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# Carbon capture and sequestration for sustainable land use – A review

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ABSTRACT

Carbon sequestration (CS) has been increasingly viewed as one of the crucial issues/strategies to address the challenging issues of global warming led climate change effects besides imparting sustainability to productivity. In agricultural land use systems, increased $CO_2$ emission into the atmosphere is through repeated and frequent cultivation of croplands, crop residues, biomass burning, shifting cultivation, cultivation of low biomass producing crop cultivars, land degradation, deforestation, etc. The results of current review revealed that agricultural soils have lost about 30–75% of their inherent soil organic carbon (SOC) pool which is quite alarming. The U.N. panel (IPCC) in its current report published that to contain warming at 1.5ºC, there will be a need to reduce the global net $CO_2$ emissions (manmade) by about 45% by the year 2030 from 2010 levels and further to reach 'net zero' by 2050. The potential of carbon sequestration with cautious management of world cropland include 0.08±0.12 Pg/yr by erosion control, 0.02±0.03 Pg/yr by preservation of harshly problematic/degraded soils, 0.02±0.04 Pg/yr by repossession of salt-affected soils, 0.15±0.175 Pg/yr by taking up of minimum/conservation tillage and crop left-over administration, 0.18±0.24 Pg/yr by execution of better cropping system and 0.30±0.40 Pg/ yr as C balance via biofuel production. The total potential of carbon sequestration by the world cropland is about 0.75±1.0 Pg/yr. Each 1 Mg/ha rise in soil organic carbon pool in the root zone under the soil would enhance yields of crops by 20–70 kg/ha in case of wheat, 10–50 kg/ha in rice, and 30–300 kg/ha in corn, augmenting production of cereals and legumes in the developing countries by 32 and 11 million Mg/yr, respectively. Therefore, CS apart from mitigating global warming potential also succors the farming community and the nation in advancing food security on sustainable basis.

**Keywords**: Carbon sequestration, Conservation tillage, Crop residue/crop left-over, Nutrient management

India is having a total geographical area of 328.7 million hectare (Mha), and it accounts for 2.5% of the total geographic land area globally (Table 1). India is habitat for 1.3 billion people covering about 16% of the population worldwide. Globally, India ranks as 2nd most crowded and thickly inhabited country. Major land use of the country includes 161.8 Mha of arable/cultivable land (about 11.8% worldwide). Out of total arable land, about 57.0 Mha land is irrigated which is 21.3% of the world, 68.5 Mha is covered under forests and woodland (which accounts about 1.6% of the world), 11.05 Mha is occupied by perennial/permanent pastures (which is 0.3% of the world) and about 7.95 Mha of farmlands are occupied by permanent crops (which is about 6.0% of the world).

*Soils of India and their carbon pool*

India is also decorated with diverse soil types with variable uniqueness. Out of total available land area, the major types of soils consist of Alfisols, 81.1 Mha (27.3%), Vertisols, 60.4 Mha (20.3%), Inceptisols, 51.7 Mha (17.4%), Ultisols, 36.6 Mha (12.3%), Entisols, 24.8 Mha (8.3%), Aridisols, 18.3 Mha (6.2%), Mollisols, 1.8 Mha (0.6%), and Gelisols, 0.8 Mha (0.27%). These different types of soil are also consisting of an ample range of soil organic carbon

Table 1 Land use under different heads in India and the World in 1999

| Different heads of land use | India (Mha) | Global/World (Mha) |
|---|---|---|
| Total area | 328.7 | 13414.2 |
| Land area | 297.3 | 13050.5 |
| Perennial/Permanent crops | 7.95 | 132.4 |
| Perennial/Permanent pastures | 11.05 | 3489.8 |
| Forest and woodland | 68.5 | 4172.4 |
| Agricultural area | 180.8 | 4961.3 |
| Arable land | 161.8 | 1369.1 |
| Irrigated land | 57.0 | 267.7 |

