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Review/Overview Article

Soil management strategies to enhance carbon sequestration potential of degraded lands

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ABSTRACT

Reclamation of degraded lands has huge potential for carbon(C) sequestration to counteract the climate change. It was estimated that about 1,947 Mha of land is degraded worldwide and in Asia (excluding west Asia), the degraded soils occupied an area of 747 Mha. In India 59.3 Mha of land is degraded. The major land-degradation processes in the World and in Asia are water erosion, wind erosion, salinity and alkalinity, nutrient depletion and metal pollution. Various management strategies like conservation agriculture, integrated nutrient management, afforestation, alternate land use, plantations and amendments and use of biochar hold promise for long-term C sequestration. It has been projected that in India the largest potential lies in erosion prevention (33.6–50.4 Tg/year), secondary carbonates and bicarbonates (21.8–25.6 Tg/ha), agricultural intensification (12.7–16.5 Tg/year) and restoration of degraded soils (9.8–13.9 Tg/ha). Thus, total potential of soil organic C (SOC) sequestration in India is 77.9 to 106.4 Tg/year. Conservation agriculture has tremendous potential on soil C sequestration to the tune of 1.8 t/ha/year during the first decade of adoption. In dryland agriculture, conjunctive use of crop residues and *Leucaena* clippings had greater effect on C build up. The C sequestration potential of integrated nutrient management (100% NPK + FYM) was at the tune of 0.95 Mg/ha/year under rainfed agriculture. Overall the C sequestration potential of soils under arid and semi-arid climate is lesser than the soils under humid, per-humid climate. Afforestation could have remarkable increase in C sequestration in tropical climate than in either temperate of boreal climate. Alternate land use by adoption of agroforestry system is a promising strategy for enhancing the C sequestration by vegetation as well soil. Agroforestry plant species, e.g. *Prosopis juliflora* (SW.) DC.,) *Vachellia nilotica* (L.) P.J.H. Hurer & Mabb.; syn. *Acacia nilotica, Casuarina equisetifolia* L., *Tamarix aphylla* (L.) Karst.; syn), *Tamarix articulate* Vahl*, Diplachne fusca* (L.) P. Beauv. Ex Roem & Schult.; syn. *Leptochola fusca* which are well adapted to saline and alkali soils are reported to increase in SOC contents. Certain plantations like *Stylosanthes guianensis* (Aubl.) Sw., *Acacia auriculiformis* A. Cunn. Ex. Benth. and *Dalbergia sissoo* DC. hold promise to reclaim acid soils and enhancing SOC content. From long-term fertilizer experiment, it has been proved that balanced fertilization alone (NPK or NPK + FYM) or with lime (NPK + lime) not only reclaim the Alfisols but also enhance SOC content. Biochar, a pyrolysed product of biomass being resistant to microbial decomposition has huge potential for carbon sequestration in soil. The reclamation of degraded land by various means can be promising for C sequestration and it has greater implications on enhancing yield of crops.

Key words: Agroforestry, Biochar, Carbon sequestration, Conservation agriculture, Degraded land

Land degradation, has often been an ignited issue and topic of debate among the soil scientists, ecologists, and environmentalists, across the states, countries, continents and world. Land degradation is the reduction in the capacity of the land to provide ecosystem goods and services and assure its functions over a period of time for the beneficiaries of these (FAO, 2015). Soil degradation affects 1,216 Mha by moderate plus severe categories in the world and 130 Mha in South Asia (Lal, 2004). The latest scenario of dominant type of problem lands has been indicated by FAO (Fig. 1; FAO, 2015). The FAO is concerned with the effect of agriculture on climate change, the impact of climate change on agriculture and with the role that agriculture can play in mitigating climate change. Historically, land-use conversion and soil cultivation have been an important source of greenhouse gases (GHGs) to the atmosphere. It is estimated that they are responsible for about one-third of GHG emissions. However, improved

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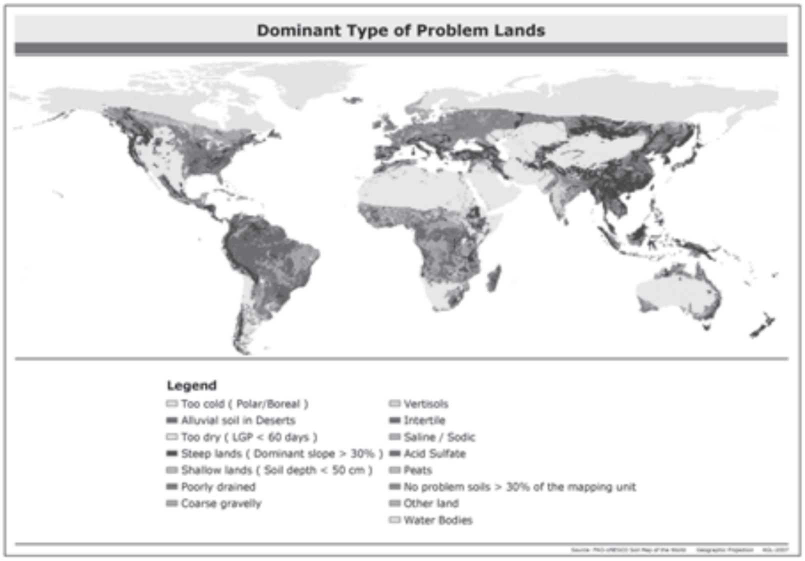


Fig. 1. Different types of degraded lands in the world
Source: FAO Home Page, 2015. http://www.fao.org/nr/land/degradation/global/en/

agricultural practices can help to mitigate climate change by reducing emissions from agriculture and other sources and by storing carbon in plant biomass and soils. It is essential to identify, develop and promote cultural practices that may potentially reduce agricultural CO_2 emissions and sequester carbon. It other way helps to improve the livelihoods of farmers, especially in developing and marginally-developed countries, through increased production and additional incomes from carbon credits under the mechanisms that have emerged since the Kyoto Protocol.

