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Soil organic carbon pools under *Terminalia chebula* Retz. based agroforestry system in Himalayan foothills, India

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Knowledge of carbon (C) pools in soils is helpful in devising practices for efficient carbon management in intensive cropping systems. Carbon fractions of soil organic carbon are used as an indicator for land-use induced change in soil quality. The present study evaluated carbon pools under *Terminalia chebula* (chebulic myrobalan) based agroforestry system supplied with different nutrient sources, viz. farmyard manure, poultry manure, vermicompost, wheat straw and inorganic fertilizer (NPK @ 100 : 80 : 60). Carbon fractions, viz. very labile (C_1 *frac*), labile (C_2 *frac*), less labile (C_3 *frac*) and non-labile (C_4 *frac*), were analysed at 0–15 and 15–30 cm soil depth. The higher value of C_1 *frac* (13.8%), C_2 *frac* (4.8%), C_3 *frac* (8.3%) and C_4 *frac* (11.1%) were recorded under agroforestry as compared to open system. Among the nutrient sources, all the carbon fractions were higher under 100% integrated nutrient sources as compared to controlled treatment. Microbial biomass carbon (MBC) was recorded higher (298.31 $\mu g\ g^{-1}$) under agroforestry system compared to the open system (290.63 $\mu g\ g^{-1}$) at 0–15 cm. Among the different nutrient sources, higher MBC (458.66 $\mu g\ g^{-1}$) at 0–15 cm and lower (340.59 $\mu g\ g^{-1}$) at 15–30 cm soil depth was recorded in 100% integrated treatment. Thus, agroforestry-based land-use types and integrated nutrient management are more efficient for soil health and carbon management in Himalayan foothills.

Keywords: Active pool, carbon fractions, labile, non-labile, nutrient sources, passive pool.

DIVERSIFICATION of existing farming systems by developing suitable agroforestry models will provide diversified products such as food, fibre, fodder, fruit, timber, etc. for local consumption. Agroforestry add to the sustainability of agriculture and help in its diversification to attain huge benefits per unit land when carefully selected and managed[1]. Agroforestry systems are known for higher soil carbon sequestration[2]. Tree-based systems contribute more carbon stock compared to grassland system[3]. The tree of *Terminalia chebula* is a moderate to large deciduous tree growing up to 30 m in height and trunk up to 1 m in diameter[4]. It is a fast growing species and commonly known as *Chebulic myroblans*. The tree is well known for tanning leather, dyeing cloth and medicinal uses. Because of the economic benefits associated, this tree is suitably grown as an agroforestry tree with different intercrops. Organic matter in soil (SOM) is measured as an important constituent of every terrestrial ecosystem; perhaps it is the most recognized indicator for soil quality[5]. SOM is comprised of a variety of materials ranging from extremely high decomposable material to labile organic carbon (OC) which is corresponds to the stabilized of OC[6]. The quantity and quality of SOM is effective under agroforestry due to the addition of carbon in the form of litter production, crop residues, production of root and its exudates as well as the losses of carbon through decomposition. Soil total organic carbon (TOC) includes various fractions, which consist of different quantities of organic compounds and are broadly grouped as active and passive pools. The active pool (labile and non-labile) mainly comprises microbial biomass carbon (MBC), whereas, the passive pool is a multifaceted

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material that is resistant to decomposition, is called humus, and is associated with clay in the soil[7]. The relative proportion of labile and non-labile pools governs soil quality and its vulnerability to rapid mineralization and is, therefore, a critical determinant of soil carbon dynamics. Fluctuations in these pools with different soil management practices have been studied across the world[8]. However, limited studies exist in agroforestry[9]. Therefore, it is imperative to manage agroforestry practices through canopy pruning, as well as with addition of soil nutrients/fertilizers in order to avoid competition between species[10]. The judicious combination of organic and chemical fertilizers in agroforestry can reduce the competition between agricultural crops and trees, and make the system viable and sustainable. The differences in SOM fractions between agroforestry and agricultural fields can yield information about the mechanism of soil carbon sequestration[11,12]. Limited studies have focused on the OC pool and lability of carbon with carbon management index (CMI). The CMI is used as a measure of soil carbon restoration in which higher values designate that soil carbon is being rehabilitated and lesser values reflect that the system is degrading. It is therefore important to understand how different carbon pools and CMI are influenced under agroforestry by the use of various sources of fertilizers. The specific objectives of our study were: (1) to examine the effect of organic and inorganic sources of fertilizers on carbon pools under the open and agroforestry systems; and (2) to assess the effect of organic and inorganic sources of fertilizers on CMI under these two systems.

