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Soil organic carbon fractions, carbon stocks and microbial biomass carbon in different agroforestry systems of the Indo-Gangetic Plains in Bihar (India)

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Abstract

An investigation was undertaken in the Vaishali district (Bihar) during 2020 to assess the effect of different agroforestry systems (AFS) on distribution of different pools of soil organic carbon (fraction I-very labile, fraction II-labile, fraction III-less labile and fraction IV-non-labile pools), carbon stocking and soil microbial activity. The mean (0-45 cm) total organic carbon (TOC) in different AFS ranged from 5.55 to 6.64 Mg C ha^{-1} with the highest under poplar based-AFS (PB-AFS). Across the AFS studied, the C stocks (0-45 cm) varied from 36.24 (Mango based-AFS) to 41.43 Mg C ha^{-1} (PB-AFS). Overall, the magnitude of C fractions showed an order of fraction I > fraction IV > fraction III > fraction II. Significantly higher soil microbial biomass carbon (SMBC) was recorded under PB-AFS (219.36 ug g^{-1}) in 0-15 cm depth. Similarly, basal respiration was also the highest under PB-AFS (0.54 µg CO_2-C g^{-1} hr^{-1}) followed by TB-AFS (0.50 µg CO_2-C g^{-1} hr^{-1}) in 0-15 cm depth. Principal component analysis (PCA) result showed that PC 1 & PC 2 represented about 97 % of the total variation. TOC and active carbon pool have the maximum loading in PC 1 while microbial metabolic quotient (qCO_2) and bulk density represent the maximum value in PC 2.

Keywords: Carbon stock; carbon fractions; carbon management index; poplar-based agroforestry system

Introduction

The protection and enhancement of soil organic matter content is an essential element in achieving sustainable agricultural production. However, continued intensive cultivation has led to its depletion leading to a decline in soil fertility, crop productivity and increased atmospheric CO_2 concentration[1]. The combination of liable and recalcitrant fractions of carbon in the soil denotes the total organic carbon (TOC) of soil. However, the measurement of TOC alone does not truly reflect a clear picture of carbon dynamics in any cropping system, since the status of liable fraction (LF) can be easily affected by land management practices while the recalcitrant fraction (RF) in the soil cannot be changed easily due to alteration in land use practices[2]. Soil microbial biomass carbon (MBC) influences major nutrient cycling patterns in the ecosystem vis-à-vis cycling of SOM[3]. In the light of the present climate change scenarios, there is a need for identifying efficient and sustainable land use systems that could lead to long term storage and sequestration of carbon.

On this contention, agroforestry, a practice of cultivating trees along with agricultural crops or animal husbandry, is considered as one of the viable land use systems while delivering the services of crop diversification, natural conservation as well as sequestering the atmospheric carbon. By considering the importance of agroforestry practices in terms of carbon sequestration, Intergovernmental Panel on Climate Change (IPCC) and other prominent organizations viz., Consultative Group on International Agricultural Research (CGIAR) have recognized the services of agroforestry and incorporated this land use practice in many of their programmes. Although preliminary studies on dry matter dynamics of poplar-based agroforestry system in Indo-gangetic plains of Bihar (Samastipur) have been studied[4], information regarding soil organic fractions and carbon stocks across different agroforestry systems (AFS) of Bihar is limited. Therefore, the present investigation was undertaken to evaluate the effect of different AFS on distribution of different soil organic carbon fractions, carbon stocking and soil microbial activity in different AFS.