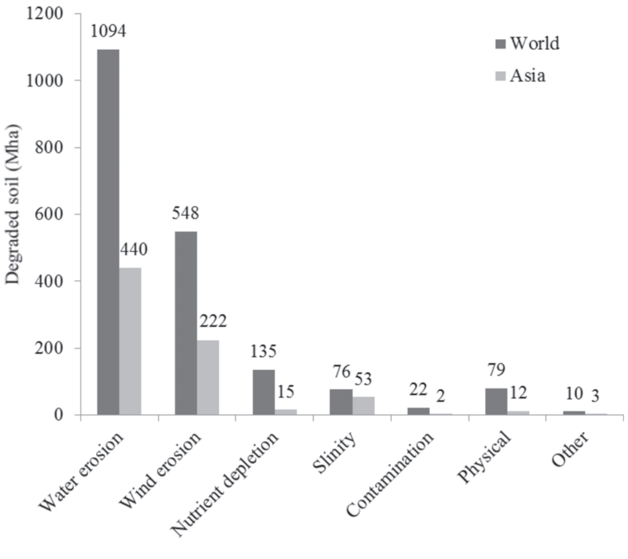
Carbon(C) sequestration refers to the provision of long-term storage of carbon in the terrestrial biosphere, underground, or the oceans as long-lived pools, so that the build-up of carbon dioxide (the principal greenhouse gas) concentration in the atmosphere (present CO_2 concentration: 398 ppm as per IPCC Report, 2015) will reduce or slow. Atmospheric concentrations of carbon dioxide can be lowered either by reducing emissions or by taking carbon dioxide out of the atmosphere and storing C in stable forms in terrestrial, oceanic, or freshwater aquatic ecosystems. A sink is defined as a process or an activity that removes greenhouse gas from the atmosphere. The long-term conversion of grassland and forestland to cropland (and grazing lands) has resulted in historic losses of soil carbon worldwide; but there is a major potential for increasing soil C through restoration of degraded soils and widespread adoption of soil-conservation practices. The major land-degradation components include soil erosion, desertification, salinization, sand-dune encroachment, rangeland degradation, soil acidification, deforestation inter alia. Soil-management practices that usually improve soil organic matter include. (*i*) more complex crop rotations, especially those with high-residue/ high biomass-producing crops, (*ii*) intensive use of cover crops, (*iii*) use of variety of organic amendments, (*iv*) balanced fertilization, (*v*) reduced tillage, (*vi*) amelioration of degraded land and with latest addition and (*vii*) use of biochar. All the above-said practices may differ in their degree of C sequestration but one thing was assured that all of them may more or less effective as revealed from last two decades' study.

It is extremely essential to reverse land degradation due to deforestation and inadequate land use/ management in the tropics and sub-tropics through the promotion of improved land-use systems and land-management practices which provide win-win effects in terms of economic gains and environmental benefits, a greater agro-biodiversity, and improved conservation and environmental management and increased C sequestration (IPCC, 2015). The development of agricultural management during the past centuries and particularly in last decades has entailed depletion of substantive soil C stocks. Agricultural soils are among the planet's largest reservoirs of C and hold potential for expanded C sequestration (CS), and thus provide a prospective way of mitigating the increasing atmospheric concentration of CO_2. It is estimated that soils can sequester around 20 Pg C over a span of 25 years, more than 10% of the anthropogenic emissions (IPCC, 2015).

FACETS OF LAND DEGRADATION AND THEIR CARBON(C) SEQUESTRATION POTENTIAL

Land degradation

Poor and inappropriate land management is the main cause of physical, chemical and biological degradation of cultivated lands, pasture, rangelands and forest lands. Causes for land degradation are numerous and include decline of soil fertility, development of acidity, salinization, alkalization, deterioration of soil structure, accelerated wind and water erosion, loss of organic matter and biodiversity. Global Assessment of Human-induced Soil Degradation (GLASOD) indicated that overall 15% of land is degraded (Bai *et al.*, 2008). Continent-wise, the highest proportions were reported for Europe (25%), Asia (18%) and Africa (16%); while the least was estimated for North America (5%). By the same measure, as a proportion of the degraded area, soil erosion affects about 83% of the global degraded area (ranging from 99% in North America to 61% in Europe). The analysis reported that nutrient depletion affects 4% area globally but 28% in South America; salinity less than 4% area worldwide but 16% in West Asia; chemical contamination about 1% area globally but 8% in Europe; and soil physical degradation accounted 4% area globally but 16% in Europe. Recent estimates of Bai *et al.* (2008) stated that worldwide 1,964 Mha soils are degraded and in Asia (excluding west Asia) the degraded soils occupied an area of 747 Mha (38%) sharing the largest part (Fig. 2).



