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Mini Review Paper

SOIL CARBON MANAGEMENT FOR CLIMATE CHANGE MITIGATION AND SUSTAINABLE AGRICULTURE

Dinesh K Benbi*

Former ICAR National Professor, Department of Soil Science
Punjab Agricultural University, Ludhiana – 141 004, Punjab

Carbon dioxide (CO_2) cycles globally among the land, the ocean and the atmosphere. The atmospheric concentration of CO_2 has increased globally by about 50% above the pre-industrial levels to ~420 parts per million (ppm). Anthropogenic activities including fossil fuel combustion and land use changes has contributed towards increasing CO_2 emissions. Until the beginning of the 20th century, land use change and management was dominant source of CO_2 emissions, but the emissions from fossil fuel combustion progressively increased and are currently ~6 fold higher than from land use changes. Annual CO_2 emissions from fossil fuel burning during 2010-19 averaged 9.4 ± 0.5 Gt C compared to 1.6 ± 0.7 Gt C due to land use changes. Of the total anthropogenic CO_2 emissions (during 2010-19), 46% accumulated in the atmosphere, 31% was stored in vegetation and 23% was taken up by the ocean (IPCC, 2022). India is expected to contribute 0.74 Gt C towards total anthropogenic emissions in 2021. Increasing concentration of CO_2 in the atmosphere is considered to force climate change; the global surface temperature has been pushed up ~1.07 °C (range 0.8°C to 1.3°C). Each of the last four decades has been successively warmer than the preceding one since 1850 (IPCC, 2022). Increasing CO_2 concentration and global climate change threatens human, animal and ecosystem health and biodiversity around the world. Thus it calls for "urgent action to tackle climate change and its impacts" and to limit global warming to well below 2°C and even 1.5°C in this century (UN Sustainable Development Goal 13). In accordance with the Paris agreement adopted at the 21st session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), the signatories to the agreement are required to convert their energy, industry, transport, food, agriculture and forestry systems to reduce greenhouse gas (GHG) emissions by 7.6% each year. If urgent measures are not taken the remaining C budget of 120 to 350 Gt C to limit temperature rise to 1.5°C or 2°C would be finished in next 11 to 32 years assuming 2021 emissions levels.

Agriculture sector is both source and sink of CO_2 and its improved management can enhance carbon sequestration in croplands and grasslands, thus offering opportunities for climate mitigation (Benbi, 2013). The emissions from agriculture increased globally by 16% between 1990 and 2019; however, its share in total emissions decreased, from 40% to 31%. In the past three decades, agriculture C management has received great attention for the potential role soils can play in mitigating atmospheric CO_2 concentration. Several climate-smart practices for agricultural C management have been advocated to help policy makers and stakeholders take appropriate land use and management decisions. Besides contributing to mitigation and adaptation, increasing soil C levels can provide additional benefits for reducing land degradation, improving crop yields and food security, optimizing nutrient cycling and water availability. This paper presents a critical assessment of the technological options for agricultural C management that can potentially contribute towards climate mitigation and sustainable agriculture.

*Corresponding author : dkbenbi@yahoo.com
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Soil carbon management

The importance of soil organic matter (SOM) in crop production and soil health is known since ancient times. It fuels soil functions and governs a range of soil physical, chemical and biological processes. Several studies, in India and elsewhere have documented the contribution of soil organic carbon (SOC) towards soil quality elucidating that soils with higher organic matter content are better in performing functions critical to crop production and environment conservation. Increased crop yields have usually been related to improved SOC pool. Over the last four decades, the focus of research on SOC has widened from crop production or yield gains through sustainable agriculture to environment moderation or climate change mitigation. Soil C sequestration is now considered among the major GHG mitigation options. The SOC stocks, representing a balance of input versus output, are spatially and temporally variable, typically constituting less than 5% by mass in the upper 30-cm soil. However, in agricultural soils of India SOC content is generally less than 1%. About 8.2 Pg C, accounting for 1.2% of the global SOC stock, is held by Indian soils. Organic C stocks are generally higher in soils under forests and perennial vegetation compared to croplands (Benbi, 2015). Soils under croplands in India hold 6.43 Gt C in the top 30 cm soil (Zomer *et al*., 2017).

