Soil organic carbon stocks and fractions in different orchards of eastern plateau and hill region of India

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Soil organic carbon stocks and fractions in different orchards of eastern plateau and hill region of India

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Abstract Soil organic carbon (SOC) plays an important role in soil fertility and productivity. It occurs in soil in labile and non-labile forms that help in maintaining the soil health. An investigation was undertaken to evaluate the dynamics of total soil organic carbon (C_{tot}), oxidisable organic carbon (C_{oc}), very labile carbon (C $frac_1$), labile carbon (C $frac_2$), less labile carbon (C $frac_3$), non-labile carbon (C $frac_4$), microbial biomass carbon (C_{mic}) and SOC sequestration in a 6-year-old fruit orchards. The mango, guava and litchi orchards caused an enrichment of C_{tot} by 17.2, 12.6 and 11 %, respectively, over the control. The mango orchard registered highest significant increase of 20.7, 13.5 and 17.4 % in C $frac_1$, C $frac_2$ and C $frac_4$, respectively, over control. There is greater accumulation of all the C fractions in the surface soil (0–0.30 m). The maximum total active carbon pool was 36.2 Mg C ha^{-1} in mango orchard and resulted in 1.2 times higher than control. The passive pool of carbon constituted about 42.4 % of C_{tot} and registered maximum in the mango orchard. The maximum C_{mic} was 370 mg C kg^{-1} in guava orchard and constituted 4.2 % of C_{tot}. The carbon management index registered 1.2 (mango orchard)- and 1.13 (guava and litchi orchard)-fold increase over control. The mango orchard registered highest carbon build rate of 1.53 Mg C ha^{-1} $year^{-1}$ and resulted in 17.3 % carbon build-up over control. Among the carbon fractions, C $frac_1$ was highly correlated ($r = 0.567$**) with C_{mic}.

Keywords Carbon fractions · Carbon pool · Carbon management index · Eastern India · Fruit orchard · Soil microbial biomass carbon

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Introduction

The dynamics of organic carbon storage in agricultural soils is gaining increasing importance because of its impacts on climate change and benefits for crop productivity. Good farming practices have the potential to make such soil a net sink for carbon thereby attenuating CO_2 load in the atmosphere and improving soil fertility and hence productivity (Lal 2004). The majority of carbon in the terrestrial pool is stored below ground in soils (Janzen 2004). Total global carbon in soils constitutes between 1500 and 2000 Gtons; the majority of it stored in forest biomes (Janzen 2004; Smith 2004). Carbon stock in soil depends largely on the aerial extent of the soils besides other factors such as carbon content, depth and bulk density of soils. The Eastern plateau and hill region

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covers 13 % of the total geographic area of the country and contributes 9, 1 and 7 % of the soil organic carbon (SOC), soil inorganic carbon (SIC) and total carbon (TC) stocks of the country, respectively (Bhattacharyya et al. 2008). Cropping systems and management practices that ensure greater amounts of crop residue returned to the soil are expected to cause a net build-up of the SOC stock. Identifying such systems or practices is a priority for sustaining crop productivity. The soils of tropical, subtropical, arid and semiarid regions are expected to be contributing more oxidative products (particularly CO_2) per unit SOC to the atmosphere vis-a-vis the soils of temperate and cooler regions. Again, crop species that are cultivated may also play an important role in maintaining the stock because both quantity and quality of their residues that are returned to the soils vary greatly affecting their turnover or residence time in soil. Chan et al. (2001) suggest that certain fractions of soil organic matter are more important in maintaining soil quality and are, therefore, more sensitive indicators of the impact of management practices. Changes in SOC due to management practices are difficult to quantify as these changes occur slowly, are relatively small compared to the vast SOC pool size, and vary both spatially and temporally (Russell et al. 2004).

Upon application of organic amendments, a part of their carbon is stabilized into SOC and distributed among different pools. To better understand the mechanisms by which carbon is lost or stabilized in soil, the total soil organic carbon (TSOC) stock is separated into a labile or actively cycling pool, a slow pool, and a stable or passive, recalcitrant pool with varying residence times (Parton and Rasmussen 1994). The labile carbon pool is the fraction of TSOC with the most rapid turnover rates. The labile pool consists of living microbes and their products besides soil organic matter. At the same time, this pool is important from the point of view of crop production. It fuels the soil food web and therefore greatly influences nutrient cycling for maintaining soil quality and its productivity (Janzen 1987; Chan et al. 2001; Majumder et al. 2007). Highly recalcitrant or passive pool is only very slowly altered by microbial activities (Sherrod et al. 2005). The passive pool is comparatively more stable than the active pool and is slowly decomposable having a larger turnover time.

In this investigation, we hypothesized that different orchard systems would have influence on the soil carbon pools in the acidic alfisols. We examined the soils of 6-year-old orchard of mango, litchi and guava in an alfisol of the eastern plateau and hill region with respect to soil carbon pool, soil carbon stock, carbon management indices and carbon sequestration.

