Environment and Ecology 40 (2C) : 893—898, April—June 2022
ISSN 0970-0420

Carbon Sequestration in Plantations and Agriculture Systems : A Review

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Received 3 August 2021, Accepted 29 October 2021, Published on 7 June 2022

ABSTRACT

Trees capture atomospheric CO_2 through photosynthesis and act as a sink for several centuries. As more photosynthesis occurs, more CO_2 is converted into biomass, reducing carbon in the atmosphere and sequestering it in plant tissue above and below ground resulting in growth of different parts. Above ground biomass, below ground biomass, dead litter, soil organic matter is the major carbon pools in any ecosystem. Biological carbon sequestration is the process through which agricultural and forestry practices remove CO_2 from the atmosphere and store it in the terrestrial ecosystem for a very long period of time. Being the largest terrestrial C pool, soils play a crucial role in the global C balance by regulating dynamic biogeochemical processes and the exchange of greenhouse gases (GHGs) with the atmosphere. Globally, Soil Organic Carbon (SOC) stocks are estimated at an average of 1,500 ±230 Pg C in the first meter of soil, which is nearly twice as much as atmospheric carbon (828 Pg C) and thrice as that of terrestrial vegetation (500 Pg C). Estimating C pools under existing land uses provides baseline data to project C sequestration over time.

Keywords Carbon stocks, Land uses, Plantations, Agriculture systems.

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INTRODUCTION

Sequestering atomospheric CO_2 into long lived wood biomass through afforestation and reforestation is an important tool to mitigate global warming and climate change. Updegraff *et al.* (2004) highlighted the importance of plantation forestry as a greenhouse gas mitigation option, as well as the need to monitor, preserve and enhance terrestrial carbon stocks. Soils host the largest terrestrial carbon pool (Scharlemann *et al.* 2014) and play a crucial role in the global carbon balance by regulating dynamic bio-geochemical processes and the exchange of greenhouse gases (GHG) with the atmosphere (Lal 2013). Globally, Soil Organic Carbon (SOC) stocks are estimated at an average of 1,500 ±230 Pg C in the first meter of soil, which is nearly twice as much as atmospheric carbon (828 Pg C) and thrice as that of terrestrial vegetation (500 Pg C) (Quere *et al.* 2016). In principle, the amount of SOC stored in a given soil is dependent on the equilibrium between the amount of C entering the soil and the amount of C leaving the soil as carbon-based respiration gases resulting from microbial mineralization and, to a lesser extent, leaching from the soil as dissolved organic carbon. Levels of SOC storage are therefore mainly controlled by managing the amount and type of organic residues that enter the soil (i.e. the input of organic C to the soil system) and minimizing the soil C losses (FAO and ITPS 2015).

After the burning of fossil fuels, land use and land cover change (which includes agriculture) is the largest anthropogenic source of carbon into the atmosphere (IPCC 2014) and within agriculture, soils have been a global net source of GHGs. These processes and emissions are strongly affected by land use, land use change, vegetation cover and soil management. SOC stocks in the upper soil layers (800 Gt C in 0-40 cm) are especially sensitive and responsive to such changes in land use and management, which provides an opportunity to influence the amount of CO_2 in the atmosphere. This can be achieved by maintaining existing soil carbon stocks (of particular importance in soils with high SOC content), or by soil carbon sequestration (Quere *et al.* 2016).

The 2015 Status of the World's Soil Resources report (FAO and ITPS 2015) highlights that more carbon resides in soil than in the atmosphere and all plant life combined. However, roughly 33% of the world's soils are degraded, which has led to large losses of SOC Lal (2013) reported that soils from various global agro ecosystems (i.e. croplands, grazing lands, rangelands, peatlands) have lost 25–75% of their original SOC pool, depending on climate, soil type and historic management. This amounts to 42 to 78 Gt of carbon, of which 18 - 28 Gt have been lost through desertification. The recoverable carbon reserve capacity of the world's agricultural and degraded soils is estimated to be between 21 to 51 Gt of carbon.