*Source:* FAO 2001

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Table 2 Comparison in the reduction of soil organic carbon (SOC) content of arable soil with that of untouched soils

| Region | SOC content | | Reduction (%) |
|---|---|---|---|
| | Cultivated soil (g/kg) | Native soil (g/kg) | |
| Northwest India Indo-Gangatic plain | 4.20±0.90 | 1040±3.60 | 59.60 |
| Northwest Himalayas | 24.30±8.70 | 34.50±11.60 | 29.60 |
| Northwest (India) | 23.20±10.40 | 38.30±23.30 | 39.40 |
| Southwest (India) | 29.60±30.10 | 43.70±23.40 | 32.30 |
| West coast | 13.20±8.10 | 18.60±2.10 | 29.10 |
| Deccan Plateau | 7.70±4.10 | 17.90±7.60 | 57.00 |

*Source*: Swarup *et al.* 2000

concentration, which is directly related to the amount of clay content in the soil and the prevailing climate.

Accordingly, it was reported by many researchers that SOC concentration of majority of soils is lower than 10 g/kg, and generally it is reported less than 5 g/kg. The existing low levels of SOC concentrations are credited to traditional farming practices such as soil-mining (practice of excessive tillage), imbalanced/excessive use of fertilizers, complete removal of the crop residues, and excessive degradation of soil.

In comparison to World pool, the SOC pools of Indian soils are only 2.2% for 1 m soil depth and 2.6% to a soil depth of 2 m. Table 2 shows a gradual decrease in concentration of SOC in cultivated soils ranging from 30–60% in comparison with the previous/antecedent level of SOC present in non-disturbed ecosystems even during 1960.

The unprecedented rise in gases in the atmosphere known for global heating or greenhouse gases (GHGs) and the consequent climatic change have already started showing their effects on agriculture and other spheres of life. It is well recognized that enhancement in carbon dioxide (atmospheric $CO_2$) and some additional gases, such as nitrous oxide ($N_2O$) as well as methane ($CH_4$), lead to the change in climate (IPCC 2007). With just 1.5°C of global warming, many glaciers around the world will either disappear completely or lose most of their mass; an additional 350 million people will experience water scarcity by 2030; and as much as 14% of terrestrial species will face high risks of extinction (IPCC 2022). The worldwide $CO_2$ concentration has augmented from 277 ppm in the year 1750 to 402.8+0.1 ppm in the year 2016 (up 45%) (Dlugokencky and Tans 2018; Fig 1).

The change in land use represented about 31% of collective emissions till 2016, in the order of coal, oil, gas and other (32%, 25%, 10%, 3%) respectively. Besides this, deforestation, burning of straw, ploughing, and intensive grazing also contributes significantly towards C emission to the atmosphere (Lal 2004a). The agricultural land use systems, viz. croplands, grasslands, forests, agroforests, horticulture, home gardens can be potential sinks for atmosphere $CO_2$ through implementation of appropriate land use and judicious management practices (Liefield *et al.* 2005). The land use alteration may result in shift of C to the atmosphere in two ways (a) discharge or free release of carbon in crop biomass via breakdown or burning and (b) discharge of SOC after cultural practices due to increased mineralization and facilitating erosion (Singh and Lal 2005). According to International governmental panel for Climate Change (IPCC 2007), the chronological loss from farmlands was approximately 50 Pg C over the last five decades, which accounts for approximately 33% of the total loss from soil and green biomass.

*Concepts of carbon sequestration*

Capturing and sequestration of carbon dioxide ($CO_2$) is a combination of some technologies which can lower down $CO_2$ emissions from the new as well as accessible coal- and gas-fired power plants and big industrialized sources substantially. Carbon dioxide Capture and Sequestration (CCS) involves three-steps that include:

- Capturing of $CO_2$ from industrial sources or power plants;
- Transportation of the captured $CO_2$ after compressing it (generally in pipelines);
- Storage of $CO_2$ via underground injection and geologic sequestration deep into underneath ground rock formations. Usually these processes are extended to even a mile or even deeper under the soil surface and contain permeable rock which carries the $CO_2$. Above these processes there are present non-porous, impermeable sheets of rocks which entrap the $CO_2$ and subsequently avoid it from migrating upward. Carbon dioxide ($CO_2$) sequestration (CCS) and its capturing could play an

