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Impact of Agricultural Practices and their Management Techniques on Soil Carbon Sequestration: A Review

Harmandeep Singh Chahal, Amanpreet Singh

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ABSTRACT

Carbon emissions through various sources possess a great threat to the environment. An increase in carbon concentration in the atmosphere resulted in increased temperature. Escalating warmness in the environment started melting of glaciers, day by day water level in oceans also increasing at an alarming rate. Forests, oceans and agricultural soils act as a sink for atmospheric carbon. Sinking sites help in making the balance of various gases in the atmosphere. Managing agricultural soils provides a good opportunity for more carbon storage. Adoption of conservation tillage, incorporation or on surface management of crop residue and balanced fertilization helps in reducing carbon removal from soil. More organic matter means more humus formation and more carbon retention in soil. Such management practices not only boost soil carbon-storing capacity but also increase soil fertility through hiking nutrient availability to plants and microbial populations in the soil. Higher plant growth results in more assimilation of CO_2 in the photosynthesis process.

Key words: Carbon sequestration, Climate, CO_2 emissions, Soil organic carbon, Soil health.

Soil organic carbon

Soil organic matter (SOM) is composed of decaying plants and animals and products formed from their decomposition. Advanced decomposition of organic material leads to the formation of material known as humus (Baveye and Wander, 2019). SOM is highly carbon enriched which directly influences soil health status. Soil organic carbon (SOC) is the chief constituent that influences the soil structure, soil nutrient availability and soil water holding capacity (Gopinath *et al*., 2009). Approximately 3170 gigatons total carbon is in terrestrial ecosystems. About 2500 GT from it which constitute 80% carbon is present in soil (Lal, 2008). Carbon is present in soil either organic or inorganic form. Elemental carbon and carbonate materials are the same kind as calcite and dolomite *etc*. makeup inorganic carbon (Lal, 2004). Carbon amounts in organic form constitutes comparatively less relative to inorganic one. The concentration of carbon is 3.1 times larger than its presence in the atmosphere (Oelkers and Cole, 2008).

Soil carbon and climate change

An increase in the concentration of greenhouse gases (GHGs) are chief agents liable for global warming (WMO, 2006). Change in climate is possessing severe threats to life on earth. Carbon dioxide (CO_2) is the main gas accounts for 63 percent of total GHGs emission as a result of tremendous increment from the preindustrial era to today. In addition to it, methane (24%) significantly affects climate (IPCC, 2014) leading to an increase in temperature and melting of glaciers. Furthermore, CO_2 has about 100 years of residence time (Cawley, 2011). The total emission of CO_2 was increased from 14.1 Gt in 1971 to 29.0 GT in 2007 (IEA, 2009). Burning of fossil fuels, clearing of forests and the cultivation of field for agricultural production accounts for 2/3rd of the total increase in atmospheric CO_2 (Lal, 2004).

Department of Agriculture, Khalsa College, Amritsar-143 001, Punjab, India.

Corresponding Author: Amanpreet Singh, Department of Agriculture, Khalsa College, Amritsar-143 001, Punjab, India.
Email: nandgharia@gmail.com

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Carbon sequestration

Carbon sequestration is the process which involves conversion of atmospheric carbon dioxide (CO_2) into balanced carbon pools. The role of soil getting attention in carbon sequestration as it has a great potential of lowering the concentration of atmospheric carbon dioxide (CO_2) through the sequestration of carbon in the soil. Globally, in the upper layer of soil profile (1meter), the soil accumulates a large carbon concentration which is approximately 1500 GT (Jobbágy and Jackson, 2000; Guo and Gifford, 2002). This is much higher than the atmospheric CO_2 (Lal, 2008). In this way, the soil is preventing a build-up of atmospheric carbon dioxide. The process of carbon sequestration can be controlled naturally means or anthropogenically. Most common types of sequestration are abiotic and biotic. Injection of CO_2 into deep oceans, geological strata, old coal mines and oil wells involve abiotic means of sequestration. On the other hand, the biotic component involves the assimilation of CO_2 by higher plants and micro-organisms. Biotic sequestration is further subdivided into oceanic and terrestrial sequestration (Kambale and Tripathi, 2010). Sequestration in oceans involves carbon utilization for photosynthetic activities by phytoplankton.