Materials and methods

Experimental site

The investigation was conducted in 6-year-old litchi, mango and guava orchards planted in 2008 and laid out in a complete randomized block design at Ranchi Research Station of ICAR Research Complex for Eastern Region, Jharkhand, India. The research station was located in eastern plateau and hill region of eastern India (23°16′48″N latitude and 85°24′41″E longitude, altitude 650 m above mean sea level). The climate of the study area was seasonal with distinct warm–wet and cold–dry seasons in a year. The mean annual rainfall was about 1400 mm (>90 % received during June–October). Mean minimum and maximum temperature varied from 7.5 °C in December to 37.7 °C in May. Relative humidity ranged between 55 % (winter) and 88 % (rainy season). The soil of the area was Typic Haplustalf type, and was highly acidic (pH 4.5–5.5) in reaction with low levels of organic matter (Table 1). The fruit plants of litchi, guava and mango were planted at a spacing of 5 × 5 m accommodating 400 plants in one hectare. All the fruit orchards were received farm yard manure (FYM) at 15 t ha^{-1} $year^{-1}$. On an average, total organic C, total N, total P and total K content in FYM was 15.8, 0.45, 0.08 and 0.32 %, respectively, during the experimental period. Recommended doses of $N–P_2O_5–K_2O$ for litchi and mango was 115–30–90 and 90–30–90 g $tree^{-1}$ $year^{-1}$ of age, respectively, and the amount becomes cumulative in each year up to 10 years. After 10 years, the dose of $N–P_2O_5–K_2O$ for litchi and mango becomes constant at 1150–300–900 and 900–300–900 g $tree^{-1}$, respectively. The recommended dose of $N–P_2O_5–K_2O$ for guava was 120–60–60 g $tree^{-1}$ $year^{-1}$ of age and the amount becomes cumulative in each year up to 5 years thereafter it becomes constant at 600–300–300 g $tree^{-1}$. The $N–P_2O_5–K_2O$ were applied in the form of urea, diammonium phosphate and muriate of potash. Native vegetations (shrubs, herbs, grasses

Table 1 Initial properties of the soils of the selected fruit orchards at plandu in EPH region of India

Soil properties	*Litchi* (*Litchi chinensis*)	Guava (*Psidium guajava*)	Mango (*Mangifera indica*)	Control (No tree)
pH	4.67	4.71	4.68	4.87
Bulk density (Mg M^3)	1.54	1.56	1.54	1.58
Organic carbon (g kg^{-1})	6.15	6.00	6.12	5.40
Nitrogen (kg ha^{-1})	247.0	220.0	254.0	185.0
Phosphorus (kg ha^{-1})	24.5	21.3	31.7	16.5
Potassium (kg ha^{-1})	350	355	341	345

etc.) of the site were allowed to grow in the control (No tree) plots without any inputs (fertilizer, water, plant protection chemicals etc.).

Soil sampling and analysis

Soil samples from 6-year-old orchard of mango, litchi and guava were collected from 20 different soil profiles along with control (No-orchard) (4 treatments × 5 replications) at depths of 0–0.15, 0.15–0.30, 0.30–0.45 and 0.45–0.60 m. After hand crushing of soil samples and passing through a 2.0-mm sieve, field-moist soil samples were stored at 4 °C and were used later afresh (after not more than 24 h) for estimation of soil microbial biomass C. Air-dried soil sample that had passed through the same sieve was used for analysis of some important physicochemical properties following standard methods. A core sampler (5.0 cm diameter and 8.0 cm length) was used for measurement of bulk density of the soils of each layer of soil profiles.

Total soil organic carbon

Soil samples were prepared following the method as mentioned by Nelson and Sommers (1982) and analysed for carbon (C) by CHNS analyser (Elementar Vario EL III, Hanau, Germany). Soil samples were also analysed for inorganic carbon using dilute HCl method and the results were expressed as $CaCO_3$ equivalent. Total soil organic carbon (C_{tot}) [obtained by Elementar C minus HCl–C], expressed as megagrams per hectare, was computed by multiplying the C_{tot} content (g kg^{-1}) with bulk density (Mg m^{-3}) and depth (m) for each of the four depths and subsequently summing them up together for the entire 0–0.60 m soil profile.

The C build-up in the different orchard systems was estimated as follows:

$$\text{C build-up } (\%) = [(C_{\text{orchard}} - C_{\text{cont}})/\,C_{\text{cont}}] \times 100,$$

where C_{orchard} represents C in orchard soil and C_{cont} represents the C in control plot, respectively.

$$\text{C build-up rate } \left(\text{Mg C ha}^{-1}\text{soil year}^{-1}\right) = (C_{\text{orchard}} - C_{\text{cont}})/\text{years of experimentation.}$$

Oxidisable organic carbon and its fractions

The oxidisable organic carbon (C_{oc}) content of the soils was determined using the method of wet oxidation as proposed by Walkley and Black (1934). The fractions of organic carbon present in soil were estimated through a modified Walkley and Black method as described by Chan et al. (2001) using 5, 10 and 20 mL of concentrated H_2SO_4 resulting in three acid aqueous solution ratios of 0.5:1, 1:1 and 2:1 (which corresponded, respectively, to 12, 18 and 24 N of H_2SO_4). The amount of organic carbon determined using 5, 10 and 20 mL of concentrated H_2SO_4 when compared with C_{tot} allowed separation of C_{tot} into the following four different fractions of decreasing oxidisability: fraction I (C $frac_1$), organic carbon oxidisable under 12 N H_2SO_4; fraction II (C $frac_2$), the difference in organic carbon extracted between 18 and 12 N H_2SO_4; fraction III (C $frac_3$), the difference in organic carbon extracted between 18 and 24 N H_2SO_4 (the 24 N H_2SO_4 is equivalent to the standard Walkley and Black method); and fraction IV (C $frac_4$), residual organic carbon after reaction with 24 N H_2SO_4 when compared with C_{tot}.