Source: Adopted from Bai *et al.* (2008)

Fig. 2. GLASOD estimates of human-induced soil degradation

Intensive farming often leads to a vicious cycle of exhaustion of soil fertility and decline in agricultural yields. Approximately 40% of the agricultural land of world is severely degraded. It is estimated that worldwide about 1964 M ha land is affected by various forms of human induced degradation (Bai *et al.*, 2008) associated with erosion by water being the chief contributor (1,094 Mha), followed by wind erosion (548 Mha), nutrient depletion (135 Mha), salinity (76 Mha), contamination (22 Mha), physical (79 Mha) and other forms of (10 Mha) degradation. Report indicated that about 5–7 Mha of arable land of the world is lost annually through land degradation (Lal and Stewart, 1990). Out of India's total geographical land area of 328.7 Mha, 59.3 Mha (18%) land is estimated to be degraded (FAO AGL, 2005). Though the intensity of degradation varied from light (0.08 Mha), moderate (1.91 Mha), severe (34.32 Mha) and very severe (22.94 Mha) (FAO AGL, 2005). Estimates of land areas affected by different soil-degradative processes include 33 Mha by water erosion, 11 Mha by wind erosion, 3 Mha fertility decline, 3 Mha water logging and 6.774 Mha by salinity. In India, several agencies like National Commission for Irrigation (1972), National Commission on Agriculture (1976), and Ministry of Water Resources (1991) have estimated the extent of waterlogged area as 4.84, 6.00 and 2.46 Mha respectively.

Accelerated soil erosion is considered to be a principal cause of decline in the SOC pool. Among different land, resource regions, the highest erosion occurs in black soils (24–112 Mg/ha), followed by Shiwalik region (80 Mg/ha), north-eastern region with shifting cultivation (27–40 Mg/ha), and least in North Himalayan forest region (2 Mg/ha) (Purakayastha *et al.*, 2012). The total amounts of sediments displaced by erosion are 1.5 Pg/year by water erosion and 0.6 Pg/year by wind erosion (Lal, 2005). Assuming a delivery ratio of 10%, total amount of sediments displaced by erosion is estimated at 21 Pg/year. Further assuming SOC concentration in sediments at 8 to 12 g/kg, the quantity of C displaced by erosion is 168 to 252 Tg C/year.

Carbon(C) Sequestration Potential in Degraded Lands

Restoration of degraded soils and ecosystems and adoption of recommended land use and management practices can enhance terrestrial C pool and render biota and soils the net C sink (Lal, 2005). Restoration of degraded lands generally involves re-vegetation that increases C stocks in biomass and soil. It can occur on croplands, grazing lands, forests, or any 'other' lands (mine spoils, deserts, etc.). These soils are so poorly degraded that normal practices are no longer be effective, hence not capable of supporting crops, and soils that must be taken out of agricultural practice before progress can be made. For example, where land is polluted with heavy metals, these pollutants should be removed first before re-vegetation can start. Other important categories of degraded land are salinized, sodic, desert, and eroded soils. Areas of most categories of severely degraded land are increasing. Restoration brings benefits of many-folds: apart from soil C is sequestered, the loss of C can be arrested and unproductive land brought back into re-use. Restored lands may be put in to crops, pasture or forest to sequester still more C. Degraded land has a large potential for sequestration in relation to undisturbed land because it often contains little carbon, but there are almost always factors that limit this potential. Nabuurs *et al.* (1999) cite rates of 0.2–2 t C/ha/year. Rates as large as 7–9 t C/ha/year appear in the literature (Table 1), but these rates often involve other measures such as the application of animal manures or deal with special problems. Glenn *et al.* (1991, 1993) suggest that halophyte (salt-tolerant) shrubs may be suitable for rejuvenating coastal deserts, inland saline soils, or salinized irrigated lands. They suggest further that up to 130 Mha of land may have the potential to sequester 1–2 t C/ha at a cost of $ 44–53/t C; the marginal cost may be as little as $ 12/t C if the halophytes are used to produce agricultural products (Glenn *et al.*, 1993). Garg (1998) reported that sodic soils in Northern India have been able to sequester up to 4 t C/ha/year by afforestation with *Prosopis juliflora*. Lal and Bruce (1999) consider 100 Mha of land worldwide to be so badly degraded that it is unsuitable for agriculture; assuming a sequestration rate of 0.25 t C/ha, these lands have a global potential to sequester 0.025 Gt C/year. Lal (1999) reported that 3,500–4,000 Mha of land are susceptible to desertification throughout the world; much of this land is rangeland or degraded tropical forests. The very low C levels in most of these soils means that a 1 per cent increase in the C content of soil mass is feasible. Such an increase would take about 60 years at a rate of 0.25 t C/ha/year; in practice, however, the land is likely to be used for some other purpose, such as agriculture, before that rate and other rates of C sequestration will apply. In practical terms, the high priority lies in restoration of degraded soils and ecosystems and management of wasteland. The potential of SOC sequestration through restoration of degraded and desertified soils in India is 10–14 Tg C/year. The largest potential lies in erosion prevention (33.6–50.4 Tg/year), secondary carbonates and bicarbonates (21.8–25.6 Tg/ha), agricultural intensification (12.7–16.5 Tg/year) and restoration of degraded soils (9.8–13.9 Tg/ha) (Lal, 2005). Thus total potential of SOC sequestration in India is 77.9 to 106.4 Tg/yr. Out of this potential, 12.9% is through restoration of degraded soils, 45.6% through erosion prevention and management, 15.8% through agri-

Table 1. Rates of potential carbon gain under selected practices for degraded lands in various regions of the world, (e-source: IPCC Home Page 2015; www.ipcc.ch/ipccreports/sres/land_use/index.php?idp=202)

