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Carbon Pools and Nutrient Dynamics under *Eucalyptus*-based Agroforestry System in Semi-arid Region of North-west India

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Agroforestry systems play diverse ecosystem services. Soil properties are substantially altered in both surface and sub-surface layers by agroforestry systems. Information on the effect of agroforestry, land uses and seasonal soil samplings on soil properties and organic C dynamics is very limited. The present study investigates short-term (6-year-old) changes in *eucalyptus* (*Eucalyptus tereticornis*) based agroforestry and monocropped (2-years) sugarcane-sugarcane (*Saccharum officinarum*) system for soil physicochemical properties in the semi-arid region of north-west India. For this purpose, replicated soil samples with 15 cm interval up to 105 cm soil depth were collected before the onset of the monsoon in March 2013 and at the end of the rainy season (September 2013) for analyzing different soil properties. Microbial biomass C (MBC), Walkley and Black C (WBC), total organic C (TOC), macro and micronutrients concentrations decreased with soil depth. Averaged across depth, soil under *eucalyptus* had 17 and 77 per cent higher values of available N and P; 100 per cent higher DTPA extractable Zn and Cu; and 38 per cent greater Mn than monocropped sugarcane. Furthermore, *eucalyptus* based agroforestry system contained 22 and 13 per cent greater TOC stock; and 15 and 23 per cent greater MBC concentration in soils sampled in March and September 2013, respectively compared with monocropped sugarcane in averaged across depth of 105 cm soil layer. Despite surface soils in *eucalyptus* showed greater values of WBC in the month of September compared with March 2013, it was nearly similar for monocropped sugarcane system in both samplings.

Key words: Agroforestry, *eucalyptus*, organic C, C stock, microbial biomass C

Agroforestry occupies ~25.32 million hectare (Mha) or 8.2% of the total geographical area in India (Dhyani *et al*. 2013) and its area is expected to increase after the implementation and adoption of National Agroforestry Policy 2014. These systems emerge as an option for crop diversification in north-west India by enhancing productivity, net profitability and mitigating climate change (Chaudhari *et al.* 2014). *Populus* (*Populus deltoides*) and *eucalyptus* (*Eucalyptus tereticornis*) of block plantation dominate in this region. Trees combine with farm land tend to improve the ecosystem by regulating microclimate of site and changing physical structure, infiltration capacity, moisture regime and other chemical properties of soils. Furthermore, litter fall, root extension and crown expansion facilitate the nutrient cycling and organic matter build-up in the topsoil (0-15 cm), leading to improvement of soil properties in the root zone (Mukhopadhyay *et al*. 2016). In addition, agroforestry has a great impact on nutrient cycling and soil quality. Past studies have shown that soil organic carbon (SOC) and microbial biomass C (MBC) increased with plantation age, canopy cover and declined with soil depth for the *populus* and *eucalyptus* plantation in this region (Chaudhari *et al*. 2014; Kumar *et al*. 2014; Benbi 2015).

Soil C sequestration research has historically focused on the top 0-30 cm of the soil profile, ignoring deeper soil depths that might also respond to management practices (Syswerda *et al*. 2011). Meersmans *et al*. (2012) observed that appreciable amounts of stable SOC are stored at deeper soil depth for cropland, grassland, forest and vineyard/orchard with 2,158 profiles evenly (16×16 km^2) distributed in whole France. Despite their low C content, most subsoil horizons contribute more than half of the total