Table 1: Countries having high CO_2 emissions (UCSUSA, 2019).

Rank	Countries	CO_2 Emissions
1	China	9056.8 MT
2	United States	4833.1 MT
3	India	2076.8 MT
4	Russian Federation	1438.6 MT
5	Japan	1147.1 MT
6	Germany	731.6 MT
7	South Korea	589.2 MT
8	Iran	563.4 MT
9	Canada	540.8 MT
10	Saudi Arabia	527.2 MT
11	Indonesia	454.9 MT
12	Mexico	445.5 MT
13	Brazil	416.7 MT
14	South Africa	414.4 MT
15	Australia	392.4 MT
16	United Kingdom	371.1 MT
17	Turkey	338.8 MT
18	Italy	325.7 MT
19	Poland	293.1 MT
20	France	292.9 MT

Influence of soil microorganisms on soil carbon sequestration

Soil organisms often act as a huge biomass in soils, having a great impact on soil organic matter fate (Chevallier *et al*., 2001). Microorganisms play a pivotal role in the ecosystem functions through various type of functioning. Soil microorganisms help in mineralization of soil nutrients as well as increasing soil organic carbon storage (Van der Heijden *et al*., 2008). Furthermore, microorganisms utilize labile compounds in soil and stabilized them as microbial residues in various complexes of organo-mineral compounds (Haddix *et al*., 2016). This carbon use efficiency varies depending on the nutrient availability necessary for microbial metabolism and microorganism (Lashermes *et al*., 2016). Moreover, climatic and atmospheric conditions also make carbon use efficiency to change (Sistla *et al*., 2014). Bacteria also play a major role in carbohydrate degradation that directly influences the fate of soil organic carbon (Martiny *et al*., 2017). Microorganism like saprophytic fungi producing oxidative enzymes helps in decomposition of lingo-cellulose *i.e.,* carbon substrate (Berg and Laskowski, 2006). Fungi is one of the main microbes that decay litter in which cell wall lignin is completely mineralized to CO_2 (Eisenlord *et al*., 2013). Higher fungal activity in soils can be attributed to a longer retention of carbon retention (Malik *et al*., 2016).

Carbon stock under different biomes

Soil carbon stocks vary ecosystem to ecosystem. Boreal ecosystems are a particular concern. A large amount of the soil organic carbon stored in permafrost and wetlands as melting on a huge scale will release a higher amount of carbon. Lower layers of permafrost soils accumulate huge stocks for long periods that leading to the large carbon stocks stored there. Carbon from tropical forests indicate a direct loss in biomass of 1.4 Pg C yr^{-1} over 2000-2008 (Houghton, 2003) deforestation of it also cause C emissions (Pongratz *et al*., 2009). Agricultural practice also affected the fate of soil carbon in newly deforested areas as they are developed into croplands. It is evident that, from the last two to three decades intensive cropping will quickly devoid the soil from carbon (C) pools (Reeves *et al*., 1997). Sustainable pasture management may stabilize them to a sufficiently sequester the carbon (Trumbore *et al*., 1995). Grassland management primarily affects SOC storage by modifying C inputs to the soil that including plants tissue turnover, C allocation between roots and shoots (Schuman *et al*. 2002). In the following data (Fig 1) C stocks in different world biomes are described, thus we can examine the effects of land-use changes on soil C pools.