Practice	Country/ Region	Rate of Carbon Gain (t C/ha/year)	Time[1] (year)	Other GHGs and Impacts	References
Saline/alkali soils				If grazed, livestock may generate CH_4	
- Saline soil reclamation	India	2			Singh *et al.* (1994); Lal and Bruce (1999)
- Alkali soil reclamation	India	4	5		Garg (1998); Sumner and Naidu (1998); Lal and Bruce (1999);
- Irrigate halophytes with seawater	Australia	1–2	20		Glenn *et al.* (1993)
Polluted soils					
- Reclamation of mineland	USA	1.5–2.0	25		Paustian *et al.* (1997b); Akala and Lal (1999) where sites are polluted with heavy metals, these pollutants may first need to be removed [e.g., hyper accumulators (McGrath, 1998)]
Eroded soils		1–7	4		Improved grazing with lower variability of production
Rehabilitation practices	Australia	0.1–0.4			Tothill and Gillies (1992); Ash *et al.* (1996)
Desertified soils					
- Restorative practices	China	<1			Fullen and Mitchell (1994); Li and Zhao (1998)
	India	0.4–0.3			Lal and Bruce (1999); Gupta and Rao (1994)

[1] Time interval to which estimated rate applies. This interval may or may not be time required for ecosystem to reach new equilibrium

cultural intensification, and 25.7% through secondary carbonates. Restoration of degraded soils and ecosystems provide an opportunity to improve the environments while off-setting fossil-fuel emissions and mitigating climate change. It has been projected that in India about 309 Mt of biochar (eqv. to 154 Mt of biochar C) could be produced annually, the application of which might offset about 50% of C emission (292 Tg C/year) from fossil fuel (Lal, 2005). Additionally, both heat and gases can be captured during production of biochar by pyrolysis to produce energy carriers such as electricity, bio-oil, or hydrogen and certain other valuable co-products.

Carbon stabilization: Prerequisite for Carbon(C) Sequestration

The stabilization of C is a prerequisite for C sequestration in soil for a long-term basis. The stabilization of C in soil can be categorized as: physical stability, chemical stability, biochemical stability and thermal stability. The physical stability of C mainly takes place inside the soil aggregates. The C stabilizes inside the aggregates mainly due to the physical protection that resists the microorganisms to cause decomposition. The C which is stabilized inside the aggregates is by nature and at various stages of decomposition products of plant origin. The macro aggregates are more potent for stabilization of C though this form of protection of C is transient in nature and largely affected by type of tillage operation. On the other hand, microaggregate protected C are generally not affected by tillage operation and more of permanent in nature. The chemical stability of C is largely achieved by formation of clay-humus complex formation. In this respect, sesquioxides (oxide and hydroxides of Fe and Al) play a major role in the formation of stable clay-humus complex. The carbonaceous materials, i.e. polysaccharides, hemicellulose, uronides, levans, and numerous other polymers excreted as mucilaginous products by microorganisms are attached to clay surfaces by means of cation bridges, H-bonding, van der waal's forces and anion adsorption mechanisms. The biochemical stability of C is directly related to its biochemical composition and ease of degradation by microorganisms. The lignin, polyphenol and quinone are inherently resistant to decomposition by microorganisms due to their complex aromatic ring structure. The thermal stability of soil C is related to temperature-driven biochemical degradation and the rate of decomposition of soil organic carbon becomes double with each 10°C rise in soil temperature. Due to this reason, in tropical countries like India the cycling of C is very rapid and it takes enough time to increase in C content in soil even under continuous application of organic sources.

SOIL MANAGEMENT PRACTICES FOR ENHANCING CARBON SEQUESTRATION

Conservation agriculture

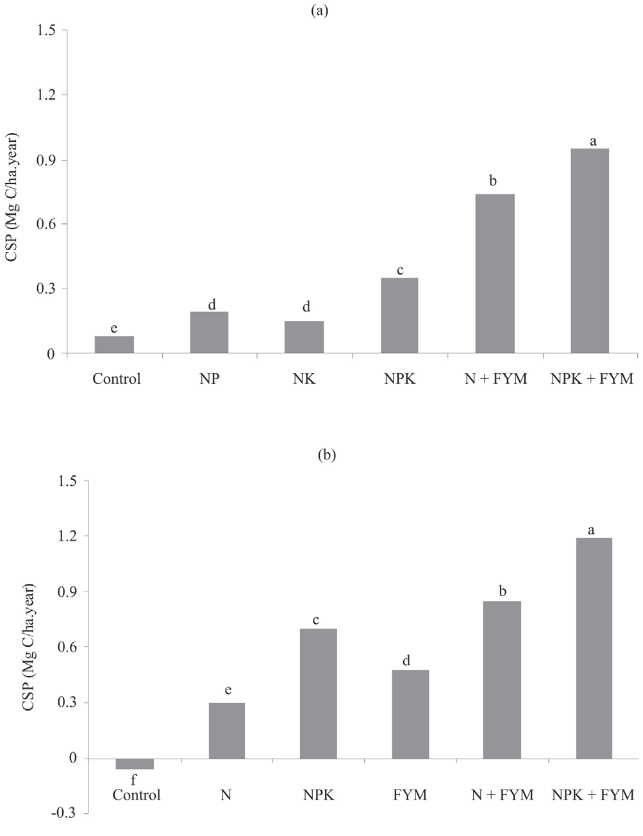
Conservation agriculture (CA) is an effective strategy of controlling erosion (Uri *et al.*, 1999). Researchers of many countries have recommended the CA for sustainable crop yield by controlling soil erosion and enhancing soil C sequestration. Soil erosion in Brazil reduced from 3.4–8.0 t/ha under conventional tillage to 0.4 t/ha under no-till, and water loss reduced from approximately 990 to 170 t/ha (Sorrenson *et al.*, 1997; 1998). A watershed study in Brazil also showed a reduction of 22% in sediment load from 1994 to 1998 because of no-till adoption (Derpsch, 2001). Based on a long-term study in India, Singh *et al.* (2006) reported that minimum tillage along with application of crop residue as mulch conserved rain water by 40% and 11% and soil by 69% and 28% over cultivated fallow and conventional tillage, respectively, under maize cultivation at 4% slope. Similarly no-till with flat bed planting for maize showed the highest SOC status of top soil (0–15 cm) (Yadav *et al.*, 2015). Minimum tillage is generally recommended for soils in the Indian Himalayan region because of reduced cultivation costs, better retention of soil water and physical protection of soil organic C (SOC) in aggregates (Ved Prakash *et al.*, 2004; Bhattacharyya *et al.*, 2012). Carbon stock was found to be more under the non-puddled/no-tilled treatments over conventional tillage in rice–wheat system (Singh *et al.*, 2014). In general, soil-C sequestration during the first decade of adoption of best CA practices is 1.8 t C/ha/year. On 5000 Mha of agricultural land, this could represent one-third of the current annual global emission of CO_2 from the burning of fossil fuels (FAO, 2008). Lal (1998) estimated that widespread adoption of conservation tillage on some 400 Mha of cropland by the year 2020 may lead to the gain of total C sequestration of 1,500 to 4,900 Mg. Leaving the crop residues on the field is another practice which could have an important impact on the global C cycle (Lal, 1997). The annual production of crop residue is estimated to be about 3.4 billion Mg in the world (Lal, 1997). If 15% of C contained in the residues can be converted to passive SOC fraction, this may lead to the C sequestration at the rate of 0.2×10^{15} g/year (Lal, 1997). Retention of crop residues of sorghum [*Sorghum bicolour* (L.) Moench.], and application of farmyard manure (FYM) equivalent to 25 kg N/ha along with 25 kg N/ha supplied through chemical fertilizers increased and maintained the SOC stock in dryland Vertisols of Solapur, Maharashtra (Srinivasarao *et al.*, 2012). Green leaf manuring with *Leucaena* clippings along with chemical fertilizers did not increase the SOC stock. However, a conjunctive use of crop residues and