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soil C stocks, and therefore, it is needed to be considered in the global C cycle. Subsoil C stocks become additionally important because they primarily constitute the intermediate and passive soil organic matter (SOM) pools (Datta *et al*. 2015). The vertical distribution of C in soils is much deeper than the vertical distribution of roots, suggesting a decrease in SOC decomposition rate with soil depth (Gill and Burke 2002). Information on vertical distribution in C stock, MBC and soil fertility for sole crop and agroforestry systems in the semi-arid region of north-west India are rare. Moreover, most of the studies described only surface soil or hardly up to 60 cm soil depth. Therefore, the current study can strengthen our understanding of how different land uses vertically redistributes soil C and nutrients. In the present study, *eucalyptus* based agroforestry and monocropped sugarcane (*Saccharum officinarum*) system was compared to examine their impact on distribution of total organic C (TOC) stock and nutrients in different soil layers of the region. Accordingly, we hypothesized that: i) organic carbon content and soil fertility may vary with land use types; and ii) nutrient build-up and soil properties may differ with depth increment across the land use systems. To test these hypotheses, the objectives of the study were: i) to determine the impact of samplings and different land uses on organic C concentration and stock and soil properties in the 105 cm soil layer; and ii) to find out the short-term changes in SOC, MBC and soil fertility along soil depth for different land uses.

Material and Methods

Study site

Eucalyptus based agroforestry and sugarcane as a sole crop at Raina Farm, Kurukshetra, Haryana, India 29°57′30″ N, 76°59′40″ E, 257 m above mean sea level) were considered for the study (Fig.1). Kurukshetra has sub-tropical continental monsoon

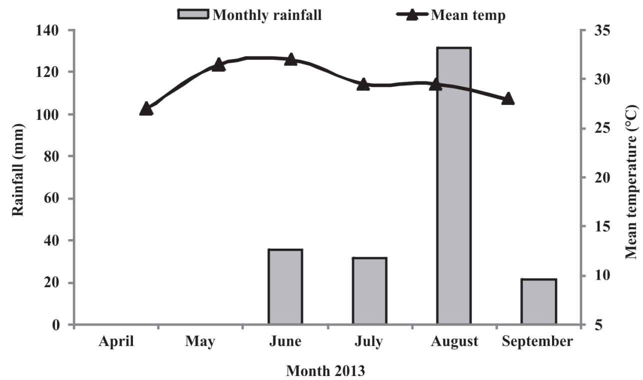

Fig. 2. Mean temperature and monthly rainfall of the study area during soil sampling events

climate and experiences extreme weather conditions. May and June are the hottest months, while December and January are the coldest season. The mean annual rainfall of Kurukshetra district is 582 mm for the last 30 years and is mainly received between June to September (monsoon period). The mean monthly temperature and rainfall during the study period are shown in fig. 2. The soil texture of the study site was sandy loam with slightly calcareous in nature having old alluvium and Banger series (Chaudhari *et al*. 2015). The soil of the study area showed a $pH_{1:2}$ of 7.50 to 8.47 and electric conductivity ($EC_{1:2}$) varied from 0.17 to 0.47 dS m^{-1}.

Six-year-old *eucalyptus* clonal plantation (clone no. 413) having tree density of 800 ha^{-1} and the monocropped sugarcane-sugarcane two-year system was studied. In *eucalyptus* based agroforestry system, for the first two years *i.e*. during establishment of the plantation, farmers grew sugarcane, followed by wheat (*Triticum aestivum* L.) and fodder sorghum (*Sorghum bicolor* L. Mocnch) and from fifth year they did not take any other crop in between the *eucalyptus* plantations (Fig. 3). The diameter at breast height (DBH) of six-years-old eucalyptus was 21.3 and 23.4 cm in March and September 2013, respectively while

Fig. 1. Location of study area (source: Google earth map)