The present study was conducted at the Agroforestry Research Centre of G.B. Pant University of Agriculture and Technology, Pantnagar, Udham Singh Nagar district, Uttarakhand, India. The experimental site is located at 29°N and 79.3°E at an altitude of 243 m above mean sea level in the Himalayan foothills. Climate of the site is humid sub-tropical with cold winters and hot dry summers. The maximum daily temperature in summer may reach up to 42°C and minimum temperature in winter may fall down to 0.5°C. Monsoon sets in the second or third week of June and continues up to the end of September. The mean annual rainfall is about 1450 mm, of which 80–90% is received during the rainy season (July and September).

The study was carried out in *T. chebula* based agroforestry system and open system. *T. chebula* trees were planted in 2003–04 at 4 × 4 m spacing. Before the plantation of trees, the land was utilized for agricultural crops like wheat, rice, sugarcane and pulses. Trees in the system were intercropped with soybean–wheat during the initial six years after which turmeric (*Curcuma longa* L.) was replaced as an intercrop due to drastic reduction in the yield of soybean and wheat. In 2015, eight treatments, viz. T_1 – control, T_2 – farm yard manure (FYM), T_3 – poultry manure, T_4 – vermicompost, T_5 – wheat straw, T_6 – recommended dose of nitrogen, phosphorus, potassium (NPK) (100 : 80 : 60), T_7 – 50% integrated and T_8 – 100% integrated, were applied to turmeric grown under *T. chebula* and sole crop (open system) combination. FYM, poultry manure, vermicompost, and wheat straw were applied @ 10 tonne ha^{-1}. In 50% integrated treatment, half of the recommended dose of NPK and 10 tonne ha^{-1} FYM were applied, while for 100% integrated treatment, full recommended dose of NPK and 10 tonne ha^{-1} FYM were given. The composition of nutrient (%) is given in Table 1. The experiment was laid out in split plot design with agroforestry and open systems in the main plots and the nutrient sources in subplots. The experiment was concluded in 2017 with the harvesting of turmeric.

Soil samples were collected from two levels (0–15 cm and 15–30 cm depth) in 2017 from all the treatments under agroforestry as well as open systems (without tree), before and after harvesting of the turmeric crop. Samples were processed and sieved through a 2 mm sieve and taken to the laboratory for analysing the oxidizable OC. TOC was calculated by multiplying the value of oxidizable OC by the factor of 1.33 (ref. 13). The initial SOC was also analysed and the status of SOC under *T. chebula* system and open system was recorded to be 0.83–0.69% at 0–15 cm soil depth and 0.72–0.61% at 15–30 cm depth respectively.

SOC with different fractions were analysed by Walkley and Black method[14]. In this method, we used different concentrations of H_2SO_4, i.e. 5, 10 and 20 ml respectively, for determining the SOC fractions over TOC of the soil[15]. Fractions 1 and 2 were indicated as potentially active pools of SOC and on the basis of these pools the CMI was calculated (Table 2). For this, the SOC lability index was analysed with respect to fractions 1, 2 and 3, and among them, the weightage was in the decreasing order i.e. fraction 3 > fraction 2 > fraction 1. Thereafter, the carbon pool index was calculated by dividing the sample value with the reference value (control) of total carbon (Table 2). MBC was estimated by the method of Jackinson and Powlson[16] and modified by Voroney *et al.*[17].