Materials and methods

Selection of agroforestry system

Selection and identification of agroforestry system was carried out following a preliminary reconnaissance survey in Vaishali district (Bihar) and these were classified according to Nair[5]. In general, two types of AFS viz., agri-silvicultural and agri-horticultural are widely practiced by farmers of this region (25° 41' to 25° 68' N latitude and 85° 13' to85° 22' E longitude). Teak (*Tectona grandis*) + agricultural crops, Poplar (*Populus spp* + agricultural crops and Sissoo (*Dalbergia sissoo*) + agricultural crops represented agri-silvicultural system while Mango (*Mangifera indica*) + agricultural crops denoted the agri-horticultural system (Table 1). Under the Teak based agroforestry system (TB-AFS), farmers of this region generally grow mustard (*Brassica spp)* and rice (*Oryza sativa)*. Wheat (*Triticum aestivum*) and rice are commonly grown as intercrop in poplar-based agroforestry system (PB-AFS). Similarly, under the Sissoo based agroforestry system (SB-AFS) farmers favor the cultivation of mustard, potato (*Solanum tuberosum)*, maize (*Zea mays*) etc, while mustard, moong (*Phaseolus vulgaris)*, and potato are commonly cultivated under mango-based agroforestry system (MB-AFS). Vaishali district of Bihar is a part of Indo-Gangetic plains where the average rainfall recorded is about 1400 mm. The study area belongs to tropical region having the characteristics of hot summers from April to June followed by a brief autumn season and a mild, dry winter. Soil texture of this region is mainly sandy, loam, and light clayey in nature.

Soil sampling and analysis

During January 2020, ten soil samples were taken from each AFS at three depths (0-15, 15-30, and 30-45 cm) using power augers. After that, composite soil samples were prepared by combining soil samples from each agroforestry system and transported to the laboratory in polyethylene bags and stored at 4°C until analysis. Soil bulk density was measured by core method[6]. The sub-samples of air-dried soil were used for analyzing the total organic carbon (TOC) and different fractions of carbon (very liable, liable, less liable and non-liable). TOC was analyzed following Haenes[7]. Different fractions of carbon were also analyzed as per method suggested by Chan *et al*.[8]

Soil OC stock (t ha^{-1}) at different soil depths in different agroforestry systems were calculated using the formula:

$$\text{SOC stock (Mg ha}^{-1}) = \text{SOC (g kg}^{-1}) \times \text{bulk density (Mg m}^{-3}) \times \text{soil depth (m)} \times 10$$

Active pool of organic carbon was calculated by summing up fraction I and II together, while, passive pool was derived by adding fractions III and IV together. Soil microbial biomass carbon

(MBC) was calculated using the method suggested by Nunan *et al.*[9] with certain alteration according with Parihara *et al.*[10] Carbon dioxide (CO_2) evolution in terms of basal respiration was calculated following the alkali absorption method[11]. Microbial quotient (MQ) and microbial metabolic quotient (qCO_2) were also calculated adopting the equation proposed by Anderson and Domsch[12].

Carbon Management Index (CMI)

The CMI was calculated by applying the formula proposed by Blair *et al.*[13] -

$$\mathrm{CMI} = \text{Carbon Pool Index (CPI)} \times \text{Liability Index (LI)} \times 100$$

Where CPI is calculated as

$$\mathrm{CPI} = \frac{\text{Sample total organic carbon}}{\text{Reference total organic carbon}}$$

LI was calculated as

$$\mathrm{LI} = \frac{\text{Fraction I}}{\text{Total organic carbon}} \times 3 + \frac{\text{Fraction II}}{\text{Total organic carbon}} \times 2 + \frac{\text{Fraction III}}{\text{Total organic carbon}} \times 1$$

Statistical analysis

One way analysis of variance (ANOVA) was carried out to elucidate the effect of different agroforestry systems and soil depths on different soil parameters. Tukey test was used for multiple comparisons among the treatments at $p < 0.05$ using Indian NARS Statistical Computing Portal http://stat.iasri.res.in/sscnarsportal. Principal component analysis biplot was prepared using open software R.