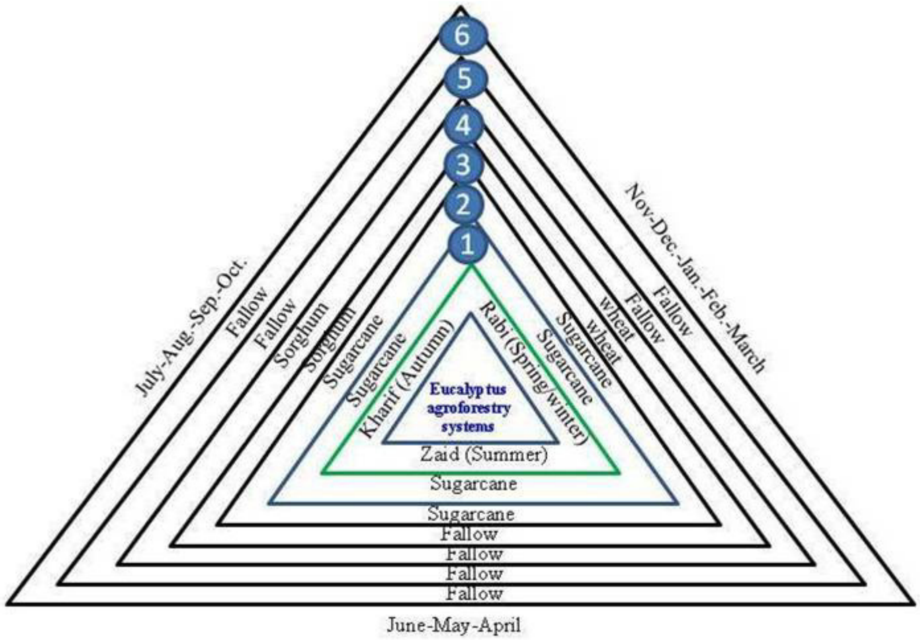

Fig. 3. Seasonal cropping pattern of the *eucalyptus* based agroforestry system

the total biomass were 198.3 and 203.6 t ha^{-1} in respective months. Fertilizers in sugarcane were applied as per the recommended dose of Haryana state (180: 60: 60 kg ha^{-1} of N, P_2O_5 and K_2O). Groundwater irrigation (6 cm) was given at 10 days interval in the pre-monsoon season (April to July 2013) at 25 days interval in the post-monsoon season (September to October 2013). However, between the study periods (2013), no chemical fertilizer and irrigation was applied.

Soil sampling and laboratory analysis

Soil sampling was carried out in two seasons (March and September 2013) in both the land uses. Soil samples were collected from 0-15, 15-30, 30-45, 45-60, 60-75, 75-90 and 90-105 cm depth of soil layer. There were 84 soil samples (3 replicates × 7 soil depths × 2 sampling event × 2 land uses). In sugarcane, during the first soil sampling, ratoon or stubble crop was present and during the second soil sampling, the crop was well established. All samples were immediately stored in sealed plastic bags (placed in a cooled ice bag) and transported to the laboratory. The soils were sieved (2-mm) and stored in sealed plastic bags at 4 °C until microbial analyses were completed. A part of soil sample was air-dried, ground in a wooden pestle with mortar, passed through a 2-mm stainless steel sieve and stored for subsequent analysis. The $pH_{1:2}$ and $EC_{1:2}$ of the soil were determined in 1:2 soil water suspension using a digital pH meter and digital conductivity meter (Jackson 1973). Walkley and Black C (WBC) was determined following wet digestion method (Walkley and Black 1934). Total soil organic C (TOC) was determined by digesting soil in digestion tubes with a mixture of 0.4 N $K_2Cr_2O_7$ and 18.0 N H_2SO_4 under 150 °C temperature for 45 min (Tiessen and Moir 1993). After cooling the mixture titration was completed against 0.2 N ferrous ammonium sulphate using *o*-phenanthroline, ferrous sulphate indicator. Depth-wise soil samples were collected using a metal core sampler (5.0 cm diameter and 5.0 cm length) for bulk density (BD) analysis.

Soil carbon stock

The total organic C stock was calculated as follows (Datta *et al*. 2015):

$$\text{TOC stock in soil} = \text{TOC} \times \text{BD} \times \text{Depth}$$

where, TOC concentration is given in g C kg^{-1}, BD in Mg m^{-3}, depth in m and TOC stock in Mg ha^{-1}.