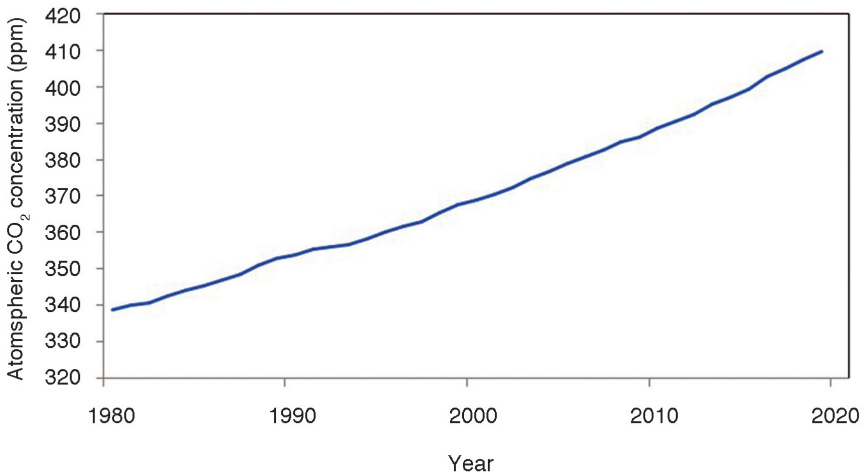


Fig 1 Global averaged surface atmospheric $CO_2$ concentration (Dlugokencky and Tans 2018).

eminent role in lowering down the greenhouse gas emissions considerably, at the same time, generation of low-carbon electricity from power plants.

*Storage of captured carbon dioxide ($CO_2$)*

Sequestration is the process that comes after capture. After capturing of $CO_2$, it is compacted, squeezed together and then shifted to a new spot where sometimes it is injected below the ground for its long term or permanent storage, which is "sequestration". Generally, carbon dioxide is shifted or taken to another place via pipeline, but it can also be taken via trucks, trains, or with the help of ships etc. The geologic formations which are appropriate for sequestration includes exhausted gas and oil fields, deeper coal seams, and saline formations of rocks. In the United States, department of energy estimated that, anywhere from 1,800–20,000 billion metric tonnes of $CO_2$ could be fixed below the ground (NACAP 2012) which is comparable to 600–6,700 years of present level emissions from large fixed or stationary sources in the United States.

Carbon dioxide ($CO_2$) is taken up and absorbed by trees, plants as well as by crops by the process of photosynthesis and it is stored as C; hence, CS occurs in two major segments, i.e. soil (via roots and other underground parts of plants, soil micro-organisms and the C stored in different soil layers) and biomass (i.e. stem, twigs, leaves, of different crops, trees and succulent/herbaceous plant components) (Nair *et al.* 2010). The whole amount of C sequestered in each segment differs and largely depends upon region, land-use, cropping system or type of system (different components and age of trees/perennial plants) and location quality.

*Sequestration of soil carbon*

In India, the potential of soil CS is calculated at 0.007–0.01 Pg/yr for reinstatement of degraded lands and ecosystems, 0.005–0.007 Pg/yr for controlling erosion and 0.006–0.007 Pg/yr for taking up of and executing good administration practices on farming lands/soils. Thus, mean total potential of soil CS is 0.045 Pg/yr. Roughly 2/3rd of the total CS occurs below ground, i.e. in soil. Worldwide quantum of C stored in soils is adding up to more than 3000 Pg. This huge amount of soil C pool is three times the atmospheric pool of 1000 Pg, and it is about 3.8 times the pool of vegetation which is 790 Pg (Jandl *et al.* 2014). Lal (2008) estimated that about 136+55 Pg quantity of $CO_2$-C went into the atmosphere from the various terrestrial ecosystems, out of which soils share was about 78+12 Pg. The organic matter present in the soil (SOM) consists of more reactive OC (organic carbon) than any other terrestrial pool of carbon. As a result, SOM plays a key role in shaping C storage in different ecosystems and in normalizing the atmospheric $CO_2$ concentrations. The stored quantity of C is influenced by the addition of C from decomposed crop and plant material, and losses of C via respiration, as well as both natural and anthropogenic or manmade disturbance of the land/soil. Management of good agricultural practices with minimal soil disturbance would promote CS and it may reduce or even overturn the losses of carbon from agricultural fields. The prevailing processes like degradation boost the overall C flux to the atmosphere through enhanced emission and reduces the sink potential of the lands/soils (Lenka *et al.* 2013).

