertility experiments with different cropping systems and inorganic and organic soil amendments in the eastern cereal belt of India. *Australian Journal of Soil Research* **48**, 413-420.

Ghosh, P.K., Das, A., Saha, R., Kharkrang, E., Tripathi, A.K., Munda, G.C. and Ngachan, S.V. (2010b) Conservation agriculture towards achieving food security in North East India. *Current Science* **99**, 915-921.

Ghosh, P.K., Saha, R., Gupta, J.J., Ramesh, T., Das, A.K., Lama, T.D., Munda, G.C., Bordoloi, J.S., Verma, M.R. and Ngachan, S.V. (2009) Long-term effect of pastures on soil quality in acid soil of North-East India. *Australian Journal of Soil Research* **47**, 372-379.

Grace, P.R., Antle, J., Aggarwal, P.K., Ogle, S., Paustian, K. and Basso, B. (2012) Soil carbon sequestration and associated economic costs for farming systems of the Indo-Gangetic Plain: A meta-analysis. *Agriculture, Ecosystems and Environment* **146**, 137-146.

Gupta, N., Kukal, S.S., Bawa, S.S. and Dhaliwal, G.S. (2009) Soil organic carbon and aggregation under poplar based agroforestry system in relation to tree age and soil type. *Agroforestry Systems* **76**, 27-35.

Hati, K.M., Swarup, A., Dwivedi, A.K., Misra, A.K. and Bandyopadhyay, K.K. (2007) Changes in soil physical properties and organic carbon status at the topsoil horizon of a vertisol of central India after 28 years of continuous cropping, fertilization and manuring. *Agriculture, Ecosystems and Environment* **119**, 127-134.

Hati, K.M., Swarup, A., Mishra, B., Manna, M.C., Wanjari, R.H., Mandal, K.G. and Misra, A.K. (2008) Impact of long-term application of fertilizer, manure and lime under intensive cropping on physical properties and organic carbon content of an Alfisol. *Geoderma* **148**, 173-179.

Jeyabal, A. and Kuppuswamy, G. (2001) Recycling of organic wastes for the production of vermicompost and its response in rice-legume cropping system and soil fertility. *European Journal of Agronomy* **15**, 153-170.

Kaur, B., Gupta, S.R. and Singh, G. (2000) Soil carbon, microbial activity and nitrogen availability in agroforestry systems on moderately alkaline soils in northern India. *Applied Soil Ecology* **15**, 283-294.

Kaur, B., Gupta, S.R. and Singh, G. (2002) Carbon storage and nitrogen cycling in silvopastoral systems on a sodic in northwestern India. *Agroforestry Systems* **54**, 21-29.

Kong, X., Lal, R., Li, B., Liu, H., Li, K., Feng, G., Zhang, Q. and Zhang, B. (2014) Fertilizer intensification and its impacts in China's HHH Plains. *Advances in Agronomy* **125**, 135-169.

Krishnan, P., Bourgeon, G., Lo Seen, D., Nair, K.M., Prasanna, R., Srinivas, S., Muthusankar, G., Dufy, L. and Ramesh, B.R. (2007) Organic carbon stock map for soils of southern India: A multifactorial approach. *Current Science* **93**, 706-710.

Kukal, S.S., Rehana-Rasool and Benbi, D.K. (2009) Soil organic carbon sequestration in relation to organic and inorganic fertilization in rice-wheat and maize-wheat systems. *Soil and Tillage Research* **102**, 87-92.

Kumari, M., Chakraborty, D., Gathala, M.K., Pathak, H., Dwivedi, B.S., Tomar, R., Garg, R.N., Singh, R. and Ladha, J.K. (2011) Soil aggregation and associated organic carbon fractions as affected by tillage in a rice-wheat rotation in north India. *Soil Science Society of America Journal* **75**, 560-567.

Kundu, S., Bhattacharyya, R., Prakash, V., Ghosh, B.N. and Gupta, H.S. (2007) Carbon sequestration and relationship between carbon addition and storage under rainfed soybean-wheat rotation in a sandy loam soil of the Indian Himalayas. *Soil and Tillage Research* **92**, 87-95.