Agriculture sector contributes to C emissions through i) direct and indirect energy use in the production, packaging, transport and application of inputs and manufacture of farm machinery, ii) direct use of energy in farm operations, and iii) non-energy related emissions resulting from cultivation of soil and loss of SOC as CO_2. Cultivation of native undisturbed soils leads to loss of SOC due to microbial decomposition of litter and SOM resulting in release of CO_2 to the atmosphere. Over the years, soils have lost considerable amount of carbon. The extent of loss depends on the intensity of soil disturbance, management practices, antecedent C level and climatic conditions. Globally, an estimated ~50 Gt C has been lost by land use activities during the industrial era. Cultivated soils in India have lost about 30 to 60% SOC suggesting that there is large potential for C sequestration (Benbi, 2015). The practices that can increase soil C stocks and reduce emission of GHGs include intensification of agriculture, balanced and integrated nutrient management, land use including diversified crop rotations and agroforestry systems, conservation agriculture and residue management, and application of biochar.

Intensive agriculture

Intensive agriculture aims to increase crop productivity by growing more than one crop in a year with judicious use of inputs thereby increasing resource use efficiency and plant mediated C input to soil through roots (biomass, exudates, rhizodeposits etc.) and litter fall. Punjab, an intensively cultivated original green revolution state of India with a cropping intensity of 189% offers an ideal situation for characterizing agriculture intensification effects on soil C sequestration. Some experts have hypothesized that intensification of agriculture and use of chemical fertilizers in Punjab is leading to decline in SOC status. But this is a myth and not based on scientific evidence. Temporal trends of results from long-term fertilizer experiments and soil test data for the last 40 years do not show any decline in SOC content. Rather the SOC content has improved and the number of soil samples falling in low category has decreased and that in the medium and high categories increased. In the state, SOC improved by 38% over a 25-year (1980-2005) period (Benbi and Brar, 2009; Benbi *et al*., 2006). The gains in SOC are expanded further with the continuation of the intensive agriculture. Overall, in the 40-years period (1980-2020), the SOC status of Punjab soils has improved by 86%, from an average of 2.9 g kg^{-1} in 1980 to 5.4 g kg^{-1} in 2020. This increase is equivalent to soil C sequestration of ~23 million tonnes and atmospheric CO_2 drawdown of 0.011 ppm (Benbi, 2022). Extensive improvements in SOC status from low to medium and high categories have been noticed. Results from PAU Soil Testing Laboratory (Kuldip Singh, pers. communication) reveal that the number of samples categorized as medium to high increased to 68.4% in the recent decade (2011-2021) from 22% during 1980s, and those in the low category declined to 31.6% from 78% in the corresponding period. The appreciation in SOC sequestration resulted from increased crop productivity by ~1.2 t ha^{-1} for rice and wheat and ~1.9 t ha^{-1} for maize. However, there is scope for further improvement in yields and thus potential for SOC sequestration. The average yields (t ha^{-1}) of wheat (4.87), rice (4.44) and maize (3.67) in Punjab are lower by ~1 to 3.4 t ha^{-1} compared to China. Higher crop yields due to intensification of agriculture also save GHG emissions that would have occurred because of land-use changes for meeting the food demands of the growing population.