If there is a downfall in soil carbon pool by 1 Pg, it will be comparable to an atmospheric enrichment of $CO_2$ by 0.47 ppm (Lal 2001). Soil carbon besides being sustainability indicator of agricultural systems is also an important marker of environmental health. The prevailing levels of SOC in soils is a sign of the long-term stability between any carbon input and output. When the amount of carbon coming out as output ($CO_2$ emissions) is higher than the C we are adding as input (via crop residues) to the soil system, SOC will be reduced. Most of our agricultural lands are generally deficient in SOC because continuous cultivation of lands leads to substantial losses of SOC as (1) disturbance of soil by extensive tillage/deep practices, (2) not returning the plant residues back to the fields, and (3) higher or inefficient use of fertilizers specially nitrogen and irrigation water (Lal 2002). Sometimes, the adopted cultivation practices are contributing to the higher mineralization of SOC while changing physical and chemical soil properties, like soil temperature, moisture in the soil, soil nutrient availability (Paustian *et al.* 2000) and structural stability (Kong *et al.* 2005). This noteworthy exhaustion of SOC will ultimately deteriorate the quality of the soil, which in turn, will result in a reduction in crop productivity and higher emissions of GHGs from the agricultural soils. Furthermore, under the current management practices, SOC may further exhaust because of the estimated increase in temperatures globally (Lal 2004a, b, 2008).

*Biomass carbon sequestration*

Biomass carbon storage is defined as the fixation of C into plant biomass in the cut or harvested plant parts, or in residues that are incorporated into the soil. Above ground biomass CS potential are estimated based on the assumption that in trees, almost 45–50% of C is constituted in the dry weight of twigs or branches and about 30% of C is constituted in foliage dry weight (Schroth *et al.* 2002). Moreover, storage of carbon in green vegetation or plant biomass is only possible in the perennial system or agro-forestry system as this system allows continuous and long-term growth of tree to their full potential and in this system woody component of trees contributes a major part of the total biomass (Singh *et al.* 2016). The sequestration has an additional component of secure storage of such big, fixed sources of C. There are some management and ecological indicators which affect the pace at which the various basic processes of atmospheric $CO_2$ fixation proceed (Nair *et al.* 2010).

*Carbon sequestration in croplands*

Worldwide, more than 1/3 of cultivable land is under agriculture (World Bank 2018). The progress of agriculture has resulted in a significant reduction of SOM. It has been reported by researchers that about 30–75% of antecedent soil organic carbon pool (SOC) has been lost by most of the agricultural lands. The extent of these losses is even more in the problematic soils and the soils which are susceptible to the process of erosion and other soil degradative processes. The global loss of C through the erosion process is calculated to be in the range of 150–1500 million Mg/yr (Lal 1997). The major losses in soil carbon are due to soil erosion and mineralization of SOM, apart from climatic factors (mainly temperature), leaching of dissolved organic and inorganic C. Soil erosion (mainly SOM in top soil) by excess rain water or high wind speed, represents the major soil degradation phenomenon and it influences approximately larger than 1 billion hectares of soils worldwide. Generally, the extent of soil loss ranges from 1–10 Mg/ha/yr and in extreme cases, this loss goes up to 50 Mg. Exact estimation of this carbon pool is not easy due to spatial and temporal variability.

Agronomic management options which could be used to raise SOM content are increasing the crop productivity and dry matter production by crops (may be through improved varieties and efficient utilization of fertilizers and irrigation water). There must be a balance between the management options which would increase the carbon input and decrease the loss from soil (Fig 2). A hike in SOC pool by 1 Mg/ha/yr can enhance the production of food grains by 32 million Mg/yr in developing countries. The available data shows that each 1 Mg/ha hike in carbon pool (SOC) in the crop root zone can increase yields of crops as 20–70 kg/ha, 10–50 kg/ha and 30–300 kg/ha for wheat, rice, and maize, respectively. In addition to advancing food security, this approach would also reduce emissions of fossil fuel through CS in arable soils of developing countries (Lal 2006). The agronomic management options to enhance the CS include the following practices:

Conservation tillage: Tillage is not a new term but is having an old history long back millennia, and its objective is to provide good soil aeration and to some extent manage weeds. Balesdent *et al.* (2000) revealed that tillage plays a major part in the deprotection of organic matter found in soil macro-as well as to the soil micro-aggregates to some extent. An augmentation in soil carbon from reduced or conservation tillage (CT) to no-till (NT), varies from 10–30% (Paustian *et al.* 1998). CS between CT and NT varies with agro-ecological zones and soil type. One principal in CA is that there should be more than 30% of crop left over/residues cover on the surface of soil (Lal 1997). In humid temperate climatic conditions, 0.5–1.0 Mg C/ha/yr can be captured with conservation agriculture (CA), and CS is 0.2–0.5 in humid areas and about 0.1–0.2 in semi-arid zones (Lal 2006). But, practicing no tillage or reduced tillage along with some cover crops and/or green manures in appropriate rotation results in fixing higher amounts of carbon. Total OC pool in Indian soils is estimated at 63 Pg, representing about 2.2% of the world pool upto a depth of 1 m (Lal 2004b). In Indo-Gangetic plains following rice-wheat cropping system, annual increase in SOC stock with adoption of CA compared to conventional practices was

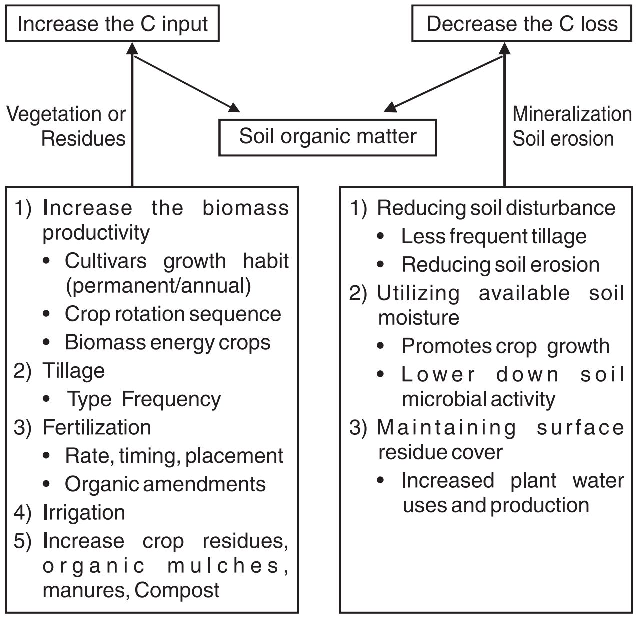


Fig 2 Agronomic practices to sequester soil organic Carbon in agriculture.

ranging between 0.16 and 0.49 Mg C/ha/yr (Powlson *et al.* 2016). Long-term reduced tillage with continuous cropping enhanced C storage when compared with a traditional system (Sainju *et al.* 2007). Soil organic CS was -0.26 Mg C/ha/yr under NT compared with CT with a cropping intensity of 0.25 (e.g. wheat-fallow), was 0.38 Mg C/ha/yr with a cropping intensity of 0.5 (e.g. continuous sorghum, wheat, or corn) (Franzluebbers and Steiner 2002). However, disturbing or tilling a previously undisturbed soil swiftly resulted in reversing almost all the previously reported benefits by upsetting soil aggregates and divulging C molecules to microbial attack (Grandy and Robertson 2006).

Cover crops/Intercropping: The advantages of reduced or conservation tillage adoption for capturing of soil organic carbon are greatly affected by cultivating cover crops such as alfalfa or other legumes in crop rotation cycle. Crop rotations based on legumes (like cowpea–mustard–sunflower, soybean–sunflower,) along with use of organic nutrient sources like compost and farm yard manure are chosen as practicable options to prevailing rice–wheat cropping sequence in India and other South Asian countries for higher crop production, and enhancements in the C pool and quality of soil (Dwivedi *et al.* 2003). These practices are relatively more resistant to microbial metabolism, could also play an eminent role in increasing the complexity and diversity of soil carbon, making soil more stable (Wickings *et al.* 2012). Ecosystems having more biodiversity can absorb and capture/fix higher carbon than those with lesser or comparatively lesser biodiversity. By planting more and more of cover crops or regular green fallows results in enhancing the average annual biomass production and could ultimately tilt the balance towards a net positive gain (+ve) of C rather than a loss (-ve) (Tiemann *et al.* 2015).