Microbial biomass carbon (MBC)

Field moist samples stored at 4 °C were used to analyze MBC. Soil MBC was determined by fumigation extraction method (Vance *et al*. 1987). Equivalent to 50 g oven dry soils were fumigated with alcohol free chloroform in vacuum desiccator and stored in the dark for 24 h. After removing the fumigant (by repeated de-evacuation of chloroform

Table 1. Level of statistical significance of soil chemical properties

Parameters/ source of variation	Land use (LU)	Sampling event (SE)	Soil depth (SD)	LU × SE	LU × SD	SE × SD	LU × SE × SD
$pH_{1:2}$	< 0.001***	< 0.001***	NS	NS	0.016*	0.006**	0.031*
$EC_{1:2}$	NS	NS	0.015*	< 0.001***	0.032*	0.008**	NS
WBC	< 0.001***	NS	< 0.001***	0.018*	NS	NS	NS
TOC	< 0.001***	NS	< 0.001***	0.017*	NS	NS	NS
TOC stock	0.004**	NS	< 0.001***	0.017*	0.048*	NS	NS
MBC	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***
Available N	< 0.001***	< 0.001***	< 0.001***	0.024*	< 0.001***	< 0.001***	0.004**
Available P	< 0.001***	< 0.001***	< 0.001***	NS	< 0.001***	0.002**	NS
Available K	0.004**	NS	< 0.001***	NS	< 0.001***	0.008**	0.007**
DTPA-Zn	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***
DTPA-Mn	< 0.001***	< 0.001***	< 0.004**	0.001***	NS	NS	NS
DTPA-Cu	< 0.001***	NS	< 0.001***	NS	< 0.001***	NS	NS

Values with *** shows $p < 0.001$, ** shows $p < 0.01$,* shows $P < 0.05$ and NS - Non significant.

from the soils), the samples were extracted with 200 mL 0.5 *M* K_2SO_4 for 30 min on a shaker. The unfumigated soil samples were extracted similarly at the start of the experiment. The filtered soil extracts of both fumigated and unfumigated samples were analyzed for organic C using the acid dichromate method. The MBC was estimated using the multiplication factor (multiplying extractable C by 2.64). Here, extractable C is the difference between C extracted from fumigated and unfumigated samples, both expressed in the same measurement unit.

Available soil macronutrients (N, P and K) and DTPA extractable micronutrients (Zn, Mn and Cu)

The available N in the soil was determined by alkaline permanganate method (Subbiah and Asija 1956), available P by sodium bicarbonate (Olsen *et al*. 1954) and available K by neutral normal ammonium acetate method (Jackson 1973). Micronutrients were extracted with DTPA extractant (Lindsay and Norvell 1978) and estimated using an atomic absorption spectrophotometer (AAS).

Statistical analysis

Analysis was performed by Microsoft Excel and SPSS window version 17.0 SPSS Inc., Chicago, USA to determine the statistical significance of the land uses and depths. Simple correlation coefficients were also developed to evaluate relationships between SOC and other soil parameters using the same statistical package. Duncan's multiple range test (DMRT) at 5% level of significance was used to test the difference between means of individual treatments.

Results and Discussion

Physicochemical properties of soil

Significant differences in soil properties for two different land uses, sampling period, interaction between land uses and soil depths, sampling period and soil depths, land uses, sampling period and soil depths are depicted in table 1. Soil $pH_{1:2}$ and $EC_{1:2}$ indicated no consistent trends throughout the soil profile in both land uses and sampling seasons. However, both soil $pH_{1:2}$ and $EC_{1:2}$ were greater in the 15-90 cm soil layer (15-90 cm). The $EC_{1:2}$ indicated low salt content in the soils. Soil $pH_{1:2}$ values were greater in sugarcane than *eucalyptus* planation (Fig. 4). The increased $pH_{1:2}$ at lower soil depth for both land uses might be due to leaching and accumulation of basic cations in deep soil profiles. Averaged across soil depths, *eucalyptus* plantations had lower $pH_{1:2}$ than sugarcane. This might be due to the production of organic acids by root exudates and the decomposition of leaf, root debris litter in the soil profile (Swaminathan 2001). Therefore, it is reasonable to expect that different vegetations had diverse impact on soil properties when soils formed under similar parent materials and topography.