Leucaena clippings was found to increase the SOC stock (68.5 Mg/ha), with a significant build-up of SOC (39.8%) and a higher amount of SOC sequestration (14.4 Mg C/ha). Another study indicated that application of pigeonpea [*Cajanus cajan* (L.) Millsp.] leaf-litter and FYM both contributed towards increased labile SOC fractions in pigeonpea–wheat (*Triticum aestivum* L.) cropping system (Mandal *et al.*, 2013). Conjoint use of FYM, green manure or municipal solid-waste compost with mineral N improved C sequestration potential in rice (*Oryza sativa* L.)–wheat system (Singh *et al.*, 2014).

Similarly, restoring presently degraded soils, estimated at about 2000 Mha, and increasing SOC content by 0.01%/year may lead C sequestration at the rate of 3.0 Pg C/year. High crop residue addition and no-tillage-based systems tend to turn the soil into a net sink of C (Greenland and Adams, 1992; Reicosky *et al.*, 1995; Bot *et al.*, 2001). Interestingly, the impact of conservation tillage on SOC sequestration may be greater in degraded soils than in fertile soils (Franzluebbers, 2005). The basis of this finding was derived from the observation that the ratio of soil organic C associated with conservation tillage-to-conventional tillage was logarithmically greater in soils with inherently lower organic C than in soils with inherently higher organic C content. Therefore on a relative basis, the improvement in soil organic C was proportionately higher in eroded or degraded soils.

Integrated nutrient management

Long-term fertilizer experiments (LTFE), conducted in the Indo-Gangetic Plains (IGP), have revealed that there is a stagnating or declining trend in productivity at several locations even with the adequate and regular application of N, P, and K fertilizers under modern intensive farming. However, many LTFE results have demonstrated that judicious application of fertilizers with appropriate crop rotations and conservation tillage may lead to sustainable yield in terms of biomass yield and lead to C sequestration in agricultural soils. Pathak *et al.* (2011) have shown that C sequestration potential (CSP), i.e. the increase in soil C stock in a treatment compared to the reference treatment under different scenarios varied in the order of use of farmyard manure (FYM) > integrated nutrient management > sole chemical fertilizers. The CSP ranged from 0.08 Mg C/ha/year (unfertilized control) to 0.95 Mg C/ha/year (INM, i.e. NPK + FYM) under the rainfed condition (Fig. 3a). However, the same was insignificant in the unfertilized control plots and increased significantly with NPK and (NPK + FYM) applications under the irrigated conditions (Fig. 3b). Balanced NPK fertilization exhibited significant increase in SOC stock in the 0–45 cm soil layer over imbalanced fertilization and without application of nutrients under the rainfed cropping condition. Integrated use of FYM with 100% NPK emerged as the most efficient management system in accumulating largest amount of organic C (72.1 Mg C/ha) in Inceptisols of semi-arid India (Rudrappa *et al.*, 2006). Nevertheless, this treatment also sequestered the highest amount of organic C (731 kg C/ha/year). In semi-arid sub-tropical India, continuous adoption of 100% NPK + FYM treatment in maize (*Zea mays* L.)–wheat–cowpea [*Vigna unguiculata* (L.) Walp.] cropping system might sequester 1.83 Tg C/year, which corresponds to about 1% of the fossil fuel emissions by India (Purakayastha *et al.*, 2008). Another multi-locational experiment showed that soil C sequestration corresponding to INM (N-P-K fertilizer partially substituted, i.e. 50% on N basis with organics) were higher in Kalyani and Sabour, falling under lower-Gangetic plain and middle Gangetic plain, respectively, lying in humid climate than Ludhiana (trans-Gangetic plain) and Kanpur (upper-Gangetic plain) lying in semi-arid climate (Nayak *et al.*, 2012).