Data were analysed by ANOVA using SPSS-16 software. Further, means were tested using Duncan's test at $P = 0.05$ significance level.

SOC fractions were significantly higher under *T. chebula* based agroforestry system as compared to the

Table 1. Composition of nutrient (%) in different nutrient sources

Nutrient source	N%	P%	K%	C%	pH
Farm yard manure (FYM)	0.5	0.2	0.75	20.6	7.4
Poultry manure	2	1.7	1.1	22.4	6.8
Vermicompost	1.5	0.75	0.75	34.7	7.2
Wheat straw	0.4	0.52	0.82	31.2	7.1

Table 2. Methods used for calculating different carbon fractions and carbon management index (CMI)

Fraction 1 (C_1 *frac*) – very labile	Organic carbon (OC) oxidizable under 12 N H_2SO_4.
Fraction 2 (C_2 *frac*) – labile	The difference in oxidizable OC extracted between 18 N and 12 N H_2SO_4 (18–12 N H_2SO_4).
Fraction 3 (C_3 *frac*) – less labile	The difference in oxidizable OC extracted between 24 N and 18 N H_2SO_4.
Fraction 4 (C_4 *frac*) – non-labile	The difference in OC extracted with 24 N H_2SO_4 and TOC determined by CHN analyser (TOC – 24 N H_2SO_4).
Active pool	C_1 *frac* + C_2 *frac* (unstable/labile).
Passive pool	C_3 *frac* +C_4 *frac* (stable/non-labile).
Lability index for the OC	[(C_1 *frac*/total organic carbon (TOC) × 3 + (C_2 *frac*/TOC) × 2 + (C_3 *frac*/TOC) × 1].
Carbon pool index (CPI)	Sample total carbon (mg/kg)/reference total carbon (mg/kg), where reference total carbon is the total carbon content (mg/kg) of control plots.
CMI	CPI × LI × 100.

Table 3. Soil organic carbon fractions under agroforestry and different nutrient sources

	Soil carbon fractions (%)							
	Very labile (C_1 *frac*)		Labile (C_2 *frac*)		Less labile (C_3 *frac*)		Non-labile (C_4 *frac*)	
	Soil depths (cm)							
Treatments	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30
Main plot (farming systems)								
Agroforestry system (AF)	0.405^{a}	0.340^{a}	0.083^{a}	0.067^{a}	0.181^{a}	0.166^{a}	0.199^{a}	0.190^{a}
Open system (AF_0)	0.349^{b}	0.295^{b}	0.079^{b}	0.062^{b}	0.166^{b}	0.149^{b}	0.177^{b}	0.167^{b}
SEm ±	0.002	0.001	0.005	0.001	0.002	0.001	0.001	0.001
LSD ($P = 0.05$)	0.015	0.005	0.03	0.004	0.01	0.006	0.004	0.004
Sub plot (nutrient sources)								
T_1 – Control	0.332^{g}	0.287^{h}	0.071^{gh}	0.041^{g}	0.150^{h}	0.135^{h}	0.164^{f}	0.153^{g}
T_2 – FYM	0.368^{d}	0.305^{de}	0.072^{gh}	0.074^{c}	0.173^{de}	0.154^{e}	0.185^{de}	0.176^{d}
T_3 – Poultry manure	0.347^{ef}	0.295^{fg}	0.075^{ef}	0.063^{de}	0.167^{f}	0.149^{f}	0.175^{de}	0.167^{ef}
T_4 – Vermicompost	0.385^{c}	0.327^{c}	0.087^{c}	0.061^{de}	0.180^{bc}	0.160^{cd}	0.189^{c}	0.181^{c}
T_5 – Wheat straw	0.354^{ef}	0.303^{de}	0.075^{ef}	0.048^{f}	0.171^{de}	0.156^{cd}	0.177^{de}	0.167^{ef}
T_6 – N : P : K (100 : 80 : 60)	0.350^{ef}	0.293^{fg}	0.080^{d}	0.063^{de}	0.160^{g}	0.147^{g}	0.177^{de}	0.166^{ef}
T_7 – Integrated (50%)	0.416^{b}	0.358^{b}	0.093^{b}	0.085^{ab}	0.185^{bc}	0.175^{b}	0.212^{b}	0.204^{b}
T_8 – Integrated (100%)	0.465^{a}	0.375^{a}	0.099^{a}	0.087^{ab}	0.204^{a}	0.186^{a}	0.226^{a}	0.214^{a}
SEm ±	0.005	0.004	0.001	0.001	0.002	0.002	0.002	0.002
LSD ($P = 0.05$)	0.014	0.012	0.03	0.003	0.006	0.005	0.006	0.005