Organic carbon and total organic carbon stock

The WBC and TOC stock for both the land uses and different soil depths were significantly by ($p< 0.001$) different and the interaction between land use and sampling season was significant ($p< 0.05$). The WBC, TOC concentrations and TOC stocks in the *eucalyptus* based agroforestry system were 20.0, 17.5 and 18.0 per cent greater than the sugarcane

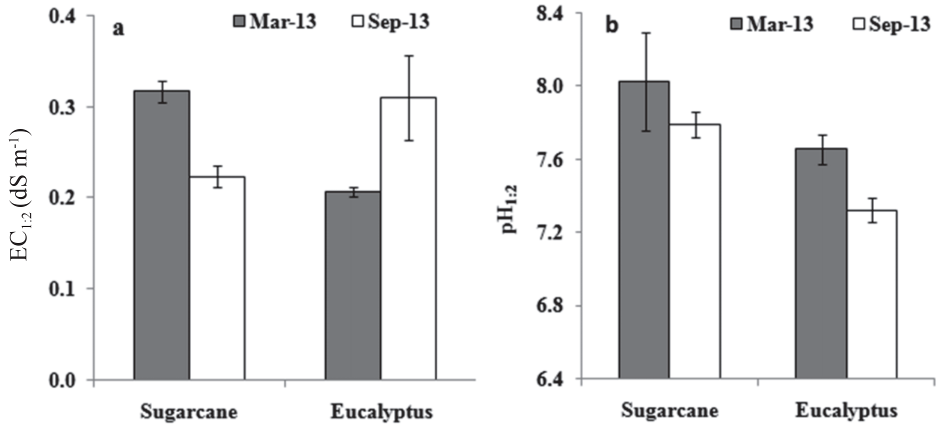

Fig. 4. Changes in soil $EC_{1:2}$ (a) and $pH_{1:2}$ (b) under monocropped sugarcane and *eucalyptus* based agroforestry systems in the average across soil layer of 105 cm depth; bars represent ± standard errors of mean

Table 2. Effect of land use on distribution of soil chemical properties along depth and sampling event