Active and passive pools

Organic carbon oxidisable under 12 N H_2SO_4 was designated as the very labile pool (C $frac_1$) and the difference in organic carbon oxidized between 18 and 12 N H_2SO_4 was termed the labile pool (C $frac_2$). These two together were designated as the active pool of organic carbon because of their easy oxidisability (by weak 12 and 18 N H_2SO_4). The passive pool represented the less labile pools (C $frac_3$) and non-labile (C $frac_4$) pools of C_{tot}.

Carbon management index

Step 1

A lability index (LI) for the SOC was computed using three of the pools (C $frac_1$, C $frac_2$ and C $frac_3$) mentioned above. The C $frac_1$, C $frac_2$ and C $frac_3$ have been designated as very labile, labile and less labile and are given weightage of 3, 2 and 1, respectively. Subsequently, their actual values are transformed to a proportional amount of C_{tot} and weighed with the weighing factor to get a LI for the organic carbon content in each of the soils under different depths (Blair et al. 1995).

$$\mathrm{LI} = [(\mathrm{C\ frac_1}/C_{tot}) \times 3 + (\mathrm{C\ frac_2}/C_{tot}) \times 2 + (\mathrm{C\ frac_3}/C_{tot}) \times 1].$$

Step 2

Carbon pool index (CPI) was derived using the formula:

$$\mathrm{CPI} = \text{Sample total } C\left(\mathrm{g\ kg^{-1}}\right) / \text{reference total } C\left(\mathrm{g\ kg^{-1}}\right),$$

where reference total carbon is the total carbon content ($g\ kg^{-1}$) of control plots (Blair et al. 1995), the carbon management index (CMI) is calculated as follows:

$$\mathrm{CMI} = \mathrm{CPI} \times \mathrm{LI} \times 100.$$

Soil microbial biomass carbon (C_{mic})

Microbial biomass carbon was analysed using the chloroform fumigation method (Vance et al. 1987). Fifty grams of field-moist soil were fumigated for 24 h in a vacuum desiccator using ethanol-free chloroform. After fumigation, chloroform fumes were removed by evacuation. Non-fumigated and fumigated soils (50 g each) were extracted using 200 mL of 0.5 M K_2SO_4. The carbon in the chloroform fumigation assay was analysed by the wet combustion technique as described by Jenkinson and Powlson (1976). Soil microbial biomass carbon can be given as

$$C_{mic} = \mathrm{Fc}/0.45,$$

where Fc is the organic carbon extracted from 0.5 M K_2SO_4 from fumigated soil – organic carbon extracted from non-fumigated soil. Microbial quotient was calculated as the ratio of C_{mic} to C_{tot} and expressed as percent.

Statistical analysis

Treatment effects were analysed using randomized block design of variance (ANOVA) using the SPSS 11.0 for windows. The significance of the treatment effect was determined using the *F* test. When ANOVA indicated that there was a significant value, multiple comparisons of treatment means were performed using the least significant difference method (LSD). Duncan's multiple range test (DMRT) was used to compare treatment means.

Results and discussion

Soil organic carbon and its fractions

Significant variation ($P \leq 0.05$) in total soil organic carbon (C_{tot}) was observed among the different orchard throughout the depth (0–0.60 m) of the soil profile (Table 2). The C_{tot} gradually decreased with increasing depth of the profile. The control, i.e. no orchard, recorded lowest C_{tot} (53.3 Mg ha^{-1}) in the entire depth of soil up to 0.60 m. Earlier studies also reported that fallowing reduces soil organic carbon (SOC) by decreasing the amount of non-harvested plant residue returned to the soil (Calegari et al. 2008), while increasing the cropping intensity increased SOC (Hutchinson et al. 2007). The maximum C_{tot} was recorded in the surface soil as compared with lower depths due to the addition of roots and plant biomass in surface layers and lack of nutrient and biological activity in deeper layers, which ultimately constraints the rooting depth (Ingram and Fernandes 2001). The

Table 2 Total and oxidisable organic C (Mg ha^{-1} soil) in soils in different layers (m) of 6-year-old orchards at plandu in EPH region of India

Orchard	Soil organic carbon (Mg C ha^{-1} soil)									
	Total soil organic carbon (C_{tot})					Oxidizable organic carbon (C_{oc})				
	0–0.15	0.15–0.30	0.30–0.45	0.45–0.60	Total	0–0.15	0.15–0.30	0.30–0.45	0.45–0.60	Total
Control	19.10^{a}	13.44^{b}	11.20^{b}	9.55^{a}	53.28^{b}	14.36^{a}	10.12^{b}	8.43^{b}	7.17^{a}	40.10^{b}
Litchi	19.43^{a}	16.32^{a}	13.31^{a}	10.12^{a}	59.17^{a}	14.60^{a}	12.29^{a}	10.00^{a}	7.61^{a}	44.50^{a}
Guava	20.28^{a}	16.24^{a}	13.28^{a}	10.30^{a}	60.00^{a}	15.24^{a}	12.21^{a}	9.98^{a}	7.73^{a}	45.18^{a}
Mango	20.49^{a}	17.32^{a}	13.61^{a}	11.05^{a}	62.47^{a}	15.40^{a}	13.00^{a}	10.23^{a}	8.31^{a}	46.94^{a}
Mean	19.83	15.83	12.85	10.26	58.73	14.90	11.91	9.66	7.71	44.18

Within a column, values indicated by the same letters are not significantly different at the 0.05 level of probability by Duncan's multiple range test (DMRT)

maximum C_{tot} in 0–0.60 m depth was 62.47 Mg ha^{-1} in mango orchard and resulted in 17.2 % increase over control. Similarly, the guava and litchi orchard recorded significantly ($P \leq 0.05$) higher C_{tot} and resulted in 12.6 and 11 % increase over control, respectively. The higher C_{tot} in mango orchard may be attributed to the different quantities and qualities of organic matter input through fresh litterfall, living organisms and root activity (e.g. turnover and exudates) (Vesterdal et al. 2008). On an average, the total C left over in soil through leaf litter biomass and FYM in 6-year-old litchi, guava and mango orchard was 5.89, 6.72 and 9.19 t ha^{-1}, respectively. In fact, the confinement of C_{tot} in the orchard subsoil is essential for long-term storage of carbon due to reduced biological decomposition. It was also thought that the exposed soil surface and breaking of aggregates due to lack of vegetation which increases the erosional activities with high precipitation could be the reasons for lowest C_{tot} content under control plot (Conant and Paustian 2002).

The oxidizable organic carbon (C_{oc}) varied from 40.1 to 46.94 Mg C ha^{-1} soil among the different orchards under study (Table 2). The C_{oc} content was found non-significant among the orchard but when compared with control, it varied significantly ($P \leq 0.05$). This increase in C_{oc} in different orchards was due to significant ($P \leq 0.05$) increases in carbon input with organic manure and leaf litter of orchard system (Purakayastha et al. 2008; Gong et al. 2009; Ma et al. 2011). Similar increases in SOC after manure application were also reported in long-term experiments at Rothamsted (UK) (Powlson et al. 1998). The mango orchard registered as much as 4 and 17 % higher C_{oc} over that of the guava orchards and control, respectively. The relative preponderance of C_{oc} under different orchard systems was in the following order: mango orchard $\geq$ guava orchard - $\geq$ litchi orchard > control. Similar to C_{tot}, there was a sharp decrease in its content along depth, with 0.15–0.30, 0.30–0.45 and 0.45–0.60 m depth layers maintaining only 80, 64.8 and 51.7 %, respectively, of the amounts in surface layer.

The different orchard system increased the very labile fraction of carbon (C $frac_1$) as compared with control (Table 3). Maximum and significant ($P \leq 0.05$) increase in the C $frac_1$ was observed under guava orchard followed by mango in surface soil (0–0.15 m). The total C $frac_1$ was significantly ($P \leq 0.05$) highest in mango orchard (21.88 Mg ha^{-1}) throughout the depth of soil profile and resulted in 20.7 % increase over control. The guava and litchi orchard resulted in 17 and 14.2 % increase in total C $frac_1$ over control and were statistically at par. Similarly, the labile carbon fraction (C $frac_2$) varied significantly ($P \leq 0.05$) among the orchard at the surface soil. The mango orchard resulted in greater accumulation of C $frac_2$ in the surface layer. The total C $frac_2$ in mango orchard (14.31 Mg ha^{-1}) was significantly ($P \leq 0.05$) highest over control resulting in 13.5 % increase. The guava and litchi orchard registered 6 and 5.4 % increase in total C $frac_2$ over control, respectively. Fresh litter fall and root residues are the primary source of SOC leading towards increased amount of C $frac_1$ and C $frac_2$ in different orchards (Vesterdal et al. 2008). The less labile carbon fraction (C $frac_3$) and non-labile carbon fraction (C $frac_4$) did not vary significantly ($P > 0.05$) throughout the depth of the soil profile among the orchard. The distribution of

Table 3 Oxidisable organic C fractions (Mg ha^{-1} soil) in soils in different layers (m) of 6-year-old orchards at plandu in EPH region of India

Orchard	Soil organic carbon fraction (Mg C ha^{-1} soil)									
	Very labile carbon (C $frac_1$)					Labile carbon (C $frac_2$)				
	0–0.15	0.15–0.30	0.30–0.45	0.45–0.60	Total	0-0.15	0.15–0.30	0.30–0.45	0.45–0.60	Total
Control	6.44^{b}	4.36^{b}	4.22^{a}	3.10^{b}	18.12^{b}	4.14^{b}	3.31^{b}	2.87^{a}	2.28^{a}	12.60^{b}
Litchi	6.64^{b}	5.48^{a}	4.59^{a}	3.98^{a}	20.69^{ab}	4.31^{ab}	3.48^{ab}	3.37^{a}	2.12^{a}	13.28^{ab}
Guava	7.58^{a}	5.54^{a}	4.25^{a}	3.84^{a}	21.21^{ab}	4.49^{ab}	3.76^{ab}	3.28^{a}	1.84^{a}	13.36^{ab}
Mango	7.14^{ab}	6.00^{a}	4.73^{a}	4.02^{a}	21.88^{a}	4.75^{a}	4.07^{a}	3.17^{a}	2.33^{a}	14.31^{a}
Mean	6.95	5.35	4.45	3.74	20.47	4.42	3.66	3.17	2.14	13.38
Orchard	Soil organic carbon fraction (Mg C ha^{-1} soil)									
	Less labile carbon (C $frac_3$)					Non-labile carbon (C $frac_4$)				
	0–0.15	0.15–0.30	0.30–0.45	0.45–0.60	Total	0-0.15	0.15–0.30	0.30–0.45	0.45–0.60	Total
Control	3.19^{a}	2.44^{b}	1.93^{b}	1.80^{a}	9.36^{a}	4.73^{a}	3.33^{b}	2.78^{b}	2.35^{a}	13.20^{b}
Litchi	3.46^{a}	2.91^{a}	2.35^{a}	1.80^{a}	10.52^{a}	4.82^{a}	4.05^{a}	3.29^{a}	2.51^{a}	14.68^{a}
Guava	3.18^{a}	2.91^{a}	2.45^{a}	2.07^{a}	10.61^{a}	5.03^{a}	4.03^{a}	3.29^{a}	2.56^{a}	14.91^{a}
Mango	3.52^{a}	2.97^{a}	2.34^{a}	1.95^{a}	10.78^{a}	5.08^{a}	4.29^{a}	3.38^{a}	2.74^{a}	15.49^{a}
Mean	3.34	2.81	2.27	1.91	10.31	4.92	3.93	3.19	2.54	14.57

Within a column, values indicated by the same letters are not significantly different at the 0.05 level of probability by Duncan's multiple range test (DMRT)

different carbon fraction followed the order C $frac_1$ > C $frac_4$ > C $frac_2$ > C $frac_3$ throughout the depth of soil profile of different orchard. The higher proportion of non-labile C $frac_4$ in soils under different orchards was attributed to the rapid conversion of organic inputs and labile C fractions to recalcitrant forms, and its persistence under favourable conditions of moisture, thick canopy cover and minimal soil disturbance (Sreekanth et al. 2013). Lefroy et al. (1994) also found similar variations in C$frac_1$, C$frac_2$ and C$frac_3$, which indicated that these fractions were mainly responding to cropping. Among the orchards, a relatively higher proportion of the carbon fraction was found in surface soil, whereas it was found to decrease with increasing soil depth. This was due to supply and the availability of additional mineralisable and readily hydrolysable carbon resulting in higher microbial activity in surface layers (Kaur et al. 2008).

Active and passive carbon pool

The active carbon pool corresponds to very labile and labile pool of oxidisable organic carbon and varied significantly ($P \leq 0.05$) among the different orchard in surface soil (0–0.30 m), whereas it was non-significant ($P > 0.05$) in the sub-surface soil (0.30–0.60 m) (Table 4). The mango and guava orchard recorded significantly ($P \leq 0.05$) higher active carbon pool over control in 0–0.30 m depth. Irrespective of orchard systems, the maximum active carbon pool was recorded in the 0–0.15 m layer being highest in guava orchard (12.06 Mg ha^{-1}) and lowest in control (10.57 Mg ha^{-1}). The data showed that the total active carbon pool in 0–0.60 m depth among soils of different orchard did not show considerable variation, however, when compared to control, it varied significantly ($P \leq 0.05$). The maximum total active carbon pool was recorded under mango orchard (36.2 Mg ha^{-1}) followed by guava orchard (34.57 Mg ha^{-1}). Minimum total active carbon pool was detected under control (30.72 Mg ha^{-1}) which is nearly 1.2 times smaller than the highest value recorded. The higher active carbon pool in different orchard compared to control may be attributed to the tannins and lignin constituents formed from the decomposition of leaf litters and root biomass of the orchard systems protected the carbon from rapid decomposition and thus preserved it in the aggregates (Kalambukattu et al. 2013).

The passive carbon pool corresponds to less labile and non-labile pool of oxidisable organic carbon

Table 4 Active carbon pool in soils in different layers (m) of 6-year-old orchards at plandu in EPH region of India

Orchard	Active carbon pool (Mg ha^{-1})				
	0–0.15	0.15–0.30	0.30–0.45	0.45–0.60	Total
Control	10.57^{b}	7.67^{b}	7.08^{a}	5.38^{a}	30.72^{b}
Litchi	10.94^{ab}	8.96^{ab}	7.96^{a}	6.10^{a}	33.97^{a}
Guava	12.06^{a}	9.30^{a}	7.53^{a}	5.68^{a}	34.57^{a}
Mango	11.88^{a}	10.06^{a}	7.89^{a}	6.36^{a}	36.20^{a}
Mean	11.36	9.00	7.62	5.88	33.87

Within a column, values indicated by the same letters are not significantly different at the 0.05 level of probability by Duncan's multiple range test (DMRT)

Table 5 Passive carbon pool in soils in different layers (m) of 6-year-old orchards at plandu in EPH region of India

Orchard	Passive carbon pool (Mg ha^{-1})				
	0–0.15	0.15–0.30	0.30–0.45	0.45–0.60	Total
Control	7.92^{a}	5.77^{b}	4.72^{a}	4.15^{a}	22.56^{b}
Litchi	8.28^{a}	6.96^{a}	5.64^{a}	4.31^{a}	25.20^{a}
Guava	8.21^{a}	6.94^{a}	5.74^{a}	4.63^{a}	25.52^{a}
Mango	8.60^{a}	7.26^{a}	5.72^{a}	4.69^{a}	26.27^{a}
Mean	8.25	6.73	5.46	4.45	24.89

Within a column, values indicated by the same letters are not significantly different at the 0.05 level of probability by Duncan's multiple range test (DMRT)

(Table 5). The maximum passive carbon pool in 0–0.15 m depth was recorded in mango orchard (8.60 Mg ha^{-1}) and minimum in control (7.92 Mg ha^{-1}). The passive carbon pool gradually decreased with increasing depth of soil profile. The results confirmed that the total passive carbon pool in 0–0.60 m depth among soils of different orchard did not show considerable variation, however, when compared to control, it varied significantly ($P \leq 0.05$). The maximum total passive carbon pool was recorded under mango orchard (26.27 Mg ha^{-1}) followed by guava orchard (25.52 Mg ha^{-1}).

Soil microbial biomass carbon and microbial quotient

The soil microbial biomass carbon (C_{mic}), which normally constitutes about 1–5 % of the C_{tot}, can provide an early warning for a possible degrading and/or aggrading effect of different management practices on soil quality (Powlson 1994; Mandal 2005). The C_{mic} in surface soil varied significantly ($P \leq 0.05$) among the orchards (Fig. 1). The maximum and significant ($P \leq 0.05$) C_{mic} was 370 mg kg^{-1} recorded in guava orchard followed by mango orchard (343 mg kg^{-1}) and resulted in 63.7 % increase over control. The lower value of C_{mic} in the control seemed to be related to its unfavourable environment arising out of depletion of nutrients following without any fertilization and surface runoff, while a higher value in the orchard systems was due to its congenial environment for microbial growth for C enrichment through FYM and leaf litter addition (Grego et al. 1998). The cumulative leaf litter biomass added in 6-year-old litchi, guava and mango orchard was 11.6, 11.9 and 12.2 t ha^{-1}, corresponding to total C content of 41.5, 39.1 and 38.5 %, respectively. Further, the higher C_{mic} in guava and mango orchard was attributed to the quantity and quality of litter with higher rate of decomposition, greater availability of nutrients due to the addition of higher plant quality (Ramesh et al.

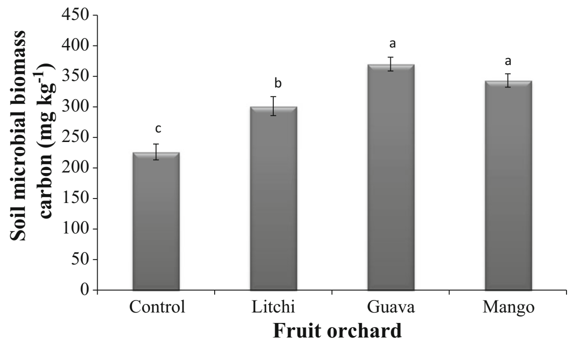

Fig. 1 Microbial biomass carbon in soils of different orchards at Plandu in EPH region of India. *Bars* are ±SE of the mean. Values indicated by the same letters are not significantly different at the 0.05 level of probability by Duncan's multiple range test (DMRT)

2013). The microbial quotient (MQ, C_{mic} as a proportion of C_{tot}) ranged from 2.79 to 4.26 with a mean value of 3.62 % (Fig. 2). The MQ between guava and mango orchard was non-significant ($P > 0.05$), when compared with litchi and control, it varied significantly ($P \leq 0.05$). The values of MQ for the soils of the present study were within the range of 1–5 % as advocated by number of researchers (Powlson 1994; Carter 2002). The higher value of MQ in guava and mango orchard suggested a greater stability of organic carbon under the orchard system (Sparling et al. 1992). The lowest value of MQ in the control indicated lower soil microbial biomass carbon and a poor quality soil with impairment of its capacity for C cycling (Chaudhury et al. 2005). The better nutritional environment to microbial population in the soils of guava and mango orchard increased the quotient (Rudrappa et al. 2005).

Total fungal and bacterial count varied widely among the different orchard systems (Fig. 3). The mango and guava orchard recorded significantly ($P \leq 0.05$) highest microbial count over litchi and control orchard in the surface soil suggesting higher decomposition rate of leaf litter over litchi resulted in higher labile carbon fractions. Further, the fungal count was more in mango orchard compared to guava, whereas the bacterial count was more in guava orchard compared to mango. The bacterial and fungal count between mango and guava orchard was non-significant ($P > 0.05$). However, a general range of the count showed an improvement in mango, guava and litchi orchard over control.

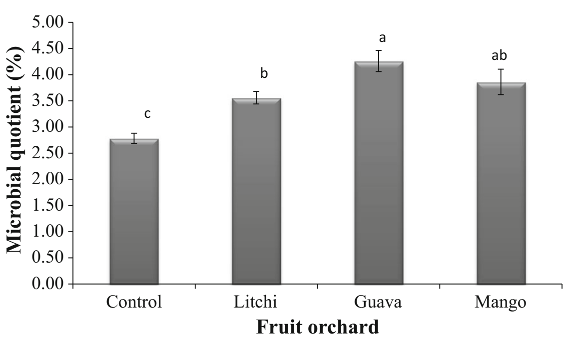

Fig. 2 Microbial quotient in soils of different orchards at Plandu in EPH region of India. *Bars* are ±SE of the mean. Values indicated by the same letters are not significantly different at the 0.05 level of probability by Duncan's multiple range test (DMRT)

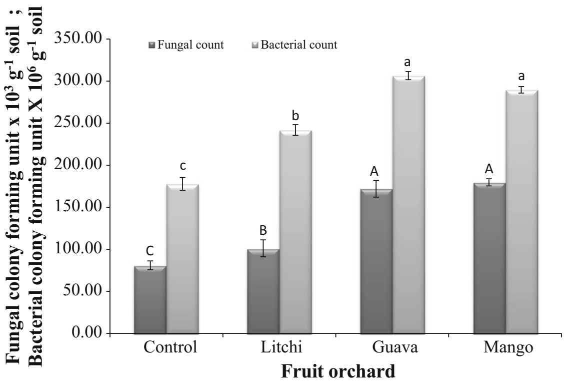

Fig. 3 Fungal and bacterial colony forming units in soils of different orchards at Plandu in EPH region of India. *Bars* are ±SE of the mean. *Values* indicated by the *same letters* are not significantly different at the 0.05 level of probability by Duncan's multiple range test (DMRT)