Results and Discussions

Total organic carbon (TOC)

TOC content was significantly ($p \leq 0.05$) influenced by both AFS and soil depths (Table 2). On an average, the TOC in different AFS ranged from 5.55 to 6.64 Mg C ha^{-1}. Amongst the AFS , the top soil (0-15 cm) in PB-AFS had the highest (9.06 Mg C ha^{-1}) TOC followed by TB-AFS (8.43 Mg C ha^{-1}), while, the MB-AFS recorded the lowest (7.44 Mg C ha^{-1}) TOC content in soil. A variation in TOC under different AFS was strongly linked with the species characteristics and their litter input patterns[14]. Carbon dynamics in any system can also be related with adoption of different management practices along with their past cropping pattern[15]. Das and Chaturvedi[4] in Samastipur (Bihar) had reported that the annual litterfall accumulation by poplar trees under poplar + wheat-based agroforestry system ranged from 2.46 (3 years) to 10.63 (9 years) Mg $ha^{-1}yr^{-1}$. Contrarily, Rathore *et a*l.[16] reported that 10 years old agri-horticultural system (mango+cowpea-toria) accumulated around 1.46 t ha^{-1} of dry leaves biomass on the floor. This amount of litter biomass is far less than the litterfall added by poplar (2.46-10.63 Mg $ha^{-1}yr^{-1}$) as earlier reported by Das and Chaturvedi[4]. Irrespective of AFS, the TOC content in the surface soil (0-15 cm) was significantly higher than bottom layers (15-45 cm); registering a decrease of ~ 28% and ~ 50% in 15-30 cm and 30-45 cm soil layers, respectively. This might due to higher input of litter and dry biomass in surface soil as compared to the sub-surface layer[15].

Total organic carbon stock in soil (Mg C ha^{-1})

The TOC stocks varied from 12.08 to 13.81 Mg C ha^{-1} across the different AFS. In 0-15 cm soil profile, PB-AFS contained the highest (18.18 Mg C ha^{-1}) TOC stocks followed by TB-AFS based AFS (17.27 Mg/ha), while MB-AFS recorded the minimum (15.74 Mg C ha^{-1}) TOC stock. The significant variation in TOC stocks across the different AFS is correlated with TOC accumulation in the soil. Singh *et al*.[17] have reported that spatial and temporal admixture of various components in different AFS and their resulting *in-situ* interface with the abiotic components favored carbon storage. Significantly higher TOCS content was recorded in upper layer than lower layer of soil. On an average, the surface layer (0-15 cm) contained 35 % higher carbon stocks than the lower layers (15-45 cm) of soil. The rhizo-deposition effects caused by varied nature of different tree species have also significant influence on the distribution of SOC across the soil depth[18]. The mean stratification ratio (SR) (ratio of C stocks in 0-15: C stocks in 15-30 cm) as proposed by Franzluebbers[19], in our study sites of different AFS was 1.33, which is comparable with the finding of Ramesh *et al*.[14]

Distribution of different carbon fractions

Significant variations in different carbon fractions were observed across the different AFS throughout the depth (0-45 cm) of the soil profile (Table 2). Our results revealed that the very liable carbon fraction (FI) represented the highest proportion followed by recalcitrant fraction (F IV) in all the AFS. The pattern of distribution of different carbon fraction (different oxidability level) determines the permanency of SOC status of soil and this characteristic is largely influenced by adoption of several management activities[20]. The soil of PB-AFS had consistently contained the highest carbon fractions of different oxidasibilty than other counterparts. On the other hand, the MB-AFS had the lowest carbon fractions of different oxidisability. MBS-AFS and SB-AFS had recorded the minimum C pools and this could be partly linked with the intercrops grown under these systems; maize and potato, which are nutrient exhaustive crops, leading to more consumption of organic carbon from soil[21]. In this study, the order of allocating different carbon fraction (fraction I > fraction IV > fraction III > fraction II) was similar across AFS. Our result is consistent with the finding of Benbi *et al*.[22] where liable fraction represented the most dominating (56-60%) under PB-AFS in Punjab.