Crop residue management: Crop residue management not only sequesters C in soil but also increases the SOM content. Burning of crop residues result in negative impacts, even if they are controlled or mitigated by the larger steadiness of the mineral carbon which is produced. India produced a decent amount of crop residues as high as 371 metric tonnes (MT) of which nearly ½, i.e. 51–57% is contributed by rice and 27–36% by wheat. North-western India is also a contributor for 20% organic C and elemental C in the overall budget of emission from agricultural crop residue burning (Lohan *et al.* 2018). Addition of crop residues in rice-wheat system served as greater sink of organic carbon than without residue application in conventional system. The residues from different crops can successfully be used as mulch in CA and for producing manures, ethanol, some biodiesel products and in preparing biochar resulting in reduction of net GHG release to the tune of 70 billion tonnes of $CO_2$ equivalent (Battacharyya and Barman 2018, Kaur *et al.* 2020). The encouraging effects of using different crop residues or left over of crops to stimulate CS have been evaluated by Lal (1997) at 0.2 Pg C/yr with conversion of 15% of the total C (1.5 Pg C globally).

Nutrient management: We all know that use of traditional organic sources for various plant nutrients and compost boosts the SOC pool higher than supplying the similar amount of plant nutrients through inorganic nutrient sources (Gregorich *et al.* 2001). The possible outcomes of applying fertilizer on soil organic carbon pool are linked to the quantity of biomass C formed/returned to the soil (as crop residues) and its humification/decomposition. Optimum amount of nitrogen and other nutrients present in soil can enhance the formation of biomass under raised concentration of $CO_2$ (Van *et al.* 2000, Kingra *et al.* 2019, 2021). Also, application of organic manures on long term basis, enhances the C pool of soil and helps in improving soil aggregation (Gilley and Risse 2000), and these benefits are long lasting and may exist for a century or even longer (Compton and Boone 2000). Whereby soils are supplied/amended with different organic sources/manures, the tillage practices like minimum or conservation tillage practice greatly enhanced the soil potential to sequester soil organic carbon (SOC). Smith and Powlson (2000) concluded that application of organic manure to cropland can increase its carbon pool comparatively more than it does on grassland and it is expected that if arable lands were amended with all manures in the European Union, there would be a net fixing of 6.8 Tg C/yr, that would be equivalent to 0.8% of the 1990 $CO_2$-C emissions for the region. In India, CS potential in tropical soils varies from 2.1–4.8 Mg/ha with addition of organic source like farmyard manure (FYM) together with application of inorganic fertilizers to arable crops, in a period of 17 years (Pathak *et al.* 2011). Application of sole FYM reported higher quantity of C sequestration (3.9 Mg/ha) than integration of FYM with inorganic and sole inorganic fertilization in rice-rice cropping system in hot semi-arid climate of India over 14 years (Chaitanya *et al.* 2017).

Irrigation management: Judicious application of irrigation water enhances dry matter accumulation, increase the dry matter of upper-ground and the under-ground (root-biomass) plant parts going back to the soil and speed up soil CS in croplands and grasslands. Bordovsky *et al.* (1999), reported that, in Texas, SOC content of surface soil, in field plots planting of irrigated sorghum and wheat grown for grain purpose, increased with time. Roldan *et al.* (2005) observed the effects of tillage and water regime on the SOM and soil CS in a maize field under subtropical conditions and reported that in soil layer with 0–5 cm depth, OM reduced with a greater number of tillage but, was improved with irrigation. Application of four irrigations in rice and wheat crops resulted in 323 and 630 kg/ha/yr higher SOC recorded in the surface 30 cm soil depth than with lesser number, i.e. two and one irrigations in rice and wheat, respectively (Bhattacharyya *et al.* 2008).