Source: Pathak *et al.* (2011)

Fig. 3. Total soil organic C sequestration potential (CSP) of different treatments under rainfed (a) and irrigated conditions of the Indian Himalayas (b) bars with different letters are significantly different at $P < 0.05$.

Maia *et al.* (2009) found that degraded grassland management decreased C stocks by about 0.27–0.28 Mg C/ha/year; nominal management on Oxisols in Brazil decreased C at a rate of 0.03 Mg C/ha/year; while nominal management (following the same management year after year maintaining reasonable productivity) on other soil types and improved management, presumably due to more appropriate grazing regimes (like fertilization, lime, irrigation, seeding legumes, or planting more productive species of grasses) on Oxisols increased C stocks by 0.72 MgC/ha/year and 0.61 MgC/ha/year, respectively.

Afforestation

Converting non-forest land to forest typically increases the chance of diversity of flora and fauna, except in situations where biologically diverse non-forest ecosystems are replaced by forests that consist of single or a few species (i.e. plantations of monocultures and especially exotic species). Where afforestation or reforestation is generally followed to restore degraded lands, it is also likely to have other environmental benefits, such as reducing erosion, controlling salinization, and protecting watersheds. In dry countries, expansion of forested areas can also be viewed as a desertification-reduction activity. Afforestation and reforestation potentially could achieve annual carbon sequestration rates in aboveground and below-ground biomass of 0.4–1.2 Mgc/ha/year in boreal regions, 1.5–4.5 Mgc/ha/year in temperate regions, and 4.0–8.0 Mgc/ha/year in tropical regions (Dixon *et al.*, 1994; Nabuurs and Mohren, 1995; Nilsson and Schopfhauser, 1995; Brown *et al.*, 1996; Yamagata and Alexandrov, 1999). Hence the maximum average potential of C sequestration rate would be 1.1–1.6 GtC/year in both above and below-grounds (Brown *et al.*, 1996).

Forest ecosystems potentially stored more than 80% of all terrestrial aboveground C and more than 70% of all soil organic C (Batjes, 1996; Jobbágy and Jackson, 2000; Six *et al.*, 2002). The annual CO_2 exchange between forests and the atmosphere via photosynthesis and respiration is ≈50 Pg C/year, i.e. 7 times the anthropogenic C emission. Previous land use affects the C sequestration potential of afforested sites. Since pasture soils already have high C stocks and high root densities in the upper part of the mineral soil, so afforestation seemed to have a smaller effect (Römkens *et al.*, 1999; Guo and Gifford, 2002). Chronosequence studies from New Zealand on former pastures, northern Spain on arable land, and northern England on peat land found that soils initially lost, but later gained C (Romanyá *et al.*, 2000; Halliday *et al.*, 2003; Zerva *et al.*, 2005). Forest clearing followed by continuous cultivation of crops caused a loss of 43% total SOC (75.4 Mg/ha) and 73% forest derived SOC (128.4 Mg/ha) after nearly 75 years (Lemma *et al.*, 2006). The net loss of SOC was lower due to addition of 53.0 Mg/ha of SOC of C4 crop origin (mainly maize) to the farmland. On the other hand, afforestation of farmland led to a net accretion of SOC of 69.6 and 29.3 Mg/ha after 20 years under *Cupressus lusitanica* Mill. and *Pinus patula* seem stands respectively.

Alternate land use

It has been observed that alternate land-use systems, viz. agro-forestry, agro-horticulture and agro-silvi culture, are more remunerative for SOC restoration than the sole cropping system (Murthy *et al.*, 2013). Das and Intal (1994) reported that organic C content was about double in agro-horticultural and agro-forestry systems compared to the sole cropping scenario. But Purakayastha *et al.* (2007) reported that vegetable growing plots exhibited similar SOC contents as field crop (rice–wheat) growing plots. Both SOC and microbial biomass C (MBC) in agroforestry was significantly higher than in either of the two systems reported above. Dhaliwal (2003) reported higher SOC and MBC in natural forest system, followed by cultivated and pasture ecosystem. Floor litter and humus C also varied significantly with land use (Table 2). Total carbon (TC) content in floor litter ranged from 1.50 to 5.20 Mg/ha. *Cardamom*-based agroforestry system had significantly higher floor litter C concentration than other stands (Sharma and Rai, 2007). Total C mass in humus ranged from 0.63 to 1.41 Mg/ha and showed significant differences between temperate natural forest dense (TNFD) with other forests and agroforestry system (Table 2). Total carbon (TC) concentration down to 1-m depth soil in different land-use covers ranged from 37 Mg/ha in open cropped area temperate (OCAT) and 472 Mg/ha in TNFD (Table 2). As observed TC storage decreased with increasing soil depth. The total mean C densities varied more than 15-fold between the land-use cover classes, from as low as 46 Mg/ha in OCAT to as high as 669 Mg/ha in TNFD (Table 2).