Soil depth	March 2013					September 2013				
(cm)	$pH_{1:2}$	$EC_{1:2}$ (dS m^{-1})	BD (Mg m^{-3})	WBC (g kg^{-1})	TOC (g kg^{-1})	$pH_{1:2}$	$EC_{1:2}$ (dS m^{-1})	BD (Mg m^{-3})	WOC (g kg^{-1})	TOC (g kg^{-1})
					Sugarcane					
0-15	7.60^{b}	0.36^{a}	1.15^{f}	3.83^{a}	4.21^{b}	7.63^{c}	0.18^{b}	1.12^{e}	4.23^{b}	4.65^{d}
15-30	8.17^{ab}	0.36^{a}	1.18^{e}	3.70^{a}	4.03^{bc}	7.67^{bc}	0.24^{ab}	1.15^{e}	4.59^{a}	5.01^{bc}
30-45	8.47^{a}	0.41^{a}	1.24^{d}	3.36^{b}	3.87^{c}	7.43^{c}	0.25^{a}	1.21^{d}	4.09^{b}	4.71^{cd}
45-60	8.10^{ab}	0.36^{a}	1.37^{c}	3.31^{b}	4.47^{a}	7.93^{ab}	0.24^{ab}	1.33^{c}	4.00^{b}	5.40^{a}
60-75	8.00^{ab}	0.27^{b}	1.39^{c}	2.93^{c}	4.07^{bc}	8.03^{a}	0.24^{ab}	1.37^{b}	3.71^{c}	5.16^{ab}
75-90	8.03^{ab}	0.25^{bc}	1.43^{b}	2.81^{c}	3.94c	7.93^{ab}	0.22^{ab}	1.40^{b}	3.01^{d}	4.22^{e}
90-105	7.83^{ab}	0.18^{b}	1.49^{a}	2.40^{d}	3.87^{d}	7.92^{ab}	0.20^{ab}	1.46^{a}	2.35^{e}	3.31^{f}
					Eucalyptus					
0-15	7.63^{bc}	0.23^{a}	1.10^{e}	5.59^{a}	6.21^{a}	7.53	0.29	1.14^{g}	5.67^{a}	6.29^{ab}
15-30	7.83^{a}	0.23^{a}	1.14^{e}	4.37^{b}	5.37^{b}	7.33	0.31	1.19^{f}	5.36^{a}	6.59^{a}
30-45	7.73^{ab}	0.22^{a}	1.20^{d}	4.02^{c}	5.55^{b}	7.40	0.31	1.23^{e}	4.77^{b}	6.58^{a}
45-60	7.77^{ab}	0.20^{ab}	1.33^{c}	3.54^{d}	4.96^{c}	7.40	0.31	1.34^{d}	4.22^{c}	5.91^{b}
60-75	7.53^{c}	0.21^{ab}	1.37^{bc}	3.46^{d}	4.94^{c}	7.20	0.31	1.38^{c}	3.23^{d}	4.26^{c}
75-90	7.60^{bc}	0.20^{ab}	1.41^{d}	2.60^{e}	4.15^{d}	7.07	0.31	1.43^{d}	2.29^{e}	3.67^{d}
90-105	7.50^{c}	0.17^{b}	1.47^{a}	2.40^{e}	4.15^{d}	7.30	0.34	1.49^{a}	1.70^{f}	2.94^{e}

$EC_{1:2}$: Electrical conductivity at 1: 2 soil and water ratio; BD: bulk density; WBC: Walkley and Black C; TOC: Total soil organic C; Values with the same lower case letters in a column denote no significant difference at $p < 0.05$ to Duncan Multiple Range Test (DMRT) for separation of mean within land use throughout the soil depth

system, irrespective of the soil depths (0-105 cm) and the sampling seasons (Table 2). Higher volume of litter fall, supply of pruned materials and dense rhizospheric root network (Chaudhari *et al*. 2015) increased the SOC build-up in the agroforestry. Additionally, changes in micro-climate *viz*., soil moisture, temperature, light, humidity, *etc*. under tree canopy of *eucalyptus* might have favoured more C hoarding and consequently greater SOC was noticed.

Microbial biomass carbon (MBC)

Average across soil layers, values of MBC were highly significant ($p< 0.001$) in both the land uses and sampling seasons. Their interactions, like land use × sampling seasons, land use × soil depth, sampling seasons × soil depth and land use × sampling seasons × soil depth *etc.* were also significant (Table 1). The MBC was ~15 per cent greater in *eucalyptus* based agroforestry system compared with sugarcane irrespective of soil depth. Our findings are in agreement with the studies of Kumar *et al*. (2014), who reported significantly greater MBC values in the canopy of *eucalyptus* compared to sub-canopy and adjacent open zones. The greater soil moisture and soil microbial diversity might encourage MBC of higher range. In addition, the quantity and quality of

Table 3. Distribution of macronutrients (kg ha^{-1}) within the soil profile in the land uses between the sampling events