Balanced and integrated nutrient management

Numerous studies have documented the favorable effects of balanced application of fertilizers and integrated nutrient management (INM) involving conjoint application of inorganic and organic fertilizers on SOC sequestration in Indian agro-ecosystems. Balanced application of NPK is reported to increase C sequestration by 20-600 kg ha^{-1} y^{-1} depending on soil, crop and climatic conditions. Integrated use of inorganic fertilizer at recommended rates along with organic sources such as farmyard manure (FYM), compost and green manure further improves SOC sequestration. Carbon sequestration potential of INM is estimated at 100-1200 kg C ha^{-1} y^{-1} in different agro-ecological regions of India (Benbi, 2012). The favourable effect of organic amendments on SOC is ascribed to better soil aggregation and increase in crop yields. Addition of organic amendments improves the formation of macroaggregates and C storage inside the aggregates, which is protected from decomposition. This imparts greater stability to sequestered C and reduces soil CO_2-efflux and improves Net Ecosystem Carbon Balance (NECB) transforming a cropping sequence from potential source to sink of carbon (Benbi *et al*., 2020). Balanced and INM resulting in increased crop productivity and nutrient and water use efficiency invariably lead to indirect emission reductions and climate change mitigation. For instance, each tonne of C sequestrated in the plough layer can reduce N-fertilizer application by 4.75 kg ha^{-1} (Benbi and Chand, 2007). Not only nitrogen, a strong interaction between SOC and soil P status exists suggesting that SOC can act as a surrogate for fertilizer P (Benbi and Brar, 1992). Addition of organic amendments besides influencing total SOC pool also impacts its distribution among various C pools considered to represent susceptibility to decomposition viz. active, slow and passive pools. The chemical composition of the organic source such as C/N ratio, lignin content and water soluble components influences the stabilization of SOC in different pools (Nisar and Benbi, 2020; Benbi and Khosa, 2014). Addition of relatively low C/N and high lignin content substrate such as rice straw compost leads to greater C stabilization in passive or recalcitrant pool as opposed to FYM that enriches the active SOC pool. Benbi *et al*. (2012) in an 11-year field experiment on rice-wheat system observed that addition of FYM and rice straw impacted the active pool of SOC to the greatest extent (263 to 383% increase) followed by slow pool (62 and 127 % increase) and had insignificant effect on passive or mineral associated SOC. Consequently, addition of FYM leads to higher CO_2 emissions than solitary application of NPK fertilizers suggesting that use of FYM for C sequestration is practical when its favourable effect on net primary productivity counters the additional CO_2 emissions (Benbi *et al*., 2020). Furthermore, an equitable application of organic fertilizers is required for obtaining benefits at farmers' fields similar to those obtained at research farms. To achieve intended benefits from fertilizers, there is a need to adopt soil-test balanced application of nutrients as the current fertilizer use in Punjab is highly skewed towards N with N: P: K use ratio of 27:6.9:1 compared to national average of 6.5:2.8:1.

Diversified crop rotations

Soil organic C stocks are greatly influenced by land-use and choice of cropping system. Agroforestry is considered an important option for C sequestration and poplar-based agroforestry systems in northern India are reported to have 88% higher SOC stocks than the rice-wheat system (Benbi, 2015). Enhancing rotation complexity such as changing from monoculture to continuous cropping or increasing the number of crops in a rotation and introducing legumes in the rotation are known to improve C sequestration; the effect varying with soil type, crop and management. Submerged paddy soils lead to higher C sequestration because of incomplete decomposition of organic matter under reduced conditions. It has been observed that SOC rehabilitation capacity of sugarcane is higher than maize-wheat and rice-wheat systems. The choice of crop (s) influences not only the total SOC pools but also the quality of accrued C. Maize-wheat systems are characterized by mainly active C (56-61% of SOC) as opposed to rice-wheat system wherein majority (63%) of organic C is stabilized in passive pool. Similarly, agroforestry systems are characterized by mainly labile forms of SOC suggesting that the sequestered C may be lost rapidly if the land-use is altered.

Assessment of C footprints and the global warming potential (GWP) could help in selecting an appropriate crop/cropping system for climate mitigation. Although SOC sequestration potential of submerged rice soils is higher compared to aerobic soils yet the CO_2eq emissions per kilogram of produce are higher for rice than maize, wheat and pulses (Fig. 1). The CO_2eq emissions per kg of wheat grain production are less than 1/3rd of rice. However, prohibiting rice residue burning will bring down the emissions by 50%. Relatively low GWP of maize and kharif pulses coupled with less irrigation water requirement make these crops ideal choice for diversification (Benbi, 2018). Though crop management has large potential for C sequestration but factors such as soil type, resource availability and marketing may constrain large scale changes.