*Carbon sequestration in grasslands*

Grasslands are playing an important role in all the ecosystems globally, and they are spreading over an area of 37% of the terrestrial area of the earth. Grassland soils serve as C sinks, with global C stocks approximated at about 343 Gt C, which accounts around half or 50% higher than the quantity fixed in forests lands globally (FAO 2018). Lal (2004) reported that the potential of organic carbon sequestration of the world's grasslands is about 0.01–0.3 Gt C/yr. The carbon-sink activity of the European grassland has been calculated to be ranging between –0.57+34 and –104+73 g C $m^2$/yr (Schulze *et al.* 2010; negative values indicate CS). Soil C content under grassland is expected at 70 Mg/ha, which are more or less similar to the quantity fixed in forest soils (Balesdent *et al.* 2000). Maria (2012) studied that management of grazing lands and pastures development has a decent global technical mitigation potential of almost 1.5 Gt $CO_2$ equivalents in 2030, with supplementary lowering/mitigation resulting from renovation of problematic/degraded farmlands. Similar to croplands; different management practices adopted for improving pastures consists of efficient use of fertilizers, restricted grazing, planting of recommended cultivars of pulses/legumes and some grasses or other superior plant species comfortable to the location/area, upgrading of soil biota and improved irrigation practices (Follett *et al.* 2001). The rates of SOC-sequestration via pasture upgrading varying from 0.11–3.04 Mg C/ha/yr with a mean of 0.54 Mg C/ha/yr was studied by Conant *et al.* (2001).

*Carbon sequestration in forests*

Forests are both sources as well as sinks of carbon. An active/growing forest captures C from atmosphere and a mature forest is a store house of C. According to Global Forest Resource Assessment Report, the total world's forest carbon stock is 652 Gt/ha. Out of this, forest biomass constitutes 289 Gt; the dead OM contains 72 Gt; and forest SOC contains 293 Gt of C (Table 3). India ranks at 10th position in the category of densely forested nations globally, with forest cover of 21.54% of geographic area of country

(329 Mha). Carbon stocks stored in Indian forests have been estimated to be 7083 MT comprising above ground carbon 2238 MT, below ground carbon 699 MT, dead wood 30 MT, litter 136 MT and SOC 3979 MT (FSI 2017). The annual removal of GHGs by forests is sufficient to counter balance 9.31% of India's total annual emissions of 2000. It is reported by Kishwan *et al.* 2009 that, even if 50% (3 MT) of the yearly biomass increase (6 MT) is removed yearly on a sustainable basis from the year 2025 onwards, Indian forestry sector, emission removal capability would still be able to offset every year 5.02% of the 2020 level emissions. The shifting to a cultivable/agricultural land use consistently results in the exhaustion of soil organic carbon stock by 20–50% (Davidson and Ackerman 1993). The exhaustion of SOC stock is credited to several factors comprising reduction in the quantity of total dry matter or biomass going back to the soil, alteration in soil moisture as well as soil temperature regimes which bring to light the rate of breakdown of OM, more decomposition ability of crop left-overs because of more C:N ratio and lignin content, tillage-related changes and high enhanced in soil erosion. Due to this, arable soils especially soils suffering from erosion have lesser SOC stock compared with their actual potential capacity. Plantation trees or afforestation of farmlands can overturn some of the processes like preventing the soil degradation processes and could be helpful in the enrichment or sequestration of SOC stock (Ross *et al.* 2002).