Carbon pool in different soil orders

Generally, Histosols are still under forests, but the deforested area used for agriculture is being under Andisols, Oxisols and Ultisols, this the main reason for their low concentrations of carbon. The primary mechanism for carbon sorption onto clays or colloids is through pH-dependent and ion exchange (Bronner and Goss, 2011). Andisols that form from minerals with little orderly crystalline structure can result in a higher capacity to store organic C in soil. Histosols are soils that are dominantly organic without perma-frost and mainly form from decomposed plant tissues (Bockheim and Hartemink, 2017). Consequently, the higher pH of Mollisols implies that there are both fewer sites on mineral surfaces available for the sorption of carbon. On the other hand, Ultisols have low pH implies that the most of charge on minerals surfaces enhances the sorption of carbon. Ultisols are conducive to the sorption of carbon with less regard for its characteristics, while Mollisols and Alfisols sorb only the portions of carbon (Kaiser *et al*., 2012).

Carbon stock in agricultural soils

The development of forest lands into agricultural land has resulted in the reduction of SOC levels, resulting in a release

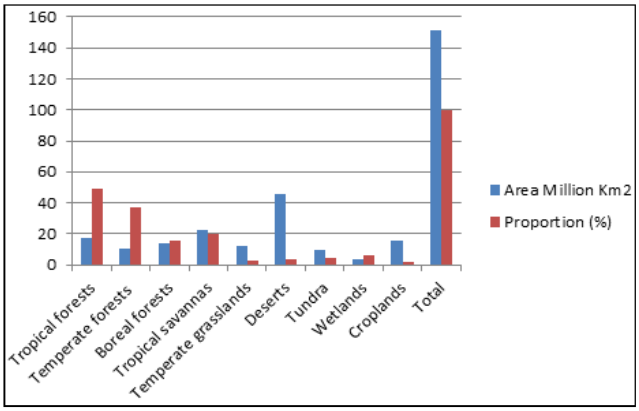


Fig 1: Carbon pool of different biomes across the world (Eswaran *et al*., 1993).

of 50 to 100 GT carbon from that soil into the atmosphere (Lal, 2008). Depletion in the amount of SOM and aggregate stability due to increased soil tillage and increased soil erosion are reasons behind soil carbon loss (Lemus and Lal, 2005). The depletion of SOC stocks has developed a soil carbon deficit that represents a chance to increase organic carbon stock through different land management practices. Soil properties, climatic conditions and land use are the factors that affect extent of SOC stocks across the world. Loss of organic carbon in soil under agricultural fields is not the same throughout the globe; minor escalations are observed when the soil of naturally low fertility is improved by proper management (Lal, 2004).

Carbon sequestration in different croplands

Carbon sequestration in rice cropping system

In submerged soils, the formation of recalcitrant complexes with organic matter makes them less available for microbial attack. Also, the biological fixation of nitrogen, the increase in overall primary productivity and the decrease in humification lead to a net accumulation of organic matter in the soils and sediments of wetlands. Cultivation of crops such as rice which include practice of alternate wetting and drying of soil can influence iron transformation in soil (Sahrawat, 2004). In dry soil, the iron species (Fe^{2+}) undergo oxidation and the iron species undergo a reduction (Fe^{3+}) in wet soils. So, iron cycle has the potential to limit both carbon oxidation and methane release (by acting as an underground oxidizing agent and a competing electron acceptor in microbial respiration). Net retention of organic matter and plant debris can be observed in most wetlands (Mitsch and Gosselink, 2007). Consequently, a long period of immersion in the soil favors the formation of passive SOC deposits against carbon sequestration (Majumder *et al*., 2008). On the contrary, the formation of humic compounds is maximized under conditions of partial oxidation: if there is too much oxygen, complete mineralization occurs; if there are too few, the oxidative polymerization is suppressed. Frequent wetting and drying cycles prevent stagnation that occurs under oxidative or reducing conditions and promotes the oxidative polymerization reaction that stabilizes carbon (Post *et al.*, 2004).

Carbon sequestration in agroforestry

The agroforestry system is land use system which involves integration of trees, crops and livestock on same piece of land. Trees capture and store carbon when respiration rates drop and increase rapidly, exploring the benefits of a favourable temperature at the start of growth (Rotenberg and Yakir, 2010). Root penetration to forest trees and perennial crops in deeper soil horizons result in build up of soil organic carbon lower horizons far from the tillage depth (Lorenz and Lal, 2014). Residue from trees and crops on land surface acts as a mulch and covers the land surface of the cultivated field which decomposes over time and increases soil carbon. Besides, crop residue on soil surface reduces wind speed and soil runoff that also affects soil carbon dynamics. In a study conducted on carbon stocks under different land system, results showed that the maximum total biomass, total carbon stock and potential for total carbon sequestration comprised of 1311.82 t ha^{-1}, 654.91 t ha^{-1} 130.98 t C $ha^{-1}yr^{-1}$, respectively were observed in the mono-cropping of *tereti cornis*. Similarly, under *P. deltoids* cultivation along with *T. grandis*, total biomass (210.29 t ha^{-1}), total carbon stock (109.11 t ha^{-1}) and potential for total carbon sequestration (21.83 t C ha^{-1} yr^{-1}) were observed and lowest carbon stock was recorded under the land use system based on pure agriculture (Rice-wheat cropping system) in Punjab (Sarangle *et al*., 2018).

Carbon sequestration in grasslands land use system

Globally, the grasslands cover 3460 Mha area (Lal, 2004). Based on potential of grasslands to sequester carbon, they are divided into three categories. First, there are Natural meadows is one of them. Basically, they are not protected and are not subject to agricultural use and therefore are well stable in their natural state. Next one is degraded grasslands and these grasslands are poorly managed and such types of grassland are not easily improved in short phase. Last and third include such grasslands that have feasibility of improvement. There are many possibilities to improve the storage of SOCs and SICs from degraded grasslands by restoring and implementing sustainable approaches to soil conservation. The transformation of marginal cultivated land into more livestock pastures area also possesses potential to store more carbon. Grassland ecosystem shares more than 10% carbon pools of the total C stocks under all type of vegetation areas worldwide (Nosberger *et al*., 2000). Hence grassland ecosystem making the soil the largest C store in the C land basin (Jones and Donnelly, 2004). Management of grassland areas basically affects C sequestration through roots decomposition and their exudates (Schuman *et al*., 2002). In most grassland ecosystems, approximately 75 to 80% of the biomass the augmenting root remains in the upper layer of the soil profile (30 cm), but the proper evaluation of carbon movement from different sources is difficult because growth of roots and their decomposition rate varies according to vegetation type and weather conditions prevailing in that area.

Management techniques for improving the soil carbon stock

Several agricultural management practices help to increase the sequestration of carbon by increasing carbon inputs to the soil and enhancing various soil processes that protect the carbon from microbial mineralization. An increase in soil carbon leads to improvements in soil structure and fertility. Soil organic carbon stock can be increased by proper adoption of tillage operation, retention of crop residues and through proper nutrient management (Cooperman, 2016).

Agricultural practices

Adoption of proper tillage practices

Tillage is done to mechanically manipulate the soil. Various

types of benefits are related with the tillage practices. Tillage helps in loosening of top soil that better aeration in soil which facilitates good seedbed preparation. Apart from it, the incorporation of crop residues into the soil as well as mechanical destruction of weeds is done by the practice of tillage. However, conventional tillage is practiced on a large scale that results in compact soil below the tillage depth which forms a hardpan. Similarly, tilled soils are highly prone to water and wind erosion. Mechanical operations costs are also very high required to manipulate compact soils (Lal *et al.*, 2007). In conventionally tilled soils, depletion of carbon pools were estimated as high as 75% of the carbon stock in the native lands (Lal *et al*., 2007). In recent years, the promotion of conservation tillage and zero tillage helps to reduce some of these negative impacts of traditional tillage (conservation tillage) on soil physical properties and to preserve organic carbon. Conservation and zero tillage aim at maintaining plant residues on the surface thereby increasing carbon stock especially in the upper layer of soil (Kern and Johnson, 1993). Adoption of conservation tillage reduces energy consumption and C emissions (Holland, 2004), whilst also reducing labor requirements (Davies and Finney, 2002). Apart from its practices like zero tillage results in a significant reduction in yield (Pittelkow *et al.*, 2015). Moreover, higher nitrogen loss can occur with reduced-tillage due to denser soil conditions, which may eventually offset positive effects on SOC balances (Basche, 2014).

Crop residue management

Adoption of intensive agriculture in irrigated cropping systems leads to production of huge quantity of crop leftover (Sharma and Bhusan, 2001). In South and Southeast Asia, crop residues are burnt or removed after crop harvest to tackle insects, pests and diseases problem transmitted through crop residues (Bijay-Singh *et al.*, 2002). In Punjab and Haryana, where about 90 and 45%, respectively area is under rice cultivation, removal of crop residues from fields is done by stubble burning, which is the easiest and the cheapest way. In these states, over 80% of the rice straw and nearly 50% of the wheat straw are burnt after crop harvest (Katyal *et al.*, 2001). However, crop residue burning leads to reduced SOC content and microbial population. Retention of crop residues in a field after crop harvest and its proper incorporation increase the availability of plant nutrients and SOC and thereby maintain or improve soil fertility status (Singh and Rengel, 2007). Crop residue is a primary substrate for SOC (Havlin *et al*., 1990). Benefit of sequestering SOC by adding crop residues have been well documented by Aulakh *et al*. (2001) also in the temperate regions.

Balanced use of inorganic and organic fertilizers

The availability of nutrients is essential for the retention of SOC (Himes, 1998). Studies clearly showed that the combined use of chemical fertilizers along with organic manures were more beneficial as compared to their alone application for the build-up of organic carbon in soil. Balanced nutrient application helps in better decomposition and microbial immobilization as well as mineralization possesses probable higher root biomass (Nayak *et al*., 2009). Many long-term fertilizer trials across the world have reported that integrated nutrient management can improve the soil fertility and ultimately crop yields and biomass production that can be returned to the soil as a required organic carbon in soil (Holeplass *et al.*, 2004). Dersch and Bo hm (2001) reported that combined use of NPK fertilizers with FYM enhanced the soil carbon stock to approximately 5.6 Mg ha^{-1} after 21 years and that was quite sufficient. Jiang *et al*. (2006) also reported that the continuous application NPK chemical fertilizers combined with FYM increased carbon 10% over a study of 20 years. Similarly, Meng *et al*. (2005) after 13 years trial also described that the combined application of NPK fertilizers along with organic manure significantly increased SOC. Application of organic manures increases soil aggregation, as a result more availability of nutrients increased soil carbon as compared to unfertilized plots (Campbell *et al.*, 2001). Whalen *et al.* (2003) found that carbon content was increased with the application of composted manure for 2 years in conventional and no-tillage systems. It also led to more water-stable macro-aggregates (>2 mm). Soil aggregate stability significantly correlated with SOC, because of the binding action of humic substances and other microbial by-products (Goh, 2004). The beneficial effects of phosphorous fertilizer application by rock phosphate (RP) were less than that of SSP. Oxidizable potassium permanganate ($KMnO_4$-C) had the largest labile reserve of organic C in the soil and represented 13.6% of the total organic carbon. The Carbon Management Index (MIC) has improved with FYM and fertilizer applications which indicate the favourable impact of these treatments on the stabilization of C in the soil. The combined application of FYM and RP improved the soil organic C reserves to a greater extent than their application, suggesting the need for an integrated use of FYM and RP in these alluvial soils (Prakash *et al*., 2016).

The granulation of inorganic fertilizers with organic matter is becoming more and more popular because of its potential benefits on crop yields and soil health compared to the application of organic matter or inorganic fertilizer as the sole source of nutrients (Mazeika *et al*., 2016).