The percentage wise distribution of different carbon fractions indicated that liable form (fraction I and II) represented 51.50. The active carbon pool and passive carbon pool also showed significant difference due to variation in distribution of different forms of carbon fractions across the AFS (Figure 1). The continuous addition of leaf litter and dry matter in agroforestry floor enable to build up more liable carbon fraction across the different AFS and thus, necessitating the continuation of the current land use system in order to protect soil organic matter[23]. Moreover, the proper management of systems by farmers through incorporation of an adequate amount of farm yard manure as nutrient supplement for crop growth and development will also have a significant result on formation of very labile carbon fraction in the soil[24].

Soil microbial biomass carbon (SMBC) and Basal respiration (BR)

Overall, the SMBC in different AFS ranged from 103.08 and 131.65 ug g^{-1} (Table 2). Significantly higher value of SMBC was recorded in the surface layer than sub-surface layers in all the AFS and which can be attributed to higher availability of substrate and easily hydrolysable carbon in the upper soil layer[25]. In the 0-15 cm depth, significantly the highest SMBC was recorded in PB-AFS (219.36 ug g^{-1}) followed by TB-AFS (192.70 ug g^{-1}) while, the SMB-AFS had the lowest (161.23 ug g^{-1}) SMBC. Similar trends were also observed in both the sub-surface layers. Since, the TOC content in the soil was also the highest in the PB-AFS and this is the indication that the level of TOC content in the soil was highly correlated with SMBC[26]. The overall result on basal respiration across the different AFS shows that TB-AFS (0.41 µg CO_2-C g^{-1} hr^{-1}) registered the maximum BR but which is statistically at par with PB-AFS (0.40 µg CO_2-C g^{-1} hr^{-1}). However, in the upper soil depth (0-15 cm), PB-AFS recorded the highest (0.54 µg CO_2-C g^{-1} hr^{-1}) BR followed by TB-AFS (0.50 µg CO_2-C g^{-1} hr^{-1}) and the minimum under MB-AFS (0.34 µg CO_2-C g^{-1} hr^{-1}). This is the indication of higher biomass in

PB-AFS and TB-AFS and followed by high mineralization of litter (includes dry biomass) and root biomass and led to production of large CO_2 flux rates. Surface soil will have more CO_2 evolution rate than sub-surface soil due to higher inputs of litter and plant residues followed by better mineralization process[27].

Microbial quotient (MQ) was the highest under PB-AFS while TB-AFS recorded the highest microbial metabolic quotient (qCO_2) (Figure 2 and Figure 3). The microbial quotient (MQ) value of different AFS varied from 1.67 to 1.87 % and our results are comparable with the finding of Ramesh *et al*.[14] The maximum MQ under PB-AFS indicating higher steadiness of organic matter as MQ is generally related with the availability of C source for microbial activities. In this study, PB-AFS showed the lowest qCO_2 indicating better substrate utilization efficiency than other counterparts. The higher qCO_2 under TB-AFS and SB-AFS might be associated with the higher demand and their consumption of SOC. Bastida *et al.*[28] had also stressed that the disturbance caused by several factors primarily through intervention of different cultural practices is likely to affect the abundance of organic C in the system which is also responsible for producing varied qCO_2 under different land use systems.

Carbon Management Index (CMI)

The calculated CMI of different AFS (Figure 4) indicated that it ranged from 201.54 to 186.47 in 0-15 cm soil depth. Significantly higher CMI value was attained by PB-AFS but was statistically at par with TB-AFS and SB-AFS, while the least CMI was recorded under MB-AFS. PB-AFS achieved the maximum CMI value than the rest of AFS, indicating a large potential to have more C-stock. The dissimilarity in CMI value across the AFS was mainly attributed to the level of litter accumulation as well as root decomposition activities exhibited by different tree species, however, the effect of management practices also cannot be ruled out. The continuous addition of annual litterfall helps in building the SOC under agroforestry systems as compared to treeless farming and this is the indication of CMI value more than 100 in the present study. Higher value (>100) of CMI in agroforestry practices as compared with treeless farming has been reported by several workers[29, 30].