open system (Table 3). The very labile carbon fraction (C_1 *frac*) at 0–15 cm soil depth was found significantly higher (13.8%) under *T. chebula* + turmeric compared to the open system. Among the different nutrient source treatments, significantly higher (28.6%) C_1 *frac* was observed under 100% integrated (T_8) followed by T_7 (20.2%), over the control treatment (T_1). A similar trend was recorded at 15–30 cm soil depth. The labile carbon fraction (C_2 *frac*) at 0–15 cm depth was higher (4.8%) under *T. chebula* based agroforestry system than that of the open system. In different nutrient source treatments, significantly higher (28.3%) C_2 *frac* was recorded under 100% integrated treatment followed by 50% integrated (23.6%) over the control treatment. It was recorded similarly at the sub-surface soil depth. The less labile carbon fraction (C_3 *frac*) at 0–15 cm depth was also higher (8.3%) under *T. chebula* based agroforestry system, and, in the different nutrient sources, higher (26.5%) C_3 *frac* was recorded under 100% integrated treatment over control treatment. A similar trend was recorded at the sub-surface soil depth. The non-labile carbon fraction (C_4 *frac*) at both soil depths was found higher under *T. chebula* based agroforestry system and in the nutrient sources, it was higher under 100% integrated treatment over control. SOC fractions with different forms and stabilities are important variables to know the effect of agroecosystem management on soil quality as the change in these fractions may provide a better way for the management of soil on the SOM level. Our results revealed that C_1 *frac* was higher in agroforestry system due to continuous litter fall which leads to the increase in OC in the soil. Other researchers have also observed that agroforestry system contributed to improving the quality of SOC at the surface of soil due to continuous addition of a high amount of litter and also by high concentration of fine roots[18]. Growing trees flourish under better rooting system[19], and perhaps, litter addition[20] too increase soil carbon storage which was confirmed with positive

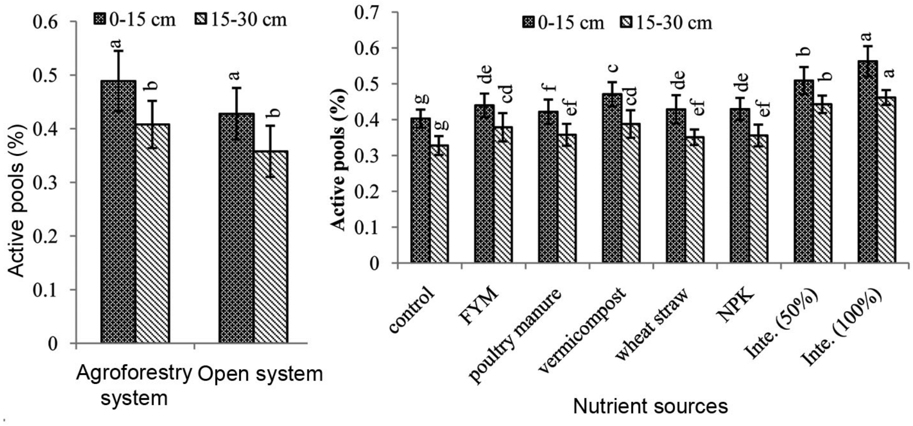

Figure 1. Active pools under the agroforestry system, open system and different nutrient sources.