Carbon management index (CMI), carbon pool index (CPI), and carbon build-up

CMI provides an integrated measure of quantity and quality of SOC. Compared to a single measure such as total SOC concentration, CMI can be used as a more sensitive indicator of the rate of change of SOC in response to soil management changes, and was suggested by Whitbread et al. (1998) to be a useful technique for describing soil fertility. The CPI value was higher in mango orchard throughout the depth of soil profile highlighting the high potential of mango orchard in restoring the original soil organic C stocks (Table 7). The highest CPI value of 1.29 recorded in mango orchard in 0.15–0.30 m depth. As a whole, CPI increased in all the orchards over control. There is not much variation of lability index among the orchard throughout the depth of soil profile (Table 6). The guava orchard recorded higher lability index (1.72) followed by mango orchard (1.68) in 0–0.15 m depth. This pattern showed that guava orchard provided a less oxidative environment, giving greater physical protection to the SOM favouring a higher proportion of labile C compared to TSOC by increasing the rate of C lability in the soil (Blair et al. 1995).

The CMI values of mango and guava orchards were significantly ($P \leq 0.05$) higher over litchi orchard and control in 0–0.15 m depth (Table 8). The highest CMI value was 228.34 recorded in mango orchard in 0.15–0.30 m depth and resulted in 1.2-fold better than control. The orchard system promoted higher CMI

Table 6 Lability index of soil organic carbon in different layers (m) of 6-year-old orchards at plandu in EPH region of India

Orchard	Lability index (LI)				
	0–0.15	0.15–0.30	0.30–0.45	0.45–0.60	Mean
Control	1.61[a]	1.65[a]	1.82[a]	1.64[a]	1.68
Litchi	1.65[a]	1.61[a]	1.72[ab]	1.78[a]	1.69
Guava	1.72[a]	1.67[a]	1.64[b]	1.68[a]	1.68
Mango	1.68[a]	1.68[a]	1.68[ab]	1.69[a]	1.68

Within a column, values indicated by the same letters are not significantly different at the 0.05 level of probability by Duncan's multiple range test (DMRT)

Table 7 Carbon pool index of soil organic carbon in different layers (m) of 6-year-old orchards at Plandu in EPH region of India

Orchard	Carbon pool index (CPI)				
	0–0.15	0.15–0.30	0.30–0.45	0.45–0.60	Mean
Control	1.00[a]	1.00[b]	1.00[b]	1.00[b]	1.00
Litchi	1.05[a]	1.21[a]	1.19[a]	1.06[ab]	1.12
Guava	1.08[a]	1.21[a]	1.19[a]	1.09[ab]	1.13
Mango	1.11[a]	1.29[a]	1.22[a]	1.16[a]	1.18

Within a column, values indicated by the same letters are not significantly different at the 0.05 level of probability by Duncan's multiple range test (DMRT)

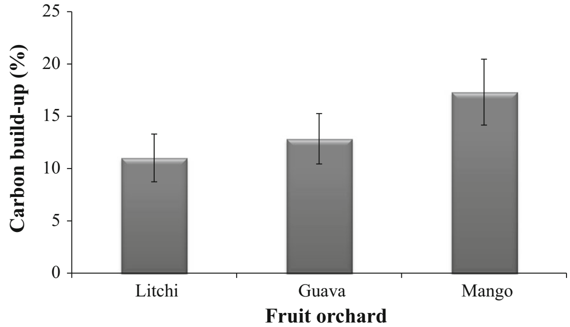

Fig. 4 Carbon build-up (%) in soils of different orchards at Plandu in EPH region of India. *Bars* are ±SE of the mean

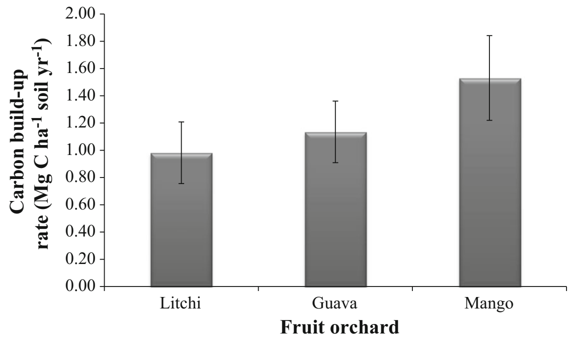

Fig. 5 Carbon build-up rate in soils of different orchards at Plandu in EPH region of India. *Bars* are ±SE of the mean

values, possibly not only due to the enhancement in the formation of organic matter, as a consequence of the increase in annual C addition, but also due to changes in organic matter quality, such as C/N ratio, contents of lignin, cellulose, hemicellulose, proteins, and carbohydrates, thus modifying the lability of C to move to an oxidized form (Tirol-Padre and Ladha 2004). The mean CMI ranked as mango orchard (204.18) > litchi orchard (192.48) = guava orchard (192.41) > control (169.47) due to different litter stocks and decomposition characteristics of the biomass. The results of the present investigation are in agreement with the findings of Lakaria et al. (2012), who reported higher CMI of 402 in mango orchard. In the present study, there is net build-up of TSOC in soils in all the orchards over control. The carbon build-

Table 8 Carbon management index of soil organic carbon in different layers (*m*) of 6-year-old orchards at plandu in EPH region of India

Orchard	Carbon management index (CMI)				
	0–0.15	0.15–0.30	0.30–0.45	0.45–0.60	Mean
Control	161.31[b]	170.17[b]	181.63[a]	164.75[b]	169.47
Litchi	172.53[b]	203.83[a]	203.91[a]	189.65[ab]	192.48
Guava	185.71[a]	207.67[a]	193.93[a]	182.35[ab]	192.41
Mango	186.21[a]	228.34[a]	205.65[a]	196.53[a]	204.18