Principal Component Analysis (PCA)

The principal component analysis result revealed that the first two PC 1 and PC 2 represented 91.5% and 2 5.5%, respectively of the total variation (Figure 5). In PC 1 TOC followed by active carbon pool were found to be the most sensitive factor while microbial metabolic quotient (qCO_2) and BD influence the most in PC 2. Across the soil depth, it was found that all the studied soil parameters except qCO_2 and BD were found higher concentration in the surface layer (0-15 cm). So, all soil variables are positively correlation between each other except qCO_2 and BD as these two variables are negatively correlated with the remaining soil variables. And qCO_2 and BD were found to be the most influential factor in the soil group of 30-45 cm. In the present study, TOC was the most influential factor in PC1 as well in soil group of 0-15cm. TOC is heterogeneous, containing both liable and recalcitrant carbon forms. As a result, changes in different fractions of organic carbon will have an impact on the total amount of TOC in the soil. And more precisely, liable form of carbon can be easily influenced by changes in land management practices[31]. The greater qCO_2 values in the subsurface layers indicated that the microorganisms' substrate utilization efficiency decreases as soil depth increases.

Conclusion

Poplar based AFS had contained higher concentrations and greater amount of C as compared to other counterparts. The choice of intercrops (mustard, rice, wheat, potato, maize, moong, etc) and perennial components as well as management activities in different AFS largely depend on farmer's interest. This has led to the variation in the distribution and stability of soil organic carbon and its various forms in different AFS. Subsequently, this also has shown significant impact on the microbial activity (biomass and basal respiration) and thus has profound effect on the overall nutrient flux and dynamics of the system. Our study concludes that tree-based farming system, especially poplar based AFS could be considered as one of the viable options not only for carbon mitigation but also enhancing the profitability of the farmers belonging to Indo-Gangetic plains of Bihar.

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Table 1: Details of different agroforestry systems investigated

Agroforestry system (AFS)	Mean DBH* (cm)	Mean height (m)	Spacing (m)	Age of tree (years)
Teak based	12.64	7.80	4m ×4m (boundary plantation)	8-10
Poplar based	24.96	18.15	5m ×5m (boundary plantation)	5-6
Sissoo based	6.74	3.15	4m ×4m	5-6
Mango based	6.02	4.55	8m ×8m	5-6

*DBH=diameter at breast height (1.3m)

Table 2: Distribution of soil total organic carbon (TOC) and TOC stocks (Mg C ha^{-1}), carbon fractions (Mg C ha^{-1}), SMBC (µg g^{-1}) and basal respiration (µg CO_2-C g^{-1} hr^{-1}) at three depths in different agroforestry systems

Soil depth (cm)	TOC	C Stock	F1 (very labile carbon)	F II (labile carbon)	F III (less labile carbon)	F IV (non liable carbon)	Soil microbial biomass carbon	Basal respiration
TB-AFS								
0-15	8.43^{a}	17.27^{a}	3.13^{a}	1.40^{a}	1.44^{a}	2.46^{a}	192.70^{a}	0.50^{a}
15-30	6.06^{b}	13.11^{b}	2.05^{b}	1.07^{a}	1.13^{b}	1.81^{b}	111.64^{b}	0.40^{b}
30-45	4.29^{c}	9.69^{c}	1.20^{c}	0.81^{b}	1.01^{c}	1.27^{c}	49.65^{c}	0.33^{c}
Mean	**6.26^{B}**	**13.36^{A}**	**2.13^{A}**	**1.09^{B}**	**1.19^{A}**	**1.85^{B}**	**118.00^{B}**	**0.41^{A}**
PB-AFS								
0-15	9.06^{a}	18.18^{a}	3.28^{a}	1.59^{a}	1.38^{a}	2.81^{a}	219.36^{a}	0.54^{a}
15-30	6.51^{b}	13.71^{b}	2.04^{b}	1.22^{b}	1.08^{b}	2.17^{b}	112.26^{b}	0.47^{b}
30-45	4.34^{c}	9.54^{c}	1.35^{c}	0.79^{c}	0.93^{c}	1.27^{c}	63.32^{c}	0.18^{c}
Mean	**6.64^{A}**	**13.81^{A}**	**2.22^{A}**	**1.20^{A}**	**1.13^{AB}**	**2.08^{A}**	**131.65^{A}**	**0.40^{A}**
SB-AFS								
0-15	7.85^{a}	16.21^{a}	2.81^{a}	1.43^{a}	1.39^{a}	2.22^{a}	170.62^{a}	0.45^{a}
15-30	5.68^{b}	12.20^{b}	1.71^{b}	1.29^{a}	1.14^{b}	1.54^{b}	94.91^{b}	0.41^{a}
30-45	4.01^{c}	8.87^{c}	1.11^{c}	0.79^{b}	0.83^{c}	1.28^{c}	46.06^{c}	0.25^{b}
Mean	**5.85^{C}**	**12.43^{B}**	**1.88^{B}**	**1.17^{A}**	**1.12^{BC}**	**1.68^{C}**	**103.87^{C}**	**0.37^{B}**
MB-AFS								
0-15	7.44^{a}	15.74^{a}	2.92^{a}	1.13^{a}	1.25^{a}	2.14^{a}	161.23^{a}	0.34^{a}
15-30	5.40^{b}	11.93^{b}	1.64^{b}	1.03^{a}	1.08^{b}	1.65^{b}	101.46^{b}	0.34^{a}
30-45	3.81^{c}	8.57^{c}	1.03^{c}	0.71^{b}	0.84^{c}	1.23^{c}	46.55^{c}	0.23^{b}
Mean	**5.55^{C}**	**12.08^{B}**	**1.86^{B}**	**0.96^{C}**	**1.06^{C}**	**1.67^{C}**	**103.08^{C}**	**0.30^{C}**

Different small letters denote significant difference ($p \leq 0.05$) among the soil depths within the agroforestry system. Different capital letters denote significant difference ($p \leq 0.05$) between the agroforestry systems.