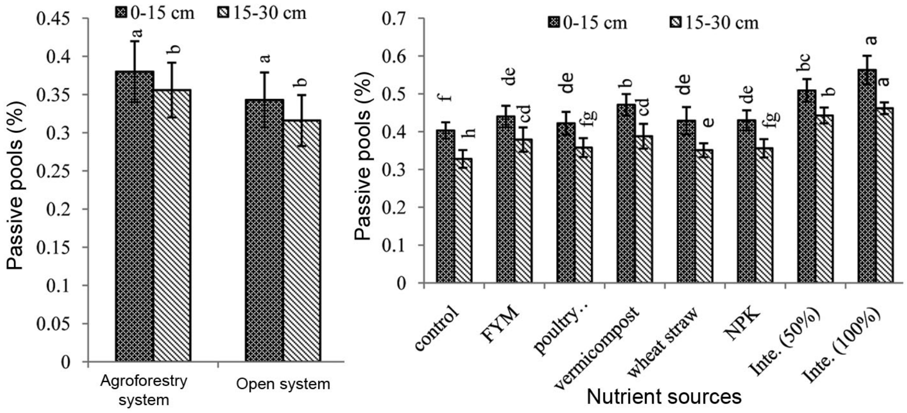

Figure 2. Passive pools under agroforestry system, open system and different nutrient sources.

correlation between SOC and quantity of litterfall[21]. This suggests that OC in soils under mono-cropping system is more stable than agroforestry system. Among the different nutrient sources, 100% integrated treatment depicted a high amount of very labile carbon fraction (C_1 *frac*) as compared to the other treatments. The application of balanced fertilizers along with organic manure increased polysaccharides in the soil resulting in the production of higher amount of very labile carbon fraction[22]. The decreased carbon fractions at decreasing soil depths might be due to availability and supply of mineralizable and easily hydrolysable carbon, leading to the intense activity of microbes and their population in the surface soil layer[23]. Results also revealed that active pools (Figure 1) dominated over the passive pool (Figure 2) under agroforestry and open system as well as in all the treatments for both soil depths (0–15 cm and 15–30 cm). This might be because agroforestry had significant labile carbon pool as compared to the uncultivated system[3]. Increased active carbon pool (Figure 1) in 100% integrated treatment signified that this pool of soil was more sensitive to change because of manuring and inorganic fertilization[16,24] and hence giving it a central role in nutrient supply.

At both soil depths, MBC was significantly higher under *T. chebula* based agroforestry system in comparison to the open system (Figure 3). The MBC was higher at 0–15 cm soil depth compared to the 15–30 cm soil depth for all the treatments. Among the different treatments, highest MBC (Figure 3) was recorded in 100% integrated followed by 50% integrated, vermicompost and lowest in poultry manure which was at par with NPK treatment at both the soil depths. MBC was higher at the surface (0–15 cm) than at the sub-surface (15–30 cm) probably because of higher organic residues over the surface soil layer compared to the sub-surface soil layer. The rate of mineralization of soil MBC increased appreciably under agroforestry systems[23]. An increased proportion of microbial carbon in the total soil organic pool indicates higher nutrient availability to the plants in agroforestry systems compared to sole cropping. In similar study soil microbial biomass carbon was higher under agroforestry as compared to open system[25], soil MBC was higher under agroforestry. Among the different nutrient source treatments, the highest soil microbial biomass was recorded under 100% integrated treatment followed by 50% integrated treatment since the application of organic amendments increased the MBC significantly (Figure 3). There

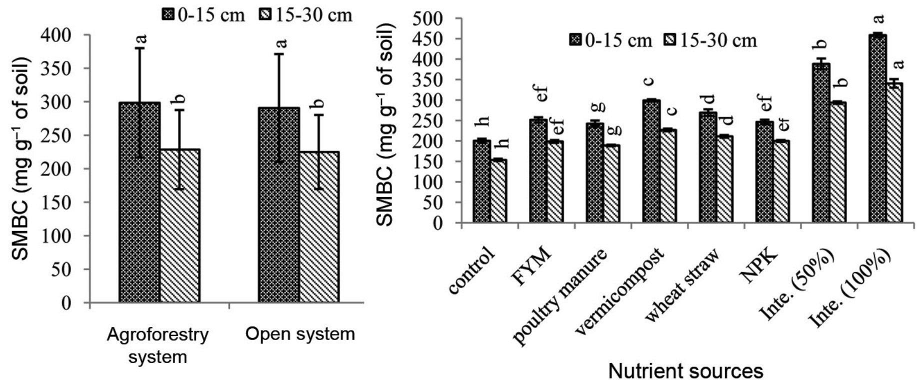

Figure 3. Soil microbial biomass carbon (SMBC) under the agroforestry system, open system and different nutrient sources.

Table 4. Carbon management index (CMI) under two land uses

	CMI		
Nutrient sources	Agroforestry system	Open system	Mean
FYM	142.37	107.97	125.17[d]
Poultry manure	127.27	100.89	114.1[ef]
Vermicompost	154.78	118.11	136.45[c]
Wheat straw	131.24	103.33	117.3[g]
Nitrogen, phosphorus, potassium (100 : 80 : 60)	127.13	103.52	115.32[ef]
Integrated (50%)	180.75	144.98	162.87[b]
Integrated (100%)	214.18	169.68	191.93[a]
Mean	154.00[a]	121.21[b]	
	SEm ±	LSD (P = 0.05)	
Farming system	0.98	6.40	
Nutrient sources	1.44	4.22	
Interaction			
To compare nutrient sources for same farming system		2.58	7.52
To compare nutrient sources either for the same or both farming system		2.12	7.85

are evidences that fertilizer application particularly nitrogen as well as increasing inputs of crop residues increase soil organic matter and MBC[26,27]. Generally, MBC is closely related to the amount of soil organic matter[28,29].

T. chebula and turmeric system showed higher (21.3%) CMI than open system (Table 4). Among the nutrient sources, 100% integrated treatment showed the highest CMI. Thus our results revealed that there was an improvement of CMI in agroforestry system, i.e. FYM (31%), poultry manure (26%), vermicompost (31%), wheat straw (27%), NPK (22%), 50% integrated (24%) and 100% integrated (26%) over the treatments of open system. CMI is used as a more sensitive indicator of the rate of change of SOC in response to cropping system and soil management changes[30]. Hence, soil's physical, chemical and biological attributes, as well as its self-organization capacity, are directly influenced by SOC pools[31]. In the present study, the agroforestry system showed higher CMI than open systems. The agroforestry system was characterized by a predominantly high per cent very labile carbon fraction (fraction 1) as opposed to open system soils[32]. Among the different nutrient sources, organic sources showed a significant increase in CMI over inorganic treatment. This could be attributed to the increase in annual carbon input and the variation in organic matter quality, thus modifying the lability of carbon to oxidized form[33]. The manure with inorganic fertilizer significantly increased CMI compared with any other chemical fertilizer treatments[34]. Significant variation in CMI under different nutrient sources and nutrient management can be attributed to more carbon input provided by crop residues and organic amendments.

Carbon pools, MBC and CMI were higher in the agroforestry system than the open system. Among the different nutrient source treatments, 100% integrated nutrient source had a higher amount of active pool, passive pool, MBC, CMI and accounted for a better soil management practice in this study. Among the different organic nutrient sources (alone), vermicompost and FYM having higher soil MBC maintained higher SOC and CMI. Therefore, it is essential to adjust our chemical fertilizer applications, by adding organic nutrients in the farming systems. Increment in organic matter is responsible for the increment in soil's ability to hold nutrients for longerperiod. Thus agroforestry and organic nutrient sources are regarded as the most suitable management practice with respect to the maintenance of soil health and long-term outlook of productivity in Himalayan foothills of India.

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