Plantations and amendments

Reclamation of salt-affected and acid soils is an important aspect of soil-quality enhancement and increasing C sequestration in above-ground biomass and in the SOC pool. Singh (1994) reported that growing *Prosopis juliflora* is most adapted to alkaline soils and produced most biomass hence contribute well to soil C sequestration. Among the other tree species, *Vachellia nilotica, Casuarina equisetifolia, Tamarix articulata, Diplachne fusca* also caused a remarkable increase in SOC contents. Adaptable fruit trees for north-western regions in India include jamun (*Syzygium cumini*), tamarind (*Tamarindus*

Table 2. Estimated carbon (C) densities (Mg C/ha) for the Mamlay watershed on land use cover classes

Land use cover	Vegetation	Floor litter	Humus	Soil up to 1-m depth	Total C density
Temperate natural forest dense (TNFD)	191.27c	4.57b	1.41b	472	669.24
Temperate natural forest open (TNFO)	86.13b	2.94a	0.87a	219	308.81
Subtropical natural forest open (SNFO)	90.23b	3.03a	0.63a	126	219.89
Cardamom-based agro-forestry system (CAFS)	46.79a	5.20c	1.12a	255	308.11
Mandarin based agro-forestry system (MAFS)	5.47a	1.50a	-	150	156.96
Open cropped area temperate (OCAT)	9.28a	-	-	37	46.28
Open cropped area subtropical (OCAS)	8.20a	-	-	48	56.20
Wasteland area temperate (WAT)	-	-	-	89	89.00
Wasteland area subtropical (WAS)	-	-	-	124	124.00

Means with the same superscript in each column are not statistically different ($P > 0.05$) from other means in the same.
Source: Sharma and Rai (2007)

indica), ber (*Ziziphus mauritiana* Lam.), and guava (*Psidium guajava* L.). In north-central India, significant improvements in SOC content of a sodic soil was observed through planting salt-tolerant tree species over a period of 8 years (Garg, 1998).

Application of manure and gypsum is also important in improving soil structure and reclaiming sodic soils. Use of manure and compost is facilitated by integrating livestock with cropping system (Chaudhary *et al.*, 1981; Harris, 1995). More (1994) reported that applications of farm by-products and organic manures improved the quality of sodic Vertisols, enhanced SOC contents and yield of crop. Batra *et al.* (1997) observed the increase in SOC content significantly owing to growing Karnal grass (*Diplachne fusca*) and of application of gypsum within three years.

Acid soils developed in high-rainfall area have very low internal buffering capacity and low surface charge characteristics. These intrinsic soil attributes have a profound impact on agricultural productivity. If acid soils are managed properly, it could be productive and enrich the soil with C. Noble *et al.* (2008) reported that growing of Gamba grass (*Andropogon gayanus* Kunth) and stylo grass (*Stylosanthes guianensis*) over a study period of three years showed a 6-fold increase in soil C at >30 cm depth from the initial values, indicating a significant rate of C sequestration. The highest organic C storage was observed in the surface horizons (0–20 cm), with a mean value for all treatments of 620 Mg/ha compared to 346 Mg/ha in the 2001 samples.

Surface mining for coal drastically alters soil properties, destabilizes SOC and depletes SOC pools. Typical grassland reclamation practices at Singer site included sowing rye grass (*Lolium perenne* L.), timothy (*Phleum pratense* L.), birds foot trefoil (*Lotus corniculatus* L.), orchard grass (*Dactylis glomerata* L.), blue grass (*Poa pratensis* L.), alfalfa (*Medicago sativa* L.) and mammoth clover (*Trifolium pratense* var. *perenne* L.) (Lorenz and Lal, 2007). After 45 years, the reclaimed soil under pasture at the Singer site stored the largest pool of C (79.9 Mg/ha), followed by Dyes Fork site under forest plantations (29.8 Mg/ha) (Lorenz and Lal, 2007). Thus pasture may have a high potential for C sequestration in 0 - to 30- cm soil depth. Re-vegetation with trees like *Acacia auriculiformis* and *Dalbergia sissoo* reported to had more C density in reclaimed coal mine soil in Jharkhand, India (Mukhopadhyay *et al.*, 2016).

Universally lime is used as an amendment to reclaim acid soils. After 29 cropping cycles in acidic Alfisol of Ranchi, the SOC content in all the treatments decreased from initial levels, but the decrease was considerably less in 100% NPK + FYM (8.7%) and 100% NPK + Lime (10.9%) treatments than that in 100% N (28.3%) treatment (Hati *et al.*, 2008). The 100% NPK + FYM, 100% NPK + Lime and 100% NPK treatments up to 30 cm soil depth recorded significantly higher SOC over 100% N and control. Similarly, in Alfisols of Palampur, Bengaluru, Pattambi and Bhubneshwar, the balanced application of nutrients (NPK, NPK + FYM) resulted in increase in SOC contents.

Use of biochar

In recent years, biochar gained lot of attention owing to its long-term C sequestration potential. Biochar is a pyrolysed product of biomass which is produced in absence or presence of little amount of oxygen by thermal decomposition. Agricultural grade biomass is produced between pyrolysis temperatures of 400 to 600 ^{o}C. In the recent past, *Terra Preta* soils in the Amazonian Basin have been linked to the ability to sequester C, as well as improve agricultural production. These *Terra Preta* soils have received large amounts of charred materials, the residues from biomass burning (Sombroek *et al.,* 2003). Large amounts of biochar-derived C stocks remain in these soils today, hundreds and thousands of years after they were abandoned.

It is a matter of great concern that in north-west India, large amounts of rice straws are burnt annually, releasing CO_2 to the atmosphere, in addition to methane, nitrous oxide and air pollutants (Punia *et al.*, 2008). In this scenario, biochar offers a significant, multidimensional opportunity to transform large-scale agricultural waste streams of financial and environmental liability to valuable assets. Use of biochar thus opened up a new avenue for soil C sequestration in the last one decade.