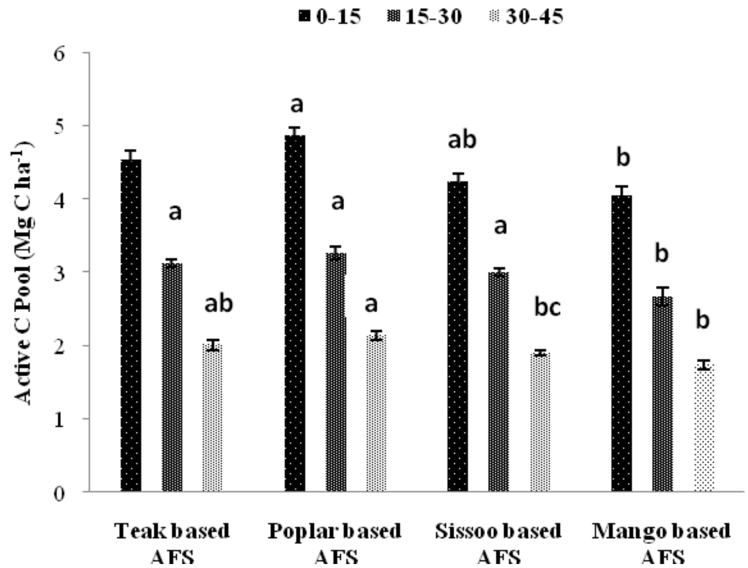

Fig. 1a: Active soil organic carbon pool

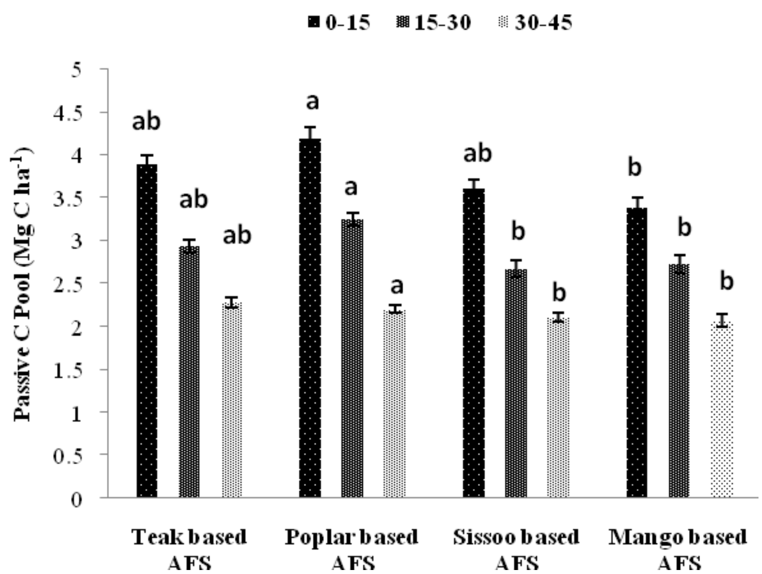

Fig. 1b: Passive soil organic carbon pool

Fig. 1**:** (a) Active and (b) Passive C pools in soil at three depths of different agroforestry systems Each bar represents the mean and standard error (n = 3). Means not sharing a letter in common differ significantly ($p \leq 0.05$) between same soil layers of different systems; ns = non-significant

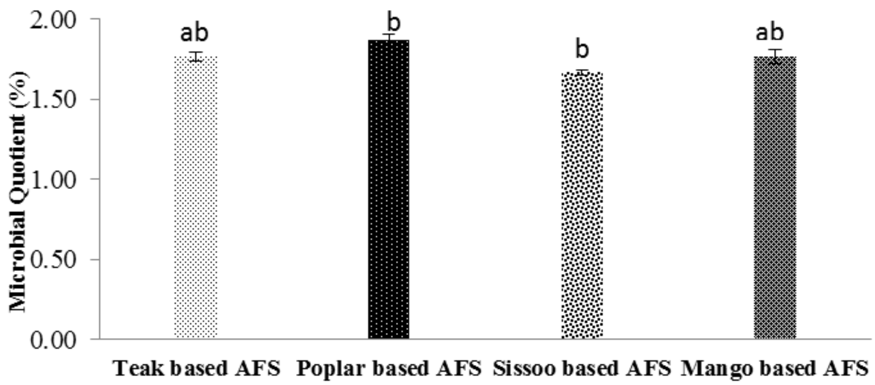

Fig. 2: Microbial quotient (MQ) of different agroforestry systems.

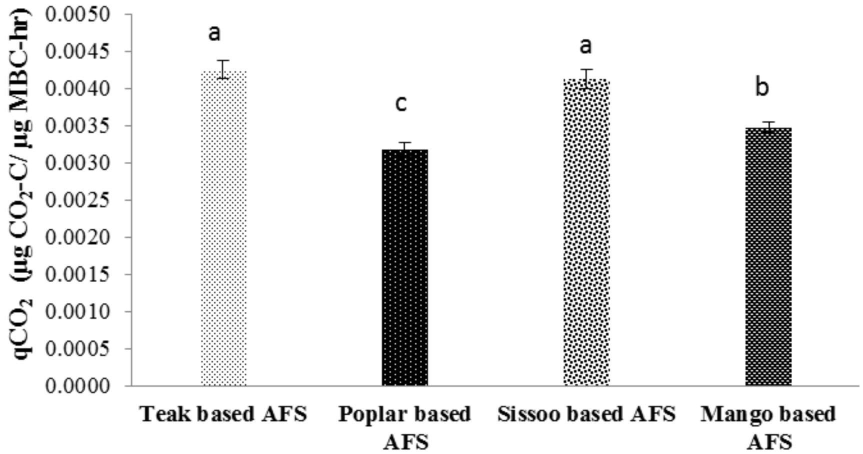

Fig. 3: Microbial metabolic quotient (qCO_2) of different agroforestry systems.

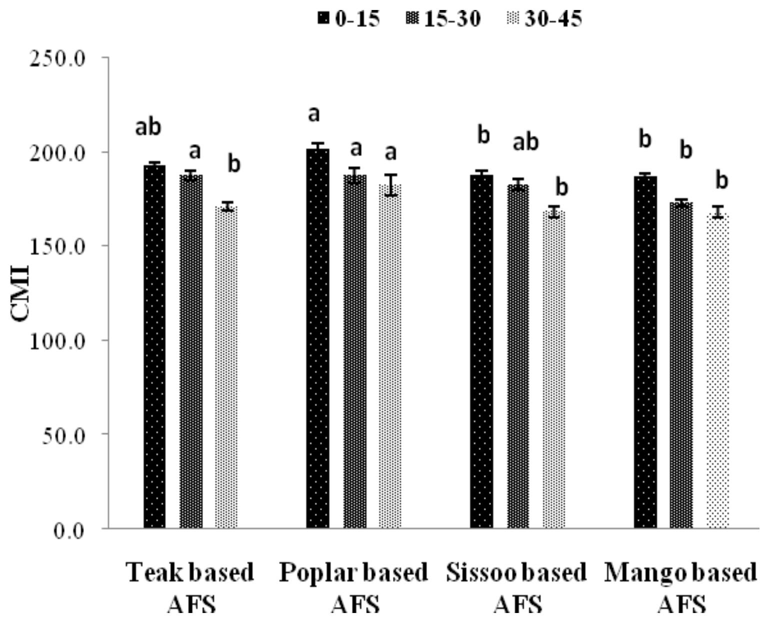

Fig. 4: Carbon management index (CMI) of different agroforestry systems

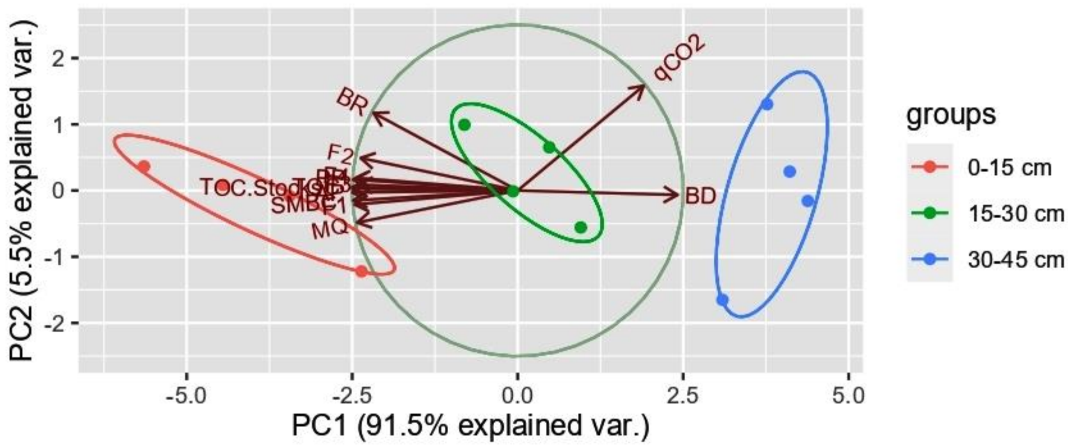

Fig. 5: Principal component analysis representing different soil parameters at three soil depths