Within a column, values indicated by the same letters are not significantly different at the 0.05 level of probability by Duncan's multiple range test (DMRT)

Table 9 Correlations coefficients (*r*) among different soil organic C pools and microbial count

Parameters	C $frac_1$	C $frac_2$	C $frac_3$	C $frac_4$	C_{oc}	C_{tot}	C_{mic}	Fungal count
C $frac_2$	0.406^{NS}							
C $frac_3$	-0.433^{NS}	0.079^{NS}						
C $frac_4$	0.358^{NS}	0.411^{NS}	0.297^{NS}					
C_{oc}	0.375^{NS}	0.507*	0.308^{NS}	0.764**				
C_{tot}	0.269^{NS}	0.482*	0.360^{NS}	0.891**	0.784**			
C_{mic}	0.567**	0.411^{NS}	0.075^{NS}	0.475*	0.424^{NS}	0.449*		
Fungal count	0.450*	0.513*	0.107^{NS}	0.477*	0.500*	0.381^{NS}	0.740**	
Bacterial count	0.526*	0.506*	0.053^{NS}	0.447*	0.489*	0.397^{NS}	0.888**	0.859**

Correlation coefficient (*r*) values for $P = 0.05$ and 0.01 are 0.444 and 0.561, respectively

Correlation is significant at * $P = 0.05$, ** $P = 0.01$

up was highest in mango orchard (17.3 %) followed by guava orchard (11 %) (Fig. 4). The carbon build-up rate (Fig. 5) is more important for a long-term perspective, which was found more (1.53 Mg C ha^{-1} soil $year^{-1}$) in mango orchard as against lowest of 0.98 Mg C ha^{-1} soil $year^{-1}$ in litchi orchard in 0–0.60 m depth of soil. The carbon build-up was less in litchi orchard soil compared to mango and guava, which was attributed to high N content in leaf litter of litchi (0.52 %) associated with resistant lignolytic products slowing down their decomposition resulted in less carbon build-up (Gundersen et al. 2006). The orchards like mango and guava, which have leaf litter of low N content of 0.28 and 0.31 %, respectively, are likely to be more efficient in C sequestration in soil than the litchi orchard, which give leaf litter of higher N content.

Relationship among different organic carbon pools and with microbial count

The correlation analysis among the different pools of C showed that most of the pools were significantly correlated with each other (Table 9). The correlation coefficient of C_{tot} varied significantly with its various fractions and decreased in the order of C $frac_4$ ($r = 0.891$**) > C_{oc} ($r = 0.784$**) > C $frac_2$ ($r = 0.482$*) > C_{mic} (r = 0.449*). A high and significant correlation between C_{tot} and C $frac_4$ ($r = 0.891$**) indicates a strong association of these two forms of C (accounting approximately 25 % C_{tot}) and signifying the usefulness of non-labile carbon i.e. C $frac_4$ as an indicator for changes in total soil organic carbon, C_{tot} (Sherrod et al. 2005). The active carbon fractions including C $frac_1$, C $frac_2$ and C_{mic} have been widely used as indicators of soil quality because of their sensitivity to environmental conditions and consistent responses in relation to SOC change (Melero et al. 2009). The highest and significant correlation between C $frac_1$ and C_{mic} ($r = 0.567$**) suggests that the C $frac_1$ could be considered as labile C fractions as proposed by Chan et al. (2001). Further, the correlation between C $frac_1$ with fungal count ($r = 0.450$*) and bacterial count ($r = 0.526$*) and C $frac_2$ with fungal count ($r = 0.513$*) and bacterial count ($r = 0.506$*) suggests that the labile fractions were the major energy source of soil microorganisms and affected by microbial activity, therefore they were strongly correlated with each other. The microbial biomass carbon is the result of microbial activity which was evidenced through highest significant correlation of fungal and bacterial count with C_{mic}.

Conclusions

The results confirmed that the mango orchard registered highest total soil organic carbon (62.5 Mg ha^{-1}) among the different orchards. Of the several soil C fractions analysed, C $frac_1$, C $frac_2$, C $frac_3$ and C $frac_4$ constituted 34.8, 22.7, 17.5 and 24.8 % of C_{tot}, respectively, and followed as C $frac_1$ > C $frac_4$ > C $frac_2$ > C $frac_3$ irrespective of different orchards throughout the 0–0.60 m depth of soil. All the carbon fractions were more in the surface soil (0–0.30 m) and gradually decreased with increasing depth of soil. The mango orchard registered higher C $frac_2$, C $frac_3$ and C $frac_4$ while guava orchard recorded higher C $frac_1$ in the surface soil. The C $frac_1$ was highly correlated ($r = 0.567$**) with C_{mic}, indicated that the microbial decomposition of leaf litter and farm yard manure stabilized the carbon into very labile fraction. The fungal biomass was more in mango orchard (179 cfu × 10^3 g^{-1} soil) while bacterial biomass was more in guava orchard (306.4 cfu × 10^6 g^{-1} soil). The active and passive carbon pool was highest in mango orchard and resulted in 17.8 and 16.4 % increase over control, respectively. The very labile fraction of carbon (C $frac_1$) contributed the largest percentage of total soil organic carbon, leading to the more active carbon pool in the surface soil can reasonably be used as good indicator for assessing soil as to its crop productivity. Among the orchards, mango orchard had greater amount of total soil organic carbon, active pool of carbon, passive pool of carbon and higher carbon management index and is considered the best orchard production system to sequester carbon in the eastern plateau and hill region of India.

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