Soil depth (cm)	Available N		Available P		Available K	
	Sugarcane	*Eucalyptus*	Sugarcane	*Eucalyptus*	Sugarcane	*Eucalyptus*
			March 2013			
0-15	280.5^{a}	238.9^{a}	28.4^{a}	61.2^{a}	238.7^{b}	295.2^{a}
15-30	194.2^{b}	235.2^{a}	26.3^{b}	60.3^{a}	252.4^{a}	286.6^{ab}
30-45	177.2^{c}	221.5^{ab}	21.9^{c}	31.0^{b}	232.9^{c}	249.0^{bcd}
45-60	163.0^{d}	210.1^{abc}	18.9^{d}	27.9^{bc}	226.8^{d}	274.4^{abc}
60-75	158.9^{e}	198.6^{bc}	18.9^{d}	23.9^{cd}	222.3^{e}	236.9^{cd}
75-90	132.5^{f}	193.2^{bc}	18.1^{d}	20.6^{de}	204.3^{f}	219.7^{d}
90-105	125.3^{g}	187.9^{c}	12.1^{e}	16.3^{e}	182.9^{g}	107.9^{e}
			September 2013			
0-15	293.2^{a}	248.3^{ab}	34.0^{a}	77.2^{a}	271.4^{a}	333.1^{a}
15-30	286.2^{b}	265.6^{a}	34.1^{a}	70.8^{a}	200.9^{c}	296.6^{b}
30-45	190.9^{c}	252.9^{ab}	28.4^{b}	40.1^{b}	249.4^{ab}	233.6^{c}
45-60	185.9^{d}	225.4^{bc}	24.5^{c}	26.0^{c}	233.7^{abc}	243.1^{c}
60-75	168.5^{e}	219.6^{c}	19.7^{d}	22.7^{cd}	226.6^{bc}	220.0^{cd}
75-90	153.5^{f}	200.1^{c}	18.1^{d}	22.5^{cd}	222.7^{bc}	180.1^{e}
90-105	112.4^{g}	162.3^{d}	12.7^{e}	15.5^{d}	190.2^{c}	195.5^{de}

Values with the same lowercase letters within land use in a column denote no significant difference at $p < 0.05$ according to DMRT for separation of mean throughout the soil depth

the rhizodeposition released by *eucalyptus* might have favoured more soil microbial biomass and its transformation in the soil (Sicardi *et al*. 2004). Averaged across soil layers (0-105 cm), MBC was 61 per cent higher in soils sampled in September 2013 (351.3 µg g^{-1}) compared to March 2013 sampling (217.2 µg g^{-1}). This may be attributed to relatively high quantity and quality of plant litter, owing to larger microbial biomass (Nsabimana *et al.* 2004). Variations in MBC and other soil microbial properties among cropping seasons for tropical soils under agroforestry were also reported earlier (Sicardi *et al*. 2004; Silva *et al*. 2012).

Macro and micronutrients

Available N, P and K significantly ($p < 0.001$) varied along soil depths for both the land uses (Table 3). Further, interaction effect of land use and sampling season for available P and K were similar ($p < 0.05$). Averaged across soil layers (0-105 cm), available N and P in *eucalyptus* based agroforestry system was ~17 and 77 per cent higher than sugarcane. For the same soil layer, available N and P were 9 and 16 per cent greater in September 2013 season than March 2013 season. This is probably due to higher decomposition and nutrient mineralization (Fig. 5a).

Available Zn (DTPA extracted) was highly significant ($p < 0.001$) with land use, sampling season, soil depth and the interactions among these factors (Table 1). The DTPA extractable Mn was highly significant ($p < 0.001$) with land use, sampling season and interaction between land use and sampling season. In addition, DTPA extractable Cu was significant ($p < 0.001$) for both land uses and interactions between land use and soil depth and sampling season and soil depth (Table 1). In the *eucalyptus* based agroforestry system, DTPA extractable Zn and Cu concentrations were two fold greater than the monocropped sugarcane. Whereas, DTPA extractable Mn was 38 per cent greater in the *eucalyptus* based agroforestry system compared to the sugarcane. Leaf litters and their decomposition under perennial vegetation of *eucalyptus* favour nutrients enrