REVIEW ARTICLE

SOIL ORGANIC CARBON DYNAMICS IN RELATION TO DIFFERENT LAND USES

Rakesh Kumar* and P.S. Sangwan

Department of Soil Science, CCS Haryana Agricultural University, Hisar-125 004
Email: rakeshsheoran143@gmail.com

Received-30.09.2019, Revised-20.10.2019

Abstract: Maintenance of organic carbon in soil (SOC) is critically important for sustained agricultural productivity and environmental quality. This review paper presents SOC dynamics resulting from different land uses. Global warming is a threat issue for whole of world. CO_2 emission from land use is a major factor responsible for climatic change. Enhancing soil carbon sequestration in agricultural land is a strategy of vital importance to decelerate the observed climate changes. However, soil physical disturbances have aggravated the soil degradation process by accelerating erosion. Thus, reducing the magnitude and intensity of soil physical disturbance through appropriate farming/agricultural systems is essential to manage soil carbon sink capacity of agricultural lands**.** Land use changes in the tropics are responsible for more greenhouse gas emissions. The dominant type of land use change is the conversion of forest to agricultural systems that promote CO_2 concentration in atmosphere. Soil organic carbon has been recorded abundantly in agroforestry systems than other land use systems.

Keywords: Soil carbon sequestration, Soil degradation, Carbon sink, Agroforestry

INTRODUCTION

More than 50% of the global annual carbon (C) emission (about 11 Gt) is absorbed by natural sinks (land and ocean); therefore, the annual uptake by the atmosphere ranges between 4 and 5 Gt C year^{-1} for the decade ending in 2015. Hence, it is important to develop strategies that increase the C sink capacity of the natural sinks, especially those in the terrestrial biosphere so as to reduce the net uptake of CO_2 by the atmosphere (Lal, 2008). The SOC as well as its potential to become managed sink for atmospheric CO_2 has been a priority research area since the beginning of the 21st century (Lal, 2004; Sainju, 2006; Saha *et al*., 2011) because of its multiple benefits including the positive effects on soil physical, chemical, and biological properties (Carter, 1996; Lal, 2004). Therefore, *in-situ* SOC conservation should be prioritized in any management system to harness the soil C sink capacity. Conservation tillage, comprising a wide range of practices, is widely promoted as the best agricultural management practice to reduce soil erosion and maintain high SOC content (Lenka and Lal, 2013). The no-till (NT) practices have the potential to sequester SOC ranging from 0.3 to 0.4 Mg C ha^{-1} year^{-1} in European agricultural land (Freibauer *et al.*, 2004).

Agroforestry system has a great scope in sequestering the above-ground and below-ground soil carbon and helps in mitigating the green house effect by reducing carbon emissions (Albrecht and Kandji 2003). Carbon can be sequestered in the mineral soil after the conversion of intensively cropped agricultural fields to more extensive land uses such as afforested ecosystems. Understanding the agroforestry systems that involve greater diversity and complexity has become a research interest worldwide posing fundamental questions like carbon sequestration (Puri and Nair, 2004). Soil organic carbon sequestration helps to restore the environment. Promoting soil carbon sequestration in agricultural land is one of the viable strategies to decelerate the observed climate changes. However, soil physical disturbances have aggravated the soil degradation process by accelerating erosion. Thus, reducing the magnitude and intensity of soil physical disturbance through appropriate farming/agricultural systems is essential to manage soil carbon sink capacity of agricultural lands**.** Land use changes in the tropics are responsible for 12–20% of the human-induced greenhouse gas emissions. The dominant type of land use change is the conversion of forest to agricultural systems with continuously high rates of 13 million hectare being deforested per year (FAO, 2005). Yimer *et al.* (2007) compared crop lands, forest lands, and grazing lands and found that soil organic carbon decreased in crop lands as compared to forest lands.

The SOC and its fractions are good indicators of soil quality and environmental stability. Among the factors affecting SOC pool land use changes and soil erosion are factors of importance. The difference in SOC and its fractions among different land uses can help to understand the process of soil carbon dynamics. A loss of SOC due to inappropriate land use can cause a decline in soil quality and potentially lead to emission of C into the atmosphere (Lal, 2002). On the other hand, appropriate land use and soil management (Banger *et al.*, 2009) can lead to an increase in SOC, improve soil quality and partially mitigate the rise of atmospheric CO2 (Lal and Bruce, 1999; Lal and Kimble, 1997). Considering all above

*Corresponding Author

aspects, we tried to review the impacts of different land use systems on SOC dynamics.

Effect of land use on SOC

Saha *et al.* (2011) conducted a study in Typic Ustochrepts of Northwest India to understand the impact of forest, grassland, agricultural and eroded lands on SOC stocks. The SOC in surface soil layer of grasslands was significantly higher (about 7 times) than in eroded lands. It significantly decreased by 27% in forest and 45% in agricultural lands (Table 1). However, the forest lands had significantly higher SOC in 15–30 cm soil layer than in other land uses. In general there was a decrease in SOC concentration at 15– 30 cm soil layer for all the land uses except in eroded soils which showed an improvement in carbon status with increasing soil depth. The depth-wise distribution of SOC under different land uses (Fig. 1) shows highest amount in the surface layers (up to 20 cm) in grasslands followed by forest, agricultural and lowest in eroded land. On the contrary in the lower layers (20-100 cm) the SOC was highest in forest land followed by eroded land. It was almost similar in agricultural and grassland soils particularly after 50 cm depth. The higher SOC concentration in pastures is attributed to the chemical stabilization of organic C in the soil matrix (Percival *et al.,* 2000). The lowest amount of SOC in surface layer of eroded lands could be due to its mobilization along with sediments in the runoff water (Jacinthe *et al.,* 2004). The deeper root biomass of trees in forest land might have increased the SOC accumulation in the subsurface layers. Kaiser *et al.* (2002) observed that forest subsoil has about 45% of total SOC of the profile. In fact, the confinement of SOC in the forest subsoil is essential for long term storage of carbon due to reduced biological decomposition. The higher SOC and SOC stock in subsoil of eroded land than agricultural and grasslands could be due to the previously existing trees in the eroded lands (Brown, 2002), which vanished due to deforestation, but the root biomass of these trees could have added to the SOC stock in the lower layers.

A field experiment on agroforestry in relation to tree age was carried out by Gupta *et al.* (2009) in pre-planted agro-forestry sites at farmer’s field. The agroforestry system consisted of poplar (*Populus deltoides* Bartr.) trees with wheat (*Triticum aestivum*) during winters and green gram (*Vigna radiata*) during summers. The carbon sequestration rates (CSR) were computed after 1, 3 and 6 years of poplar plantation. The CSR due to the poplar plantation in 0–30 cm soil profile was 6.07 Mg ha^{-1} $year^{-1}$ in 1-year plantation, which decreased to 2.63 Mg ha^{-1} $year^{-1}$ in 3-year plantation and 1.95 Mg ha^{-1} $year^{-1}$ in 6-year plantation. The CSR was higher in surface (0–15 cm) than in subsurface (15–30 cm) soils. This indicates that the CSR was higher during the first year of poplar plantation and it decreased with increase in tree age. This was in contrary to the rate of litter fall which increases with tree age. However, the lower CSR with increasing tree age could be due to the fact that the decomposition time of the organic residues increases sufficiently thereby decreasing the CSR. This may be true in this case as the soil is ploughed intensively (3–4 ploughings) for preparing a fine seed bed for wheat sowing and more disturbance of soil means higher decomposition rate of organic residues.

Amanuel *et al.* (2018) investigated the variation of SOC in four land cover types: natural and mixed forest, cultivated land, Eucalyptus plantation and open bush land in the Birr watershed of the upper Blue Nile river basin. The results showed that overall mean SOC stock was significantly higher under natural and mixed forest land use compared with other land use types and at all depths which was 36.14, 28.36, and 27.63% higher than in cultivated land, open bush land, and Eucalyptus plantation, respectively. This could be due to greater inputs of vegetation and reduced decomposition of organic matter. On the other hand, the lowest soil organic carbon stock under cultivated land could be due to reduced inputs of organic matter and frequent tillage which encouraged oxidation of organic matter. The SOC concentration was influenced by soil depth and showed decreasing trend with depth. The lower SOC concentration found in the deeper layer could be related to the reduced amount of the external inputs in to the soil. This is consistent with Alemayehu *et al.* (2010) who reported animal wastes and inorganic fertilizers temporarily remain in the top surface soil rather than going deeper.

Ali *et al.* (2017) carried out a study to evaluate the soil organic carbon stock (SOCS) dynamic across three land uses *viz.* pasture, forest, and adjacently located arable land at different altitude (ranging from 2100–4163 m). Soil under forest had significantly higher values of SOCS than pasture and arable land. Similarly, SOCS increased with increasing altitude and decreased with soil depth in all land uses. The intensive land uses such as continuous ploughing and cultivation accelerated the rate of organic matter decomposition and mineralization. Further, the removal of biomass during harvesting and periodic tillage breaks up macro aggregates, resulting in increased soil erosion and runoff. Other researchers also reported that cultivation can reduce SOC (Billings, 2006; Wang *et al.,* 2008), and can change the balance between humification and mineralization processes (Saviozzi *et al.,* 2001). Likewise, tillage changes the soil moisture, aeration, and nutrient concentrations, resulting in increased oxidation of soil organic matter (Lal, 1995; Pandey *et al.,* 2010) and the loss via soil microorganisms (Reicosky & Forcella, 1998); this can in turn reduce the inputs of organic matter from above and below-ground vegetation (Zhao *et al.,* 2005; Yimer *et al.,* 2006). In contrast, the higher SOC in the forest could be due to the greater biomass input by vegetative material, which is the main source of soil organic carbon.

Organic matter generally has a positive relationship with plant density (Rees *et al.,* 2005; Thomas *et al.,* 2007). Forests store more C than any other terrestrial ecosystems and represent a significant carbon pool for the global carbon budget (Houghton, 2007). Overall result indicated that the land use intensification and climate change (increase in temperature and decrease in precipitation) were associated with declining SOCS. These results suggest restoration of degraded agricultural land to the forest, especially at higher altitude, and decrease in intensity of land use could increase SOCS in the study area.

A study by Zhao *et al.* (2017) compared SOC stocks and their vertical distributions among three types of ecosystems: Grassland, forest, and cropland that coexist in the agro-pastoral ecotone of Inner Mongolia, China. The results indicate that grassland had the largest SOC stock, which was 1.5 and 1.8-folds more than stocks in forest and cropland, respectively. Grassland that stored more SOC than forest is consistent with the findings of Wei *et al*. (2012). The higher SOC stock in the grassland compared to the forest is likely ascribed to: (1) low forest stand density leading to less carbon input into the soil from litter; (2) plantations being mainly established on abandoned farmland, which had low SOC stock due to frequent tillage – restoring SOC takes several years to decades. Relative to the stock in 0–100 cm depth, grassland held more than 40% of its SOC stock in the upper 20 cm soil layer; forest and cropland both held over 30% of their respective SOC stocks in the upper 20 cm soil layer.

A study was conducted to assess the impact of different land use systems on soil organic carbon stocks in the foothill Himalayas. Soil samples were collected from four different land use systems viz. agriculture, forest, horticulture and degraded lands. With respect to the overall SOC content, forest and horticultural soils were leading. Agricultural and degraded lands had relatively lower SOC and were statistically at par with each other. Agricultural disturbances, like tillage, crop residue removal and enhanced erosion due to these activities could be a major source of C losses from the soil, pitting the agricultural soils at par with degraded lands. Agricultural and degraded lands had up to 12.4 Mg ha^{-1} SOC stocks lower than forest soils, indicating that deforestation or conversion of forest land to agricultural uses are contributing to losses of up to 25% over time from the top half a meter layer of soil (Sharma *et al.,* 2014).

Long-term history of tillage and cropping mediated disturbed and undisturbed soils effect on soil organic carbon (SOC) was investigated by Singh *et al.* (2016) in Indo-Gangetic plain region. In this study, shallow soils were collected from 50-year-old monoculture treatments of undisturbed (*Dendrocalamus calostachyus*, *Mangifera indica* and *Saccharum munja* Roxb.) and disturbed (*Oryza sativa* cultivated field) land use. Results showed that the SOC was significantly lower in soils of *O. sativa* treatment with respect to undisturbed treatments. This might be due to reason that tillage breaks the soil aggregates and in turn modify the soil environment (high O_2 supply) and enhance microbial accessibility to physically protected SOC, followed by rapid decomposition of SOC. It has been reported a common phenomenon in tilled field irrespective to climate (Gispert *et al.,* 2013; Plaza *et al.,* 2013). In the case of undisturbed treatments, the SOC was specifically greater in soils of *D. calostachyus* treatment compared with *S.munja* and *M. indica*. Higher SOC in present as well as in previous studies in soils beneath the bamboo community might be observed due to higher input of organic material (foliage and root) and also due to their poor mineralization by microbes. Previous studies documented that bamboo is a good silica accumulator (referred as phytoliths or plant stone) (Drees *et al.,* 1989; Parr *et al.,* 2010), which likely provides resistance against microbial mineralization. In fact, the low microbial activity in *D. calostachyus* treatment compared with other undisturbed *M. indica* and *S. munja* treatments in the study is strongly supporting this view.

After a 4 years investigation, Adhikari *et al.* (2017) revealed that SOC stock in surface soil was statistically higher on mulch, no-tillage applied plots than on conventional plots. Improved moisture retention due to soil aggregation and reduced rate of oxidation might have contributed more to higher SOC in mulch, no-tillage applied plots.

Nath and Lal (2017) selected four sites of different land use types/tillage practices, i) no-till (NT) corn *(Zea mays* L.) (NTC), ii) conventional till (CT) corn (CTC), iii) pastureland (PL), and iv) native forest (NF), at the North Appalachian Experimental Watershed Station, Ohio, USA to assess the impact of NT farming on soil organic carbon contents. The NTC plots received cow manure additions (about 15 t ha^{-1}) every other year. The CTC plots involved disking and chisel ploughing and liquid fertilizer application (110 L ha^{-1}). Macroaggregates contained 6%–42% higher organic carbon than microaggregates in soil for all sites. Macroaggregates have high TOC contents because the organic matter binds microaggregates into macroaggregates (Elliott, 1986), following the hierarchy model (Six *et al.,* 2000). Macroaggregates in soil for NTC contained 40% more organic carbon over microaggregates in soil for CTC. Therefore, a higher proportion of microaggregates with lower organic carbon contents created a carbon-depleted environment for CTC. In contrast, soil for NTC had more aggregation and contained higher organic carbon content. The SOC among the different sites followed the trend of NF > PL > NTC > CTC, being 35%–46% more for NTC over CTC Similar trends of higher SOC and aggregation with elimination of tillage have been widely reported (Blanco-Canqui and Lal, 2004; G´elaw *et al*., 2013). Retention of crop residues and detritus material as much as that for NTC, NF, and PL enhanced SOC content in the surface soil, created habitats for soil meso- and microfauna and -flora, and enhanced soil aggregate stability. Application of cow manure might have increased SOC content for NTC in comparison to CTC. High SOC for NTC were due to higher amounts of carbon-rich macroaggregates than those for CTC. A reduced rate of macroaggregate turnover is also responsible for higher SOC under NT over CT (Six *et al.,* 2000). The NT practice enhanced SOC content over the CT practice and thus was an important strategy of carbon sequestration in cropland soils.

Effect of land use on soil carbon pools

Effect of 11 years of conservation tillage on SOC fractions in wheat monoculture was reported by Chen *et al.* (2009). Conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT) were investigated. SOC contents and stocks were significantly higher under ST (11.9 g kg^{-1}, 22.3 Mg ha^{-1}) and NT (11.1 g kg^{-1}, 22.2 Mg ha^{-1}) than CT (8.9 g kg^{-1}, 19.6 Mg ha^{-1}), while ST and NT were similar. The results showed that conservation tillage effects occurred mainly in the top soil and also reflected the build-up of labile C pools under conservation tillage after 11 years. The first explanation for the differences of the labile C pools between CT and conservation tillage (NT and ST) is the result of tillage practices. Frequent tillage under CT breaks down aggregates and exposes protected organic matter to microbial decomposition and increases the loss of labile C (Elliott, 1986; Chen *et al.,* 2007). A second explanation emerges from the different quantity of residues retained between CT and the conservation tillage: 3.8 t ha^{-1} residues in ST and NT vs. residue removal in CT. Plant residue might enter the labile C pools, provide substrate for soil microorganisms, and contribute to accumulation of labile C. An increase in labile C fractions leads to improvement of soil fertility under conservation tillage through increase of labile sources of nutrients. Therefore, conservation tillage is an important factor for increasing labile C compared to conventional tillage. C sequestration can be enhanced by increasing the proportion of C rich macroaggregates in soils through the utilization of conservation tillage. Soils in agroforestry and maize-wheat systems had approximately 28% higher concentration of total carbon than those in rice-wheat system but these differences were statistically insignificant. Total organic carbon (TOC) differed significantly with respect to land-use practices. In contrast, soils in the rice-wheat system exhibited significantly lower SOC concentrations than those in the other two agro-ecosystems (Table 2). Compared to the rice-wheat system, agroforestry and maize-wheat systems were 88% and 65% higher in SOC, respectively (Fig. 2). The higher SOC concentration under agroforestry may be attributed to input of C through litter fall that occurs at the beginning of winter season and greater root biomass compared to sole annual crops. Poplar trees, grown in the region, add 2.9-3.3 t ha^{-1} of litter fall every year (Ralhan *et al.,* 1996; Tandon *et al.,* 1991) and supply 2.3 t C ha^{-1} y^{-1} through roots and leaves (Chauhan *et al.,* 2011). Soils in the maize-wheat system also exhibited higher SOC stocks than those in the rice-wheat system, probably because of C input through farmyard manure application to maize. Positive effect of manure application on SOC build-up under maize-wheat system in semi-arid India has earlier been reported by Benbi *et al*., (1998).

Soils under agroforestry had significantly higher concentration of very labile C than the rice-wheat soils (Table 3). The concentration of labile C was significantly higher in soils under maize-wheat than rice-wheat system whereas agroforestry and rice-wheat systems were at par. The three agroecosystems did not differ in the concentration of less labile C. The highest concentrations of recalcitrant C occurred in soils under rice-wheat cropping (Table 3). Agroforestry and maize-wheat cropping systems were characterized by a predominantly labile C content as rice-wheat system. The results suggested that the organic carbon in soils under maize-wheat and agroforestry systems is less stable and could be easily lost through organic matter decomposition if the current land-use is discontinued. On the contrary, soils under rice-wheat contained greater proportion (63%) of organic C in less labile and recalcitrant fractions. Our values are similar to those reported by Majumder *et al.* (2008) for rice based cropping systems in hot humid tropics of India. The greater proportion of organic C existing in less labile and recalcitrant forms in rice-wheat system may be attributed to the retarded rate of C oxidation in these soils that are flooded for 3 months during the rice season (Jenkinson 1988; Watanabe 1984). As a result of slower decomposition of C substrates in anaerobic soils than in aerated soils, plant molecules that are more resistant to microbial degradation such as lignin might gradually accumulate in the organic matter of paddy soils (Colberg, 1988; Tate, 1979).

CONCLUSION

C sequestration can be enhanced by increasing the proportion of C rich macroaggregates in soils through the utilization of conservation tillage. Conservation tillage effects occurred mainly in the top soil and also reflected the build-up of labile C pools under conservation tillage in a study. The no tillage practice enhanced SOC content over the conventional tillage practice of crop production and thus is an important strategy of carbon sequestration in cropland soils. Organic carbon in soils under maize-wheat and agroforestry systems is less stable and could be easily lost through organic matter decomposition if the current land-use is discontinued. Crop cultivation led to a decrease in total soil organic carbon. There are agricultural management practices that show promise for restoring soils and sequestering a very significant portion of atmospheric carbon. Therefore, it is important to take into account the importance of agroforestry to sequester the C and improving the soil properties. Mulch, no-tillage leads to higher C sequestration than conventional tillage.

Table 1. SOC stocks of different land uses

Land uses	**SOC (g Kg^{-1}) surface layer**	**SOC (g Kg^{-1}) sub-surface layer**
Eroded	1.95	2.50
Agriculture	7.23	4.80
Forest	9.6	7.01
Grassland	13.2	5.12
LSD(0.05)	0.74	0.28

Table 2. Total C, total organic C (TOC) and soil organic C (SOC) in soils of agroforestry, rice-wheat, and maize-wheat systems in the Rupnagar district of Indian Punjab (Benbi *et al.*, 2012)

Soil carbon pool	**Land-use**			
	Rice-wheat	Maize-wheat	Agroforestry	LSD (0.05)
Total C (g kg^{-1} soil)	6.90^{a} (1.32)	8.95 ^{a} (0.79)	8.83 ^{a} (0.83)	NS
Total organic C (g kg^{-1} soil)	6.50 ^{a} (1.41)	8.06 ^{a} (0.70)	8.35 ^{a} (0.80)	NS
Soil organic C (g kg^{-1} soil)	3.88 ^{a} (0.89)	6.52 ^{a} (0.51)	6.56 ^{a} (0.53)	1.89

Mean values in a column followed by same letter are not significantly different at P<0.05. NS = non-significant
Values in parenthesis indicate standard error of mean

Table 3. Concentration of organic C fractions (g kg^{-1}soil) of varying oxidizability in soils of agroforestry, maize-wheat, and rice-wheat systems in the Rupnagar district of Indian Punjab (Benbi *et al.*, 2012).

Land use	**Very Labile**	**Labile**	**Less Labile**	**Recalcitrant**
Agro forestry	3.24^{a}	1.63^{ab}	1.69^{a}	1.80^{b}
Maize-wheat	2.14^{ab}	2.29^{ab}	2.09^{a}	1.54^{b}
Rice-wheat	1.21^{b}	1.13^{b}	1.54^{a}	2.61^{a}

Mean values in a column followed by same letter are not significantly different at P <0.0

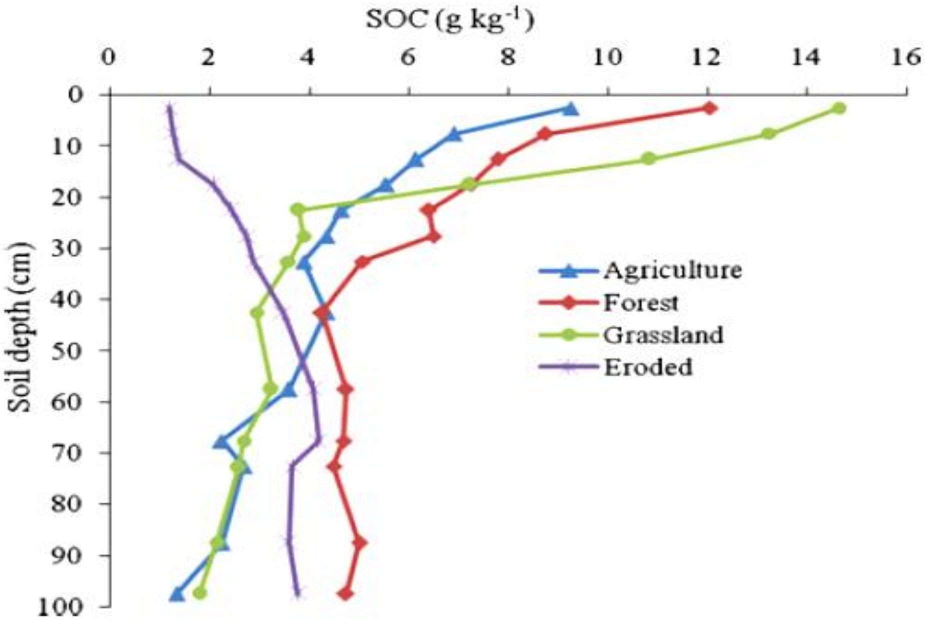

Fig. 1. Depth wise distribution of SOC under different land uses

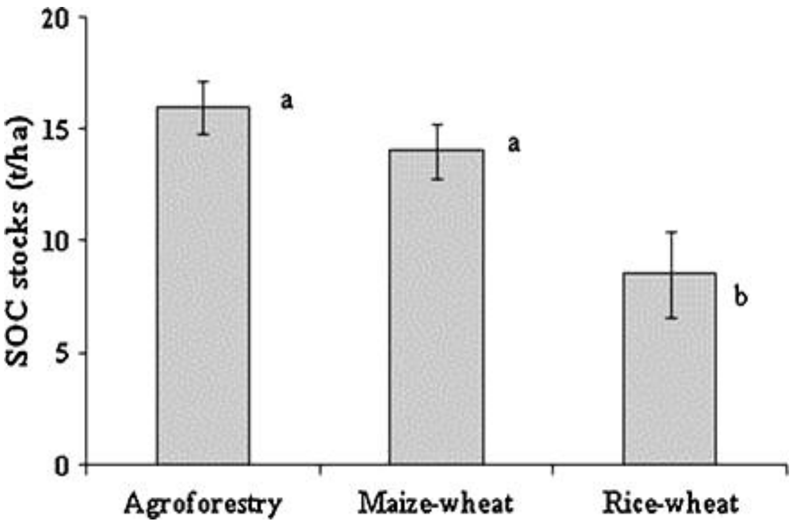

Fig. 2. Soil organic carbon (SOC) stocks in agroforestry, maize-wheat, and rice-wheat systems in the Rupnagar district of Indian Punjab (Benbi *et al.,* 2012).

Bars labeled with the same letter are not significantly different at $P<0.05$ (LSD 4.2). Line bars indicate standard error of mean.

REFERENCES

Adhikari, A.R., Dahal, K.R., Chen, Z.S., Tan, Y.C. and Lai, J.S. (2017). Rice–wheat cropping system: tillage, mulch, and nitrogen effects on soil carbon sequestration and crop productivity. *Paddy Water Environ*. **15**: 6 99–710.

Albrecht, A. and Kandji, S.T. (2003) Carbon sequestration in tropical agroforestry systems. *Agric Ecosyst Environ.* **99**: 15–27.

Alemayehu, L., Hager, H., and Sieghardt, M. (2010). Effect of land use types on soil chemical properties in smallholder farmers of central highland Ethiopia. *Ekologia (Bratislava).* **29**(1): 1–14.

Ali, S., Begum, F., Hayatc, R. and Bohannan, B.J.M. (2017). Variation in soil organic carbon stock in different land uses and altitudes in Bagrot Valley, Northern Karakoram. *Soil and Plant Science*. **67(**6): 551–561.

Amanuel, W., Yimer, F. and Karltun, E. (2018). Soil organic carbon variation in relation to land use changes: the case of Birr watershed, upper Blue Nile River Basin, Ethiopia. Journal of Ecology and Environment **42**: 16.

Banger, K., Kukal, S.S., Toor, G., Sudhir, K. and Hanumanthraju, T.H. (2009) Impact of long term addition of chemical fertilizer and farm yard manure on carbon and nitrogen sequestration under rice-cowpea cropping system in semi-arid tropics. *Pl Soil*. **318**: 27–35.

Benbi, D.K., Biswas, C.R., Bawa, S.S. and Kumar, K. (1998). Influence of farmyard manure, inorganic fertilizers and weed control practices on some soil physical properties in a long-term experiment. *Soil Use Manage*. **14**: 52–54.

Benbi, D.K., Brar, K., Toor, A.S. and Singh, H. (2012). Soil carbon pools under poplar-based agroforestry, rice-wheat and maize-wheat cropping systems in semi-arid India. *Nutrient Cycling in Agroecosystems.* **92:** 107-118.

Billings, S.A. (2006). Soil organic matter dynamics and land use change at a grassland/forest ecotone. *Soil Biol Biochem.* **38**: 2934–2943.

Blanco-Canqui, H. and Lal, R. (2004). Mechanisms of carbon sequestration in soil aggregates. *Crit Rev Plant Sci.* **23**: 481–504.

Brown, S. (2002). Measuring carbon in forests: current status and future challenges. *Environ Poll.* **16**: 363–372.

Carter, M.R. (1996). Analysis of soil organic matter in agroecosystems. *In* Carter M R, Stewart B A (eds.) Structure and Organic Matter Storage in Agricultural Soils. CRC Press, Boca Raton. pp. 3–11.

Chauhan, S.K., Gupta, N., Walia, R., Yadav, S., Chauhan, R. and Mangat, P.S. (2011). Biomass and carbon sequestration potential of poplar-wheat intercropping system in irrigated agroecosystem in India. *J Agric Sci Technol A.* **1**: 575–586.

Chen, H.Q., Billen, N., Stahr, K. and Kuzyakov, Y. (2007). Effects of nitrogen and intensive mixing on decomposition of 14C-labelled maize (Zea mays L.) residue in soils of different land use types. *Soil Till. Res.* 96: 114–123.

Chen,H., Hou, R., Gong, Y., Li, H., Fan, M. and Kuzyakov, Y. (2009). Effects of 11 years of conservation tillage on soil organic matter fractions in wheat monoculture in Loess Plateau of China. *Soil & Tillage Research*. 106: 85–94.

Colberg, P.J. (1988). Anaerobic microbial degradation of cellulose, lignin, oligolignols, and monoaromatic lignin derivatives. In: Zehnder AJB (ed) Biology of anaerobic microorganisms. Wiley, New York, pp 333–372.

Drees, L.R.,Wilding, L.P., Smeck, N.E. and Senkayi, A.L. (1989). Silica in soils: quartz and disordered silica polymorphs. In: Dixon, J.B., Weed, S.B. (Eds.), Minerals in Soil Environments. Soil Soc. Am, Madison, WI, pp. 913–974.

Elliott, E.T. (1986). Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. *Soil Sci Soc Am J.* **50**: 627–633.

FAO. (2005). Global Forest resources assessment 2005: progress towards sustainable forest management. Rome: FAO.

Freibauer, A., Rounsevell, M.D.A., Smith, P. And Verhagen, J. (2004). Carbon sequestration in the agricultural soils of Europe. *Geoderma.* **122**: 1–23.

Gelaw, A.M, Singh, B.R. and Lal, R. (2013). Organic carbon and nitrogen associated with soil aggregates and particle sizes under different land uses in Tigray, Northern Ethiopia. *Land Degrad Dev.* **26**: 690–700.

Gispert, M., Emran,M., Pardini, G., Doni, S. and Ceccanti, B. (2013). The impact of land management and abandonment on soil enzymatic activity, glomalin content and aggregate stability. *Geoderma*. **202**: 51–61.

Gupta, N., Kukal, S.S., Bawa, S.S. and Dhaliwal, G.S. (2009). Soil organic carbon and aggregation under poplar based agroforestry system in relation to tree age and soil type. *Agroforest Syst*.**76**: 27–35.

Houghton, R.A. (2007). Balancing the global carbon budget. *Annu Rev Earth Planet Sci*. **35**: 313–347.

Jacinthe, P.A., La,l R., Owens, L.B. and Hothem, D.L. (2004). Transport of labile carbon in runoff as affected by land use and rainfall characteristics. *Soil Tillage Res.* **77**: 111–123.

Jenkinson, D.S. (1988). Soil organic matter and its decomposition. In: Wild A (ed) Russel's soil conditions and plant growth, 11th edn. Longman, London, pp. 464–506.

Kaiser, K., Eusterhues, K., Rumpel, C., Guggenberger, G. and Knabner, K. (2002). Stabilization of organic matter by soil minerals—investigations of density and particle—size fractions from two acid forest soils. *J Pl Nutr Soil Sci.* **165**: 451–459.

La,l R. and Bruce, J.P. (1999). The potential of world cropland soils to sequester C and mitigate the greenhouse effect. *Environ Sci Policy.* **2**: 177–185.

Lal, R. (1995). Global soil erosion by water and carbon dynamics. In: Lal R, Kimble JM, Levine E, Stewart BA, editors. Soil and global change. Boca Raton (FL): CRC/Lewis Publishers; p. 131–142.

Lal, R. (2002). Soil carbon dynamics in cropland and rangeland. *Environ Poll*, **116**: 353–362.

Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma.* **123**: 1–22.

Lal, R. (2008). Carbon sequestration. *Philos Tran Roy Soc B.* **363**: 815–830.

Lal, R. and Kimble, J.M. (1997). Conservation tillage for carbon sequestration. *Nutr Cycl Agroecosys*. **49**: 243–253.

Majumder, B., Mandal, B. and Bandyopadhyay, P.K. (2008). Soil organic carbon pools and productivity in relation to nutrient management in a 20-year-old rice–berseem agroecosystem. *Biol Fert Soils*. **44**: 451–461.

Nath, A.J. and Lal, R. (2017). Effects of tillage practices and land use management on soil aggregates and soil organic carbon in the North Appalachian region, USA. *Pedosphere.* **27**(1)**:** 172-176.

Nimmo, J.R. and Perkins, K.S. (2002). Aggregate stability and size distribution methods of soil analysis. *In* Dane J H, Topp G C (eds.) Methods of Soil Analysis. Part 4. Physical Methods. Soil Science Society of America Book Series No. 5. Soil Science of America, Madison. pp. 317–328.

Pandey, C.B., Singh, G.B., Singh, S.K. and Singh, R.K. (2010). Soil nitrogen and microbial biomass carbon dynamics in native forests and derived agricultural land use in a humid tropical climate of India. *Plant Soil*. **333**: 453–467.

Parr, J., Sullivan, L., Chen, B., Ye, G. and Zheng,W. (2010). Carbon bio-sequestration within the phytoliths of economic bamboo species. *Glob. Chang. Biol.* **16**: 2661–2667.

Percival, J.H., Roger, L., Parfitt, A.S. and Neal, A.S. (2000). Factors controlling soil carbon levels in New Zealand Grasslands: Is clay content important? *Soil Sci Soc Am J*. **64**: 1623–1630.

Plaza, C., Courtier-Murias, D., Fernández, J.M., Polo, A. and Simpson, A.J. (2013). Physical, chemical, and biochemical mechanisms of soil organic matter stabilization under conservation tillage systems: a central role for microbes and microbial by-products in C sequestration. *Soil Biol. Biochem.* **57**: 124–134.

Puri, S. and Nair, P.K.R. (2004) Agroforestry research for development in India: 25 years of experiences of a national program. *Agrofor Syst.* **61–62**: 437–452.

Ralhan, P.K., Rasool, A. and Singh, A. (1996). Return of nutrients through leaf litter on an age series of Poplar plantation in agri-silviculture system in certain parts of Punjab. In: IUFRO-DNAES international meet on resource inventory techniques to support agroforestry and environment activities, pp. 159–163.

Rees, R.M., Bingham, I.J., Baddeley, J.A. and Watson, C.A. (2005). The role of plants and land management in sequestering soil carbon in temperate arable and grassland ecosystems. *Geoderma.* **128**: 130–154.

Reicosky, D.C. and Forcella, F. (1998). Cover crop and soil quality interactions in agro-ecosystem. *J Soil Water Conserv*. **53**: 224–229.

Sainju, U.M. (2006). Carbon and nitrogen pools in soil aggregates separated by dry and wet sieving methods. *Soil Sci.* **171**: 937–949.

Saviozzi, A., Levi-Minzi, R., Cardelli, R. and Riffaldi, R. (2001). A comparison on soil quality in adjacent cultivated, forest and native grassland soils. *Plant Soil*. **233**: 251–259.

Sharma, V., Hussain, S., Sharma, K.R. and Arya, V.M. (2014). Labile carbon pools and soil organic carbon stocks in the foothill Himalayas under different land use systems. *Geoderma*. **232–234**: 81–87.

Singh, A.K., Rai, A. and Singha, N. (2016). Effect of long term land use systems on fractions of glomalin and soil organic carbon in the Indo-Gangetic plain. *Geoderma*. **277**: 41–50.

Six, J., Paustian, K., Elliott, E.T. and Combrick, C. (2000). Soil structure and organic matter: I. Distribution of aggregate-size classes and aggregate-associated carbon. *Soil Sci Soc Am J.* **64**: 681–689.

Tandon, V.N., Pandey, M.C., Rawat, H.S., Sharma, D.C. (1991). Organic productivity and mineral cycling in plantations of .*Populus deltoides* in tarai region of Uttar Pradesh. *Indian Forester*. **117**: 596–608.

Tate, R.L. (1979). Effect of flooding on microbial activities in organic soils: carbon metabolism. *Soil Sci.* **128**: 267–273.

Thomas, G.A., Dalal, R.C. and Standley, J. (2007). No-till effects on organic matter, pH, cation exchange capacity and nutrient distribution in a Luvisol in the semi-arid subtropics. *Soil Till Res*. **94**: 295–304.

Wang, Z.P., Han, X.G. and Li, L.H. (2008). Effects of grassland conversion to croplands on soil organic carbon in the temperate Inner Mongolia. *J Environ Manage*. **86**: 529–534.

Watanabe, I. (1984). Anaerobic decomposition of organic matter. In: Organic matter and rice. International Rice Research Institute, Manila, Philippines, pp. 237–258.

Wei, J., Cheng, J.M., Li, W. and Liu, W. (2012). Comparing the effect of naturally restored forest and grassland on carbon sequestration and its vertical distribution in the Chinese Loess Plateau. *Plos One*. **7**(7): e40123.

Yimer, F., Ledin, S., and Abdu, A. (2006). Soil property variations in relation to topographic aspect and vegetation community in the south-eastern highlands of Ethiopia. *Forest Ecology and Management*. **232:** 90–99.

Yimer, F., Stig, L. and Abdelkadir, A. (2006). Soil property variations in relation to topographic aspect and vegetation community in the south-eastern highlands of Ethiopia. *For Eco Manage.* **232**: 90–99.

Zhao, W., Hu, Z., Li, S., Guo, Q., Yang, H. and Zhang, T. (2017). Impact of land use conversion on soil organic carbon stocks in an agro-pastoral ecotone of Inner Mongolia. *J. Geogr. Sci.* **27**(8): 999-1010.

Zhao, W.Z., Xiao, H.L., Liu, Z.M and Li, J. (2005). Soil degradation and restoration as affected by land use change in the semiarid Bashang area, Northern China. *Catena*. **59**: 173–186.