As an indicator for soil health, soil organic carbon is important for its contributions to food production, mitigation and adaptation to climate change and the achievement of the Sustainable Development Goals (SDGs). A high SOM content provides nutrients to plants and improves water availability, both of which enhances soil fertility and ultimately improves food productivity. Moreover, SOC improves soil structural stability by promoting aggregate formation which, together with porosity, ensures sufficient aeration and water infiltration to support plant growth. With an optimal amount of SOC, the water filtration capacity of soils further supports the supply of clean water. Through accelerated soil organic carbon mineralization, soils can be a substantial source of greenhouse gas (GHG) emissions into the atmosphere. Although the overall impact of climate change on SOC stocks is very variable according to the region and soil type, rising temperatures and increased frequency of extreme events are likely to lead to increased SOC losses. It becomes important to have a good knowledge of the current global SOC stock and its spatial distribution to inform various stakeholders (e.g. farmers policy makers land users) to make the best use of available land and provide the best opportunities to mitigate and adapt to climate change, but also ensure sufficient food production and water supply.

Maintaining and increasing SOC stocks is critical not only to reduce green house gas emissions and remove CO_2 from the atmosphere, but also to harness the benefits of increased SOC (and SOM) in the soil in terms of soil health and fertility and increasing its water holding capacity. Even though soils host the largest terrestrial carbon pool (Scharlemann *et al.* 2014), soil degradation, land use and land use change has resulted in soils having lost 25-75% of their original organic carbon pools. Further SOC losses need to be prevented to maintain existing levels, especially in high-carbon soils, while the potential to restore SOC stocks to at least part of its former levels through carbon sequestration needs to be harnessed. According to the Intergovernmental Panel on Climate Change, the major five carbon pools of a terrestrial ecosystem involving biomass are above-ground biomass, below-ground biomass, dead wood, litter and soil organic matter (IPCC 2006).

Carbon sequestration

Carbon sequestration is the process of capture and long-term storage of atmospheric carbon dioxide (Roger and Brent 2012, Watson *et al.* 2000) in soil, vegetation (especially forest), oceans and geologic formation.

Carbon sequestration in plantations

In a study on the tree carbon stocks and CO_2 sequestration in three different age classes of the *Populus deltoides* planted along the farm crops on bunds by farmers, the above ground carbon stocks (AGCS), belowground carbon stock (BGCS), total plant carbon stock (TPCS), CO_2 sequestration and CO_2 sequestration rate were highest at the 6-year-old plots and the lowest at the 2-year-old plots. The total carbon stock increased from 28.81 Mg ha^{-1} at 2 years of age to 87.27 Mg ha^{-1} at 6 years of age among all three Tehsils (Yasin *et al.* 2018). The carbon sequestration potential of block and bund plantations of Poplar (*Populus deltoides*) was 1.33 t C per ha per yr and 1.05 t C per ha per yr respectively, when wood products were not included and 2.41 t C per ha per yr and 1.80 t C per ha per yr along with wood products (Gera 2012). In a similar study, the carbon stock in Poplar, increased from 9.15 Mg ha^{-1} in 1year old plantation to 74.3 in 7-year plantation. Soil carbon stock increased with age (1-7 years) from 11.8 to 17.6 Mg ha^{-1} and decreased with soil depth. Maximum carbon sequestration rate was recorded at plantation age of 4-year (Kumar *et al.* 2016). The Walkley and Black Carbon, Total Organic Carbon concentrations and Total Organic Carbon stocks in the Eucalyptus based agroforestry system were 20.0, 17.5 and 18.0% greater than the sugarcane (Kumar *et al.* 2018). Past studies have shown that soil organic carbon (SOC) and microbial biomass C (MBC) increased with plantation age, canopy cover and declined with soil depth for the Populus and Eucalyptus plantation in this region (Chaudhari *et al.* 2014, Kumar *et al.* 2014, Benbi 2015).

Eslamdous and Sohrabi (2018) assessed the potential of 20-year old stands of three rapid-growth tree species, including *Alnus subcordata*, *Populus deltoides* and *Taxodium distichum*, for carbon (C) storage at ecosystem level and reported the highest carbon storage in plantation of *A. subcordata* (555.5 Mg ha^{-1}). The C storage and sequestration of the plantations after 20 years were considerable (25-30 Mg ha^{-1} $year^{-1}$) and broadleaves species had higher potential. Hu Du *et al.* (2018) reported the patterns of carbon (C) allocation across different stages of stand development (1, 2, 3, 4–5 and 6–8 years old in *Eucalyptus urophylla* × *E. grandis* plantations in Southern China and found higher tree biomass carbon pool with increasing stand age and a high annual rate of carbon accumulation. The C pool in mineral soil increased initially after afforestation and then declined gradually, with C density decreasing with soil depth. Ge *et al.* (2018) examined the dynamics of soil organic carbon, water-stable macro aggregates, litterfall production, fine-root (< 1 mm) biomass, and soil microbial biomass carbon with stand development in poplar plantations (*Populus deltoides* L. '35') in Eastern Coastal China, using an age sequence (i.e., five, nine and 16 years since plantation establishment) and reported that the quantity of water-stable macro aggregates and organic carbon content in topsoil (0–10 cm depth) increased significantly with stand age. Soil organic carbon pool under Shisham plantation was 27.98 t/ha and showed 72.7% increase in SOC pool over barren land in Uttarakhand (Gupta and Pandey 2008). Maximum carbon stock of 51.75 MT C ha^{-1} in plantations of *Casuarina equisetifolia* was recorded in the North-Eastern zone of Tamil Nadu (Ravi *et al.* 2012).