Kundu, S., Singh, M., Saha, J.K., Biswas, A., Tripathi, A.K. and Acharya, C.L. (2001) Relationship between C addition and storage in a Vertisol under soybean-wheat cropping system in sub-tropical central India. *Journal of Plant Nutrition and Soil Science* **164** 483-486.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y. (2003) How extensive are yield declines in long-term rice-wheat experiments in Asia? *Field Crops Research* **81**, 159-180.

Lal, R. (2014) Societal value of soil carbon. *Journal of Soil and Water Conservation* **69**, 186A-192A.

Lal, R. (2015a) Sequestering carbon and increasing productivity by conservation agriculture. *Journal of Soil and Water Conservation* **70**, 55A-62A.

Lal, R. (2015b) A system approach to conservation agriculture. *Journal of Soil and Water Conservation* (In press).

Lenka, N.K., Choudhury, P.K.R., Sudhishri, S., Dass, A. and Patnaik, U.S. (2012) Soil aggregation, carbon build up and root zone soil moisture in degraded sloping lands under selected agroforestry based rehabilitation systems in eastern India. *Agriculture, Ecosystems and Environment* **150**, 54-62.

Majumder, B., Mandal, B. and Bandyopadhyay, P.K. (2008a) Soil organic carbon pools and productivity in relation to nutrient management in a 20-year-old rice-berseem agroecosystem. *Biology and Fertility of Soils* **44**, 451-461.

Majumder, B., Mandal, B., Bandyopadhyay, P.K., Gangopadhyay, A., Mani, P.K., Kundu, A.L. and Mazumdar, D. (2008b) Organic amendments influence soil organic carbon pools and rice-wheat productivity. *Soil Science Society of America Journal* **72**, 775-785.

Majumder, B., Mandal, B., Bandyopadhyay, P.K. and Chaudhury, J. (2007) Soil organic carbon pools and productivity relationships for a 34 year old rice-wheat-jute agroecosystem under different fertilizer treatments. *Plant and Soil* **297**, 53-67.

Manjaiah, K.M. and Singh, D. (2001) Soil organic matter and biological properties after 26 years of maize-wheat-cowpea cropping as affected by manure and fertilization in a Cambisol in semiarid region of India. *Agriculture, Ecosystems and Environment* **86**, 155-162.

Manna, M.C., Ghosh, P.K. and Acharya, C.L. (2003) Sustainable crop production through management of soil organic carbon in semiarid and tropical India. *Journal of Sustainable Agriculture* **21**, 87-116.

Manna, M.C. and Singh, M.V. (2001) Long-term effects of intercropping and bio-litter recycling on soil biological activity and fertility status of sub-tropical soils. *Bioresource Technology* **76**, 143-150.

Manna, M.C., Swarup, A., Wanjari, R.H., Ravankar, H.N., Mishra, B., Saha, M.N., Singh, Y.V., Sahi, D.K. and Sarap, P.A. (2005) Long-term effect of fertilizer and manure application on soil organic carbon storage, soil quality and yield sustainability under sub-humid and semi-arid tropical India. *Field Crops Research* **93**, 264-280.

Martin, D., Lal, T., Sachdev, C.B. and Sharma, J.P. (2010) Soil organic carbon storage changes with climate change, landform and land use conditions in Garhwal hills of the Indian Himalayan mountains. *Agriculture, Ecosystems and Environment* **138**, 64-73.

Masto, R.E., Chhonkar, P.K., Singh, D. and Patra, A.K. (2006) Changes in soil biological and biochemical characteristics in a long-term field trial on a sub-tropical inceptisol. *Soil Biology and Biochemistry* **38**, 1577-1582.

Milne, E., Paustian, K., Easter, M., Sessay, M., Al-Adamat, R., Batjes, N.H., Bernoux, M., Bhattacharyya, T., Cerri, C.C., Cerri, C.E.P., Coleman, K., Falloon, P., Feller, C., Gicheru, P., Kamoni, P., Killian, K., Pal, D.K., Powlson, D.S., Williams, S. and Rawajfih, Z. (2007) An increased understanding of soil organic carbon stocks and changes in non-temperate areas: National and global implications. *Agriculture, Ecosystems and Environment* **122**, 125-136.

Moharana, P.C., Sharma, B.M., Biswas, D.R., Dwivedi, B.S. and Singh, R.V. (2012) Long-term effect of nutrient management on soil fertility and soil organic carbon pools under a 6-year-old pearl millet-wheat cropping system in an Inceptisol of subtropical India. *Field Crops Research* **136**, 32-41.

Nath, A.J., Das, G. and Das, A.K. (2009) Above ground standing biomass and carbon storage in village bamboos in North East India. *Biomass and Bioenergy* **33**, 1188-1196.

Nath, A.J., Lal, R. and Das, A.K. (2015a) Ethnopedology and soil quality of bamboo (*Bambusa* sp.) based agroforestry system. *Science of the Total Environment* **521**, 372-379.

Nath, A.J., Lal, R. and Das, A.K. (2015b) Managing woody bamboos for carbon farming and carbon trading. *Global Ecology and Conservation* **3**, 654-663.

Nayak, A.K., Gangwar, B., Shukla, A.K., Mazumdar, S.P., Kumar, A., Raja, R., Kumar, V., Rai, P.K. and Mohan, U. (2012) Long-term effect of different integrated nutrient management on soil organic carbon and its fractions and sustainability of rice-wheat system in Indo Gangetic Plains of India. *Field Crops Research* **127**, 129-139.

Pal, D.K., Dasog, G.S., Vedivelu, S., Ahuja, R.L. and Bhattacharyya, T. (1999) Secondary calcium carbonates in a soil of arid and semi-arid regions of India. In *Global Climate Change and Pedogenic Carbonates* (R. Lal, J. Kimble, H. Eswaran and B.A. Stewart, Eds.), CRC Press.

Pathak, H., Byjesh, K., Chakrabarti, B. and Aggarwal, P.K. (2011) Potential and cost of carbon sequestration in Indian agriculture: Estimates from long-term field experiments. *Field Crops Research* **120**, 102-111.

Pretty, J.N., Ball, A.S., Li, X. and Ravindranath, N.H. (2002) The role of sustainable agriculture and renewable-resource management in reducing greenhouse-gas emissions and increasing sinks in China and India. *Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences* **360**, 1741-1761.

Purakayastha, T.J., Chhonkar, P.K., Bhadraray, S., Patra, A.K., Verma, V. and Khan, M.A. (2007) Long-term effects of different land use and soil management on various organic carbon fractions in an Inceptisol of subtropical India. *Australian Journal of Soil Research* **45**, 33-40.

Purakayastha, T.J., Rudrappa, L., Singh, D., Swarup, A. and Bhadraray, S. (2008) Long-term impact of fertilizers on soil organic carbon pools and sequestration rates in maize-wheat.-cowpea cropping system. *Geoderma* **144**, 370-378.

Rajan, K., Natarajan, A., Kumar, K.S., Badrinath, M.S. and Gowda, R.C. (2010) Soil organic carbon - the most reliable indicator for monitoring land degradation by soil erosion. *Current Science* **99**, 823-827.

Ramachandran, A., Jayakumar, S., Haroon, R.M., Bhaskaran, A. and Arockiasamy, D.I. (2007) Carbon sequestration: estimation of carbon stock in natural forests using geospatial technology in the Eastern Ghats of Tamil Nadu, India. *Current Science* **92**, 323-331.

Roy, P.K., Samal, N.R., Roy, M.B. and Mazumdar, A. (2010) Soil carbon and nutrient accumulation under forest plantations in Jharkhand state of India. *Clean-Soil Air Water* **38**, 706-712.

Rudrappa, L., Purakayastha, T.J., Singh, D. and Bhadraray, S. (2006) Long-term manuring and fertilization effects on soil organic carbon pools in a Typic Haplustept of semi-arid sub-tropical India. *Soil and Tillage Research* **88**, 180-192.