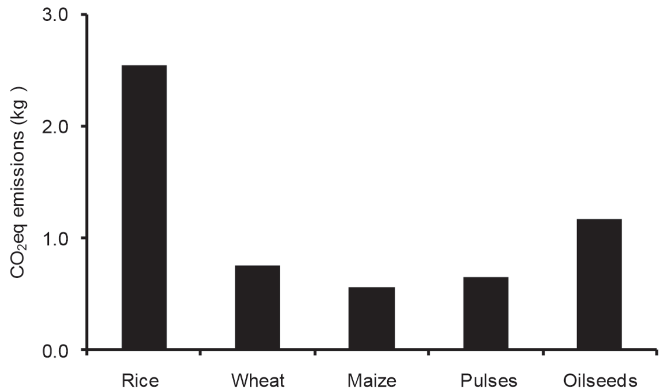

Fig.1. CO_2eq emissions per kg of produce (Source: adapted from Benbi, 2018)

Conservation agriculture and crop residue management

Carbon emissions from agricultural soils could be curtailed by adopting conservation agriculture (CA) practices involving reduced soil disturbance, maintenance of surface soil cover and adoption of appropriate crop(s). Tilling the soil disrupts aggregates and accelerates the decomposition of organic C protected therein. Croplands under no-till (NT) have been shown to increase SOC compared with more intensive tillage operations. Retention of crop residue with NT is expected to contribute to soil C sequestration, but the effect could be greater on sandy soils, while reduced tillage may be more effective than on clayey soils (Chivenge *et al.*, 2007). In an Indo-Gangetic alluvial soil, NT with surface residue in maize-wheat sequence improved SOC sequestration by 100% and crop yields by 35% and the carbon footprint by 133% compared to conventional tillage (Fig. 2; Nisar *et al*., 2021). The effect of CA depends on the duration over which the practice is continued and the rate may peak in ~10 years. Conservation agriculture also provides a viable option for crop residue management that has both direct and indirect consequences on C sequestration, crop productivity and climate moderation. In India, about 680 Tg of crop residues are produced annually, after accounting for multiple competitive uses about 180 Tg are surplus most of which are burnt *in situ*. It is estimated that incorporation of surplus crop residues can result in sequestration of 8.0 Tg C annually (Gupta *et al*., 2021). In north Indian state of Punjab, about 22 Tg of rice residue is produced out of which 80% is burnt *in situ*. On-farm management of crop residues (i.e., incorporation, mulching, and retention on the soil surface) instead of burning can lead to C accrual of 0.80 Tg C per year over an area of 3.0 m ha in Punjab, which is equivalent to about 270 kg C ha^{-1}. Still higher rates of C sequestration, up to 745 kg C ha^{-1}, can be achieved if both animal manure and rice residue are applied annually in the rice-wheat cropping sequence. However, the potential for C sequestration under NT may be overestimated, because of SOC stratification in the soil profile. *In situ* residue management also impacts the quality of SOM with greater enrichment of uncomplexed particulate organic matter pool compared to organo-mineral complexes (Benbi *et al*., 2012). On-farm management of crop residue has dual benefits of putting carbon and essential nutrients back into the soil and reducing the direct emissions of GHGs.

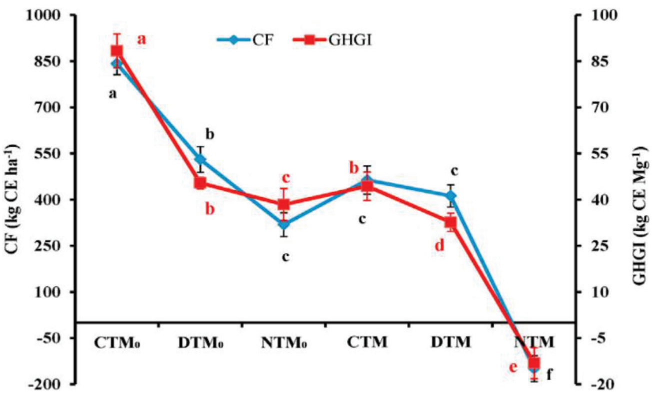

Fig. 2. Carbon footprint (CF) and greenhouse gas intensity (GHGI) of maize-wheat sequence under conventional (CT), deep (DT) and no tillage (NT) with (M) and without (M0) rice straw mulching. Line bars indicate standard error. Points labelled with different letters differ significantly ($p < 0.05$). (Source: Nisar *et al*., 2021).

Biochar application

Addition of biochar is often recommended as climate mitigation strategy and for sequestering C in soil (Lehmann *et al*., 2006; Benbi *et al*., 2021). Its functions in soil are primarily governed by nature of feed-stock and pyrolysis conditions (Sohi *et al*., 2010) besides factors such as soil fertility, soil moisture and application rate. Conversion of feedstock to biochar provides recalcitrance to the embodied C and slows its decomposition. Biochar facilitates SOC accumulation through improved C use efficiency (Fig. 3) and preferentially enriches passive SOC pool (Benbi *et al*., 2021). Mean residence time of sequestered C is higher for biochar (~2000 days) than rice straw (400 d) (Benbi and Yadav, 2015). Biochar application increases N availability through soil N priming resulting in lesser fertilizer N use and reducing GHG emissions associated with fertilizer N application. Despite presumed benefits of biochar on SOC sequestration, there is need for life cycle assessment that considers energy consumption and GHG emissions during biochar production. The economics of biochar production, development of infrastructure and availability or competitive use of feedstock (such as crop residues) in India limit its value as a C sequestration strategy. Globally, the technical mitigation potential from biochar application is estimated at 2.6 Gt CO_2-eq y^{-1}.

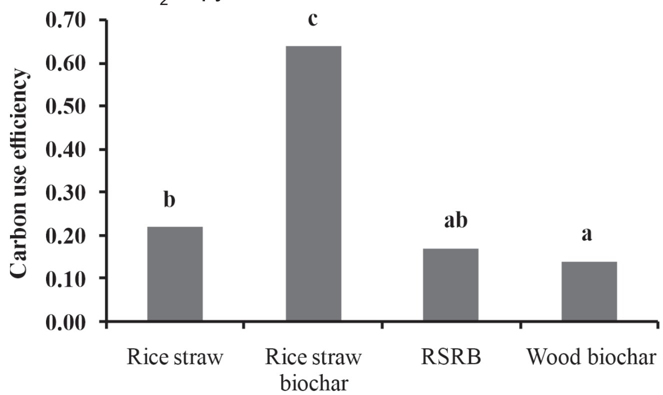

Fig. 3. Effect of rice straw, rice straw biochar, wood biochar and rice straw plus biochar (RSRB) addition on carbon use efficiency. Bars labelled with different letters differ significantly ($p<0.05$). (Source: adapted from Benbi and Brar, 2021)