In a study related to C stability in soil carried out with biochar of four different feedstock in Inceptisol for one year, Purakayastha *et al.* (2015) have reported that maize biochar showed the maximum potentiality to store more stable and least mineralizable C hence enhanced total soil C as high as 65% as compared to control (without biochar) (Fig. 4). The other kinds of biochar like pearl millet [*Pennisetum glaucum* (L.) R. Br. Emend. Stunz], rice and wheat biochars could enhance the total C in soil in the tune of 52%, 41% and 64% respectively. Biochar produced from peanut (*Arachis hypogala* L.) shell could significantly contribute to increase of SOC and MBC fractions in degraded saline soils (Bhaduri *et al.*, 2016). Stability of biochar C is greatly influenced by feedstock of biochar and pyrolysis temperature. The pyrolysis temperature significantly influenced the stability of biochar C in soil, as the pyrolysis temperature greater than 400°C causes loss of aliphatic-C moieties and a centralization of C compounds to mostly poly-condensed aromatic-C type compounds (Novak *et al.*, 2010). The biochar prepared from crop residues at high temperatures (e.g. 600°C) would be more stable in soil than that prepared at low temperatures (e.g. 400°C). Recently, Purakayastha *et al.* (2016) reported that corn stover biochar (CSBC) prepared at 600°C, showed greater stability in both the Mollisol and Ultisol. The wheat straw biochar (WSBC) and CSBC prepared at 600°C which showed negative priming of native soil organic matter (SOM), had greater potential for long-term C sequestration in soil. The volatile matter component of biochar decreased significantly at the higher pyrolysis temperature. Besides this, soil type also influences the stability of biochar carbon. In the Mollisols, the wheat straw biochar prepared (WSBC) at 600°C was more stable than the rice hull biochar (RHBC). However, in the Ultisols, RHBC was more stable than the WSBC (Purakayastha *et al.*, 2016).

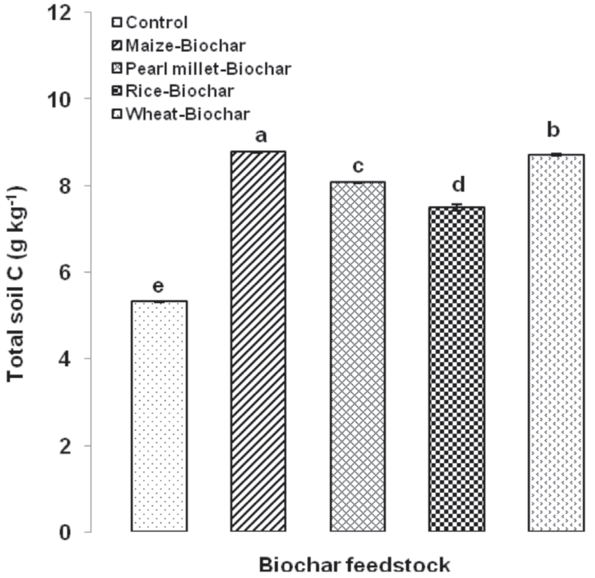


Fig. 4. Total soil carbon in biochar (BC)-amended soil, the bars with different lower case letters are significant according to Duncan's multiple range test at $P = 0.05$. Error bars show standard errors (n= 4). *Source*: Purakayastha *et al.* (2015)

Biochar is a promising amendment for ameliorating drastically disturbed soils due to its microchemcial (Amonette and Joseph, 2009), nutrient (Chan and Xu, 2009) and biological (Thies and Rillig, 2009) properties as well as its stability in soil (Lehmann *et al.*, 2009). Kimetu *et al.* (2008) reported that the application of biochar had the greatest impact on increasing productivity and soil organic C concentrations, though no improvement of nutrient availability was noticed. Smernik (2009) has suggested that biochar-amended soils can be used to control the toxicity and movement of organic chemicals.

Biochar is highly stable against microbial decomposition and applying this to farmland has the potential to mitigate greenhouse gas emission. While corn stalk biochar significantly decreased CH_4 emissions from paddy soil (Feng *et al.*, 2014), another recent report indicated that adding biochar to agricultural soil with mineral fertilizers can suppress N_2O emissions without suppressing the activity of soil biota involved in N transformation processes such as mineralization or nitrification (Case *et al.*, 2015).

FUTURE AREA OF RESEARCH

As the major potential of soil organic C sequestration is reclamation of degraded lands, the maximum C- carrying capacity of degraded lands should be established through research by employing appropriate modeling approach. This would help in C-saturation deficit in these degraded lands. The long-term experiments already are in operation in these lands, should be exploited to establish the maximum C-carrying capacity and there of C saturation deficit. The most emerging areas for enhancing soil C sequestration should be focused on addition of low-cost, environment-friendly management strategies promoting C stabilization that can be readily available and acceptable to farmers. Agronomists and soil scientists should work hand-in-hand to make this venture successful. Besides, these days more emphasis has been given to estimation of deep soil C (beyond 30 cm) while studying C sequestration. Enrichment of knowledge also comes through comparing various C fractions in total soil C pool and their relative contribution towards soil C sequestration.

We may conclude that in India, the greatest potential of C sequestration lies in prevention and management of erosion. In this respect, conservation agriculture with zero tillage and residue retention could be the best option to prevent the erosion and hence to build-up of C in soil. Degraded lands in arid and semi-arid areas have the highest hidden potential in storing C of carbonate and bicarbonate forms. The wastelands if brought under pasture or afforestation programmes could significantly improve the C content in soil. In acid soils, the balanced NPK fertilization along with lime could either maintain or enhance the C in soil, while the greatest SOC build-up is achieved by integrated application of NPK with farmyard manure. In salt-affected soils, gypsum application in field crops or planting tree species in combination with gypsum could be potent enough for aboveground and belowground carbon build-up. Owing to the nature of production being dependent on both the feedstock and the process, biochar can be developed for site-specific conditions to ameliorate a number of conditions.

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