*Carbon sequestration in agroforestry systems*

Agroforestry has a noteworthy capacity to capture and fix/sequester atmospheric carbon in plant parts or biomass and also in soils. Sequestration of the carbon is a vibrant active process and it could be separated into two main parts: establishment phase and the end of rotation period (Singh *et al.* 2016, 2017). The total area under agro-forestry as calculated by Nair *et al.* (2009a) globally is 1023 Mha, and is giving benefits to approximately 1.5 billion farmers, mainly farmers having small land holdings, in developing countries. Silvicultural operations varying from preparation of suitable site to stand management practices can affect the plant development and crop production and also enhance the above ground as well as under-ground carbon sequestration, but occasionally can be responsible for the C emissions. Tree-pruning operations are carried out to fulfil the *ex situ* green-leaf manure requirement of some field crops via green leaves, for the purpose of fire/fuel wood and to facilitate greater understory light availability. Fast-growing species like poplar and eucalyptus can build-up higher C even at their early age before 10 years old compared with some other slow-growing tree species of some trees like sheesham, teak; however, the species with slower-growing rate build-up higher carbon in the long-run and the wood from slow-growing cultivars exhibits higher specific gravity, which in turn enhances the carbon sequestration potential (CSP) for long-term (Redondo-Brenes 2007). In a 5 year study, Swamy and Puri (2005) recorded that there was 12.1 Mg/ha higher net storage of C (soil + tree) under the species *Gmelina arborea* as compared to agri-silviculture farming system. Nair *et al.* (2009b) also figured out with some best-estimates regarding the ranges of sequestration of soil carbon occurring in varying agroforestry systems of the major tropical agro-ecological regions. The recommended range varied from 5–10 kg C/ha in extensive tree-intercropping systems in arid and semiarid lands in almost 25 years to as high as 100–200 kg C/ha in a period of 10 years in cultivars in humid tropics with intensive multi-layered shaded permanent/perennial systems and home gardens. If seen worldwide in major agroforestry systems, the above ground CS rates ranged from 0.29–15.21 Mg/ha/yr and 30–300 Mg/ha/yr (upto 1 m depth) below ground (Nair *et al.* 2010). Establishment of some tree plantations later on to be used as biofuel (e.g. *Jatropha, Prosopis, Leucaena*, etc.) on wastelands/degraded and mix of trees with crop fields are important strategies to reinstate degraded lands and ecosystems, enhancing the SOC pool, improving the environment quality and also improving the livelihood (Lal 2006). Shifting (jhum) cultivation and taungya cultivation in the Northeast India are examples of traditional Indian agroforestry system with total area of 1.2 Mha, of which current jhum constitutes 0.56 Mha and abandoned jhum constitute 0.46 Mha (MoEF 2010). The overall capacity/potential for agro-forestry has been calculated at 25.36 Mha with CS potential of 0.21 Mg/ha/yr equivalent to 0.77 Mg/ha/yr $CO_2$ mitigation. Taking into consideration the already reported GHGs releases from (major component) agriculture segment as 334.41 MT of $CO_2$ equivalent in the country, India, the agroforestry systems present in farmers farms are expected to mitigate about 33% of total emissions of GHG contributed from major segment (agriculture) yearly and GHG emissions higher than 6% of total at the national level.

Table 3 Terrestrial carbon stock estimates in forest zone

| | India (MT) | World (Gt) |
|---|---|---|
| Forest biomass (Above + below ground) | 2937 | 289 |
| Dead organic matter | 166 | 72 |
| Forest soil organic carbon | 3979 | 293 |
| Total carbon stock | 7082 | 652 |

Gt – Gigatonne (*Source*: FSI 2017)

*Conclusion*

The above review paper has come up with some possibilities for best management practices to be adopted by the stakeholders as well as researchers to accelerate CS to maximum extent. The land-use type is a very important key factor in controlling organic matter (OM) present in soils as it alters the quantity as well as quality of organic residue input and their decomposition rates, and the phenomenon of stabilization of OM in soils. Agricultural or arable land use which involves the cultivation of soil may alter the total quantity of soil organic matter which is stabilized and relative importance of its protecting processes. If there is excess of C, it will result in C being lost as quickly as it is added. Adoption of some suggested management practices, like conservation tillage, cover crops, intercropping, residue retention, inclusion of organic manures in nutrient management, adequate irrigation, erosion control measures, multitier cropping, agroforestry systems, crop and tree biomass recycling may permit stable assimilation of SOC for longer time period before reaching to a point of equilibrium. A range of carbon sequestration from 0.29–15.21 Mg/ha/yr in above ground to 30–300 Mg/ha/yr (upto 1m depth) below ground was reported in an agroforestry system. The potential of carbon sequestration under various land use practices was found to be decreased in the order of forests>agroforests>grasslands>croplands. Overall, a combination of good crop production practices supported with resource conservation measures, agroforestry, forest, and grassland management practices, would be useful in enhancing C-sequestration and its long-term stability and sustainability. [Note: 1 Gigatonne (Gt) = 1 billion tonnes = 1×1015 g = 1 Petagram (Pg); 1 kg carbon (C) = 3.664 kg carbon dioxide ($CO_2$)]

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