Carbon mineralization

The percentage of carbon oxidized as a result of decomposition of incorporated residues is presented in the figure below and it was found maximum with rice residue (32.8%) followed by wheat (27.7%), sesamum (26.0%), niger (20.0%), toria (19.8%), buckwheat (17.9%) and horse gram (16.8%) residues. Hence the mineralization of organic residues in soils treated with horse gram residue was low (16.8% of carbon) as compared to other organic residues. This indicates that the superiority of the horse gram residues to other sources of organic residues in respect of building up of organic carbon status of the soil (Sarma *et al*., 2013).

Carbon density and carbon sequestration

Carbon density was higher in all crop residues incorporated plots than control. Incorporation of horse gram residue recorded maximum carbon density (1210 g m^{-2}) as a result there was a higher amount of carbon sequestered 1057 g m^{-2} over control followed by buckwheat residues. Of course, carbon sequestration is a long-term process. The incorporation of crop residues within two years can show the trend of carbon sequestration in cultivated soil. Horse gram residues increased carbon density by 31.2% over control followed by buckwheat (22.8%). This suggests that the addition of crop residues by incorporating in soil has a positive effect on the maintenance of organic matter in the soil. It can be inferred due to building up of a higher amount of soil organic matter. Sarma *et al*. (2013) reported that crop residues could add a significant amount of carbon because crop residues have a higher C: N ratio and carbon.

Impact of conservation agriculture and resource conservation technologies on carbon sequestration

Effectiveness of conservation agricultural system in terms of soil organic carbon (SOC) sequestration has described by Franzluebbers (2008). In all three scenarios, SOC sequestration under conservation agriculture was 0.15 Mg C ha^{-1} yr^{-1}. However, compared to the conventional system, the SOC sequestration rate increased to 0.25 Mg C ha^{-1} yr^{-1} in Scenario A due to the declined rate of SOC by 0.10 Mg C ha^{-1} yr^{-1} under conventional agricultural practices following degradation from a previously elevated condition. In Scenario B (the most often presumed condition), SOC sequestration was the same under conservation agriculture as that observed without comparison with conventional agriculture because soil organic C under conventional agriculture was at a steady-state condition. In Scenario C, SOC sequestration was improved under conventional agriculture by other practices similar to that under conservation agriculture.

Future challenges regarding soil carbon sequestration

Many challenges are in way prediction in SOC change about atmospheric CO_2, climate change and land use management. Several studies described that the incorporation of fresh organic matter to the soil can increase carbon mineralization in soil (Fontaine *et al*., 2007). This process provides a negative view toward the application of carbon inputs and in some studies proved good for increasing carbon stock in long term applications (Heimann and Reichstein, 2008). Several studies observed that most soil carbon sequestration is related to the chemical make-up of mineral (Mikutta *et al.*, 2006) and that mineral types have a major impact soil organic carbon pools (Torn *et al*., 1997). So, well depth study regarding the interaction of minerals with carbon sorption is much in need. Minerals composition directly influences the clay content. Minerals with higher surface area led to higher amount of organic molecules that can be adsorbed on their surfaces and protected from microbial decomposition. Kleber *et al.* (2007) reported that surface reactivity also affects the sorption of organic molecules. So, it may be necessary to deeply study soil mineralogy. Apart from it, the effects of agricultural practices on soil carbon fate are not well understood. Recent studies showed that the effect of no-till adoption does not increase carbon stock but only affects its distribution within the soil profile (Baker *et al.*, 2007). An underestimated effect of tillage of previously untilled soils induces carbon losses (Gottschalk *et al.*, 2010).

CONCLUSION

From the above review, it is evident that CO_2 emissions are increasing highly in the present age. A higher level of carbon dioxide concentration in the atmosphere result in ecological imbalance. Deforestation and intensive agriculture cultivation practices reduces the potential of soils to store carbon. There is a need for adoption of conservational agriculture that focuses on crop residue management, zero tillage and use of organic fertilizers as a source of nutrients that increases soil carbon storage capacity. By storing carbon in the soil, not only the concentration of atmospheric carbon reduces but also increases soil fertility.

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