Saha, D., Kukal, S.S. and Sharma, S. (2011) Landuse impacts on SOC fractions and aggregate stability in typicustochrepts of Northwest India. *Plant and Soil* **339**, 457-470.

Saha, S.K., Nair, P.K., Nair, V.D. and Kumar, B.K. (2009) Soil carbon stock in relation to plant diversity of homegardens in Kerala, India. *Agroforestry Systems* **76**, 53-65.

Saha, S.K., Nair, P.K., Nair, V.D. and Kumar, B.K. (2010a) Carbon storage in relation to soil size-fractions under tropical tree-based land-use systems. *Plant and Soil* **328**, 433-446.

Saha, R., Mishra, V.K., Majumdar, B., Laxminarayana, K. and Ghosh, P.K. (2010b) Effect of integrated nutrient management on soil physical properties and crop productivity under a maize (*Zea mays*)-mustard (*Brassica campestris*) cropping sequence in acidic soils of northeast India. *Communications in Soil Science and Plant Analysis* **41**, 2187-2200.

Sharma, K.L., Mandal, U.K., Srinivas, K., Vittal, K.P.R., Mandal, B., Grace, J.K. and Ramesh, V. (2005) Long-term soil management effects on crop yields and soil quality in a dryland Alfisol. *Soil and Tillage Research* **83**, 246-259.

Sharma, P. and Rai, S.C. (2007) Carbon sequestration with land-use cover change in a Himalayan watershed. *Geoderma* **139**, 371-378.

Shibu, M.E., Van Keulen, H., Leffelaar, P.A. and Aggarwal, P.K. (2010) Soil carbon balance of rice-based cropping systems of the Indo-Gangetic Plains. *Geoderma* **160**, 143-154.

Singh, G., Jalota, S.K. and Singh, Y. (2007) Manuring and residue management effects on physical properties of a soil under the rice-wheat system in Punjab, India. *Soil and Tillage Research* **94**, 229-238.

Singh, H., Pathak, P., Kumar, M. and Raghubanshi, A.S. (2011a) Carbon sequestration potential of Indo-Gangetic agroecosystem soils. *Tropical Ecology* **52**, 223-228.

Singh, S.K., Pandey, C.B., Sidhu, G.S., Sarkar, D. and Sagar, R. (2011b) Concentration and stock of carbon in the soils affected by land uses and climates in the western Himalaya, India. *Catena* **87**, 78-89.

Singh, S.K., Singh, A.K., Sharma, B.K. and Tarafdar, J.C. (2007) Carbon stock and organic carbon dynamics in soils of Rajasthan, India. *Journal of Arid Environments* **68**, 408-421.

Singh, V.K., Dwivedi, B.S., Shukla, A.K., Chauhan, Y.S. and Yadav, R.L. (2005) Diversification of rice with pigeonpea in a rice-wheat cropping system on a Typic Ustochrept: effect on soil fertility, yield and nutrient use efficiency. *Field Crops Research* **92**, 85-105.

Singh, R. and Lal, M. (2000) Sustainable forestry in India for carbon mitigation. *Current Science* **78**, 563-567.

Srinivasarao, Ch., Lal, R., Kundu, S., Babu, M.B.B.P., Venkateswarlu, B. and Singh, A.K. (2014a) Soil carbon sequestration in rainfed production systems in the semiarid tropics of India. *Science of the Total Environment* **487**, 587-603.

Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Singh, A.K., Kundu, S., Vittal, K.P.R., Patel, J.J. and Patel, M.M. (2014b) Long-term manuring and fertilizer effects on depletion of soil organic carbon stocks under pearl millet-cluster bean-castor rotation in western India. *Land Degradation and Development* **25**, 173-183.

Srinivasarao, Ch., Deshpande, A.N., Venkateswarlu, B., Lal, R., Singh, A., Kundu, S., Vittal, K.P.R., Mishra, P.K., Prasad, J.V.N.S., Mandal, U.K. and Sharma, K.L. (2012a) Grain yield and carbon sequestration potential of post monsoon sorghum cultivation in Vertisols in the semi arid tropics of central India. *Geoderma* **175**, 90-97.

Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Singh, A.K., Kundu, S., Vittal, K.P.R., Balaguravaiah, G., Babu, M.V.S., Chary, G.R., Prasadbabu, M.B.B. and Reddy, T.Y. (2012b) Soil carbon sequestration and agronomic productivity of an Alfisol for a groundnut-based system in a semiarid environment in southern India. *European Journal of Agronomy* **43**, 40-48.

Srinivasarao, C., Venkateswarlu, B., Lal, R., Singh, A.K., Kundu, S., Vittal, K.P.R., Sharma, S.K., Sharma, R.A., Jain, M.P. and Chary, G. (2012c) Sustaining agronomic productivity and quality of a Vertisolic soil (Vertisol) under soybean-safflower cropping system in semi-arid central India. *Canadian Journal of Soil Science* **92**, 771-785.

Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Singh, A.K., Vittal, K.P.R., Kundu, S., Singh, S.R. and Singh, S.P. (2012d) Long-term effects of soil fertility management on carbon sequestration in a rice-lentil cropping system of the Indo-Gangetic plains. *Soil Science Society of America Journal* **76**, 168-178.

Srinivasarao, Ch., Vittal, K.P.R., Venkateswarlu, B., Wani, S.P., Sahrawat, K.L., Marimuthu, S. and Kundu, S. (2009) Carbon stocks in different soil types under diverse rainfed production systems in tropical India. *Communications in Soil Science and Plant Analysis* **40**, 2338-2356.

Srinivasarao, Ch. and Lal, R. (2015) Soil carbon sequestration in rainfed production systems in the semi arid tropics of India. *Science of the Total Environment* (In Press).

Suman, A., Singh, K.P., Singh, P. and Yadav, R.L. (2009) Carbon input, loss and storage in sub-tropical Indian Inceptisol under multi-ratooning sugarcane. *Soil and Tillage Research* **104**, 221-226.

Swamy, S.L., Puri, S. and Singh, A.K. (2003) Growth, biomass, carbon storage and nutrient distribution in Gmelinaarborea Roxb. stands on red lateritic soils in central India. *Bioresource Technology* **90**, 109-126.

Tirol-Padre, A., Ladha, J.K., Regmi, A.P., Bhandari, A.L. and Inubushi, K. (2007) Organic amendments affect soil parameters in two long-term rice-wheat experiments. *Soil Science Society of America Journal* **71**, 442-452.

Venkateswarlu, B., Srinivasarao, Ch., Ramesh, G., Venkateswarlu, S. and Katyal, J.C. (2007) Effects of long-term legume cover crop incorporation on soil organic carbon, microbial biomass, nutrient build-up and grain yields of sorghum/sunflower under rain-fed conditions. *Soil Use and Management* **23**, 100-107.

Wani, N., Velmurugan, A. and Dadhwal, V.K. (2010) Assessment of agricultural crop and soil carbon pools in Madhya Pradesh, India. *Tropical Ecology* **51**, 11-19.

Wani, S.P., Chander, G., Sahrawat, K.L., Rao, C., Raghvendra, G., Susanna, P. and Pavani, M. (2012) Carbon sequestration and land rehabilitation through *Jatropha curcas* (L.) plantation in degraded lands. *Agriculture, Ecosystems and Environment* **161**, 112-120.

Wanjari, R.H., Singh, M.V. and Ghosh, P.K. (2004) Sustainable yield index: An approach to evaluate the sustainability of long-term intensive cropping systems in India. *Journal of Sustainable Agriculture* **24**, 39-56.

Yadav, R.L., Dwivedi, B.S. and Pandey, P.S. (2000) Rice-wheat cropping system: assessment of sustainability under green manuring and chemical fertilizer inputs. *Field Crops Research* **65**, 15-30.

Yadav, R.L., Prasad, S.R., Singh, R. and Srivastava, V.K. (1994) Recycling sugarcane trash to conserve soil organic-carbon for sustaining yields of successive ratoon crops in sugarcane. *Bioresource Technology* **49**, 231-235.