Climate change and SOC turnover

Climate change influences accumulation and decomposition of SOM, directly through variation in temperature and water availability and indirectly through changes in primary productivity and root C input to the soil. Plants capture atmospheric CO_2 and convert it to organic C through photosynthesis. About 120 Gt C as CO_2–C is exchanged annually between the land and the atmosphere as gross primary productivity and about half of it is released by plant respiration yielding net primary productivity of ~60 Gt C y^{-1}. An estimated 40-50 Gt C is returned to the atmosphere annually through heterotrophic soil respiration and litter decomposition. Rates of soil CO_2 efflux are significantly related to temperature and precipitation. Increase in temperature is likely to accelerate the decomposition of SOM and release of CO_2 to the atmosphere. However, soil moisture strongly modulates the temperature sensitivity of soil respiration indicating that in sub-tropical monsoonal climates the increased soil respiration due to warming coupled with high moisture could provide a positive feedback to climate change (Benbi *et al*., 2020). Temperature sensitivity of SOM decomposition also depends on reference temperature; the response being higher at low temperatures (Benbi *et al*., 2014; Kirschbaum, 1995). The SOC loss per degree warming may increase by 8-9% in regions with temperatures of 10-15ºC and by only 2% for a soil at 35ºC (Fig. 4; Benbi *et al*., 2014). Furthermore, the composition of SOM could influence the response to temperature. Opinions differ on the relative temperature sensitivity of labile vs. stable pools of SOM to decomposition; probably because of different methods used to estimate SOM decomposition temperature sensitivity, and the inability to consistently define and quantify labile and stable SOM (Poeplau *et al*., 2018). In Indo-Gangetic alluvial soils, coarse particulate organic matter (POM), representing labile pool is found to be more sensitive to temperature than the mineral associated stable pool (Benbi *et al*., 2014). Prevalence of a range of soil, crop and climatic conditions in India underpins the importance of conducting well-designed studies to predict climate change effects on SOM turnover.

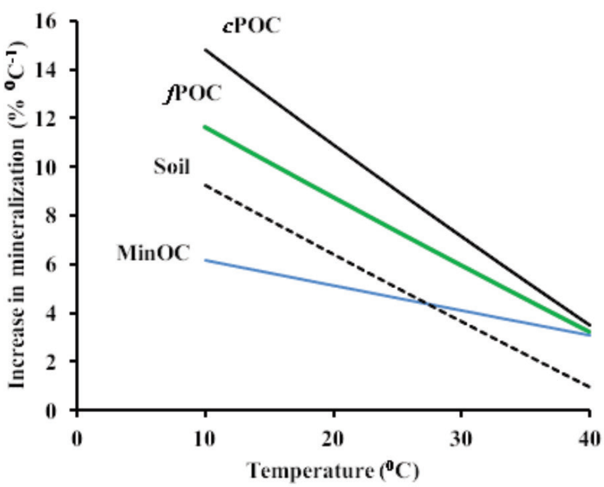

Fig. 4. Influence of one degree Celsius rise in temperature on mineralization of coarse and fine particulate organic C (*c*POC and *f*POC), mineral associated organic carbon (MinOC) and whole soil (Source: adapted from Benbi *et al*., 2014)

It is apparent that soils have considerable capacity to sequester C and mitigate atmospheric C load. However, the rate and magnitude of soil C sequestration differs with factors such as soil quality, antecedent C level, climate, land-use and management. About 18 to 37 Gt C could be sequestered in croplands globally over the next 20 years by implementing best practices for SOC sequestration (Zomer *et al*., 2017). Technical C sequestration potential of agriculture C management and biochar application ranges between 0.3-3 Gt CO_2 y^{-1}. Croplands in India have the potential to sequester ~2.08 Gt at 0.63 t C $ha^{-1}y^{-1}$. Global technical mitigation potential during 2020-2050 from agriculture, considering all gases, is ~11.2 Gt CO_2-eq. y^{-1}. Practices that increase soil C stocks and reduce emission of GHGs such as nutrient management including integration with organic amendments, crop management (diversified crop rotations, improved crop varieties, introduction of legumes in crop rotations, integrated farming systems, etc.), and conservation agriculture involving eco-friendly residue management could be viable options for mitigating the atmospheric load of CO_2 and sequestering C in the soil. However, prospect of different soil and crop management practices for C sequestration and yield gain must be carefully analyzed with respect to overall carbon footprint and sustainability of agriculture. For instance, intensification of agriculture in Punjab resulted in ~2.5 fold increase in food grain production but 3-fold increase in emission of GHGs during 1980 to 2015 (Benbi, 2018) indicating that carbon sustainability of food grain production is declining.

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