In a study on Soil Organic Matter Fractions Under Eucalypt Plantations of 1, 2 and 4 years, the total organic carbon increased by 78% after the first year of Eucalypt reform and after two years, there was an increase in Total Nitrogen and an average reduction of 52% in Light Organic Matter-C at 0-0.1-m soil layer (Soares *et al.* 2019). Soil organic carbon concentration was highest (2.74%) at 0-45 cm depth in forest and lowest in bamboo plantation (1.09%). Both, SOC concentration and SOC stock decreased with increasing soil depth. SOC stock loss estimated following its conversion from forest was maximum with shifting cultivation (−5.74 Mg C ha^{-1} yr^{-1}) followed by oil palm plantation (-2.29 Mg C ha^{-1} yr^{-1}), bamboo plantation (−1.56 Mg C ha^{-1} yr^{-1}) and the least in homegardens (–0.14 Mg C ha^{-1} yr^{-1}) (Kenye *et al.* 2019). Biomass accumulation and carbon sequestration in four different aged *Casuarina equisetifolia* coastal shelterbelt plantations in South China revealed that the annual rate of C accumulation in plant biomass during 0-3, 3-6, 6-13 and 13-18 years stage was 2.9, 8.2, 4.2, and 1.0 Mg C ha^{-1} yr^{-1} and the soil organic carbon was 17.74, 5.14,6.93 and 11.87 Mg C ha^{-1}. Above ground biomass, Below ground biomass and total plant biomass increased markedly with stand age (Wang *et al.* 2013). Gupta (2009) studied soil organic carbon pool under different land uses of Uttarakhand and reported maximum soil organic carbon pool under Deodar (140.95 t ha^{-1}) followed by Silver fir (134.90 t ha^{-1}). Under plantations, *Thuja* registered the maximum carbon pool (54.01t ha^{-1}) followed by Teak (39.43 t ha^{-1}). Arora and Chaudhry (2014) in a study on carbon sequestration in tree plantations at Kurukshetra reported that vegetation carbon pool in *Tectona grandis* and *Syzygium cumini* was 73.58 Mg C ha^{-1} and 63.64 Mg C ha^{-1} respectively. Total Soil organic carbon stock (SOC) at one meter depth was maximum in *S. cumini* (77.72 Mg C ha^{-1}) followed by *E. tereticornis* (74.69 Mg C ha^{-1}) and *T. grandis* (55.46 Mg C ha^{-1}).

According to a study conducted to assess soil organic carbon (SOC) concentration and stock under different land uses in the North East of India, forest recorded the highest mean SOC concentration with 2.74% at 0-45 cm depth and lowest in the bamboo plantation (1.09%). Mean SOC stock for 0–45 cm soil depth ranged from 27.68 to 52.74 Mg C ha^{-1} in grassland and forest respectively (Kenye *et al.* 2019). Arora and Chaudhry (2017) studied the carbon sequestration potential of *Acacia nilotica* and *Dalbergia sissoo* mixed plantation and reported that the above ground and below ground carbon pool was 32.87 Mg ha^{-1} and 8.57 Mg ha^{-1}, respectively. The carbon flux through net primary productivity and CO_2 assimilation rate of the plantation was 2.27 Mg ha^{-1} yr^{-1} and 8.33 Mg ha^{-1} yr^{-1} respectively. The total carbon stock in soil up to one meter soil depth was estimated to be 111.71 Mg ha^{-1} comprising 95.98 Mg ha^{-1} as organic and 15.73 Mg ha^{-1} as inorganic carbon stock. The micro aggregates (250 µm–53 µm) formed a large fraction of soil aggregates and protected most of soil organic carbon in the soil.

Carbon sequestration in agriculture systems

Cultivated soils resulted in a loss of 21–36% total organic carbon as compared to uncultivated soils (Benbi *et al.* 2014) which is a little lesser than the values (30–60%) reported in various agro-climatic regions of India (Lal 2004). Assessment of Carbon sequestration potential of Indo-Gangetic agro ecosystem soil revealed mean soil organic carbon density of 12.4 to 22.6 t ha^{-1} for agricultural soils of Indo-Gangetic plains (Singh *et al.* 2011). The positive effects of using crop residues to induce C sequestration have been estimated by Lal 1997 at 0.2 Pg C yr^{-1} with the transformation of 15% of the total C (1.5 Pg C globally). Generally, there is a linear relationship between the organic matter in the first 15 cm of soil and the quantity of crop residues applied. The total estimated crop biomass C and soil carbon stock of Madhya Pradesh were 34.94 Tg and 790.6 Tg. Soil C stock was approximately 25 times higher than biomass C which underlines the role of soil in sequestering atmospheric CO_2 (Wani *et al.* 2010).

By adopting strategies like no-till farming with crop residue mulch and cover cropping, Integrated Nutrient Management (INM) including the use of compost and manure, soil carbon sequestration potential could be improved. The soil organic carbon dynamics under tropical garden land systems were studied by Santhy and Devarajan (2005) they reported that organic carbon status of the soil increased with balanced application of N, P and K combined with organic manure. For assessing the impact of intensive agriculture on carbon sequestration, Benbi and Brar (2009) evaluated soil data for 25 years from 1981/82 to 2005/06 and reported that intensive agriculture had resulted in improved soil organic carbon status and increased from 2.9 g kg^{-1} in 1981/82 to 4.0 g kg^{-1}. The soil organic carbon (SOC) stock was highest in Alfisols (52.84 Mg ha^{-1}) followed by Inceptisols (51.26 Mg ha^{-1}) and Vertisols and associated soils (49.33 Mg ha^{-1}), whereas soil inorganic carbon (SIC) stock was highest in Vertisols and associated soil (22.9 Mg ha^{-1}) followed by Inceptisols (17.5 Mg ha^{-1}) and Alfisols (12.4 Mg ha^{-1}). Among the different land-use systems, total C stock was highest in forest soils followed by fodder system, paddy, maize, cotton, red gram, intercrop, chilli, permanent fallow and lowest in castor system (Venkanna *et al.* 2014).

Mulch farming and plant cover are specific land management practices allowing both coverages of the soil by specific plants, giving protection against erosion and providing biomass residues to increase soil OM. To be completely effective, plant cover or mulch management should be carried out on site and in combination with conservation tillage (agro biological management). The quantity of mulch should be in the range of several dozens of t ha^{-1} yr^{-1} in order to provide an important source of soil C up to 0.1 t ha^{-1} yr^{-1}, depending on the climatic zone (Lal 1997). Under conservation agriculture, 0.5 -1.0 t C ha^{-1} yr^{-1} can be sequestered in humid temperate conditions, 0.2 - 0.5 in humid tropics and 0.1 – 0.2 in semi-arid zones (Lal 1999). Green manures and cover crops can provide important contributions to soil carbon as experiences in Latin America demonstrate. Farmers in central America have adopted Mucuna (velvet bean) based systems, in which 150 kg N can be fixed per ha per year and 35–50 tonnes of biomass added to the soil per ha per year. This represents a very large sequestering of carbon. Koul and Panwar (2008) compared the carbon sequestration potential under seven land uses in the Terai zone of West Bengal and reported that fallow land and agricultural field sequester 5.6% and 4.73% C respectively, compared to the natural forest of *Shorea robusta*.

CONCLUSION

Carbon sequestration in plantations can play an important role in mitigating the build-up of atmospheric CO_2. Any carbon sequestration plan aims to enhance the carbon stocks in the vegetation in case of tree systems and to retain it for a longer time and to increase the soil organic carbon, improve depth wise distribution of SOC and stabilize the SOC by encapsulating it within stable micro aggregates so that carbon is protected from microbial processes. Adoption of appropriate land use coupled with best management practices is important elements of such a plan. In the present paper, an attempt has been made to pool the scientific studies conducted with respect to carbon sequestration in plantations and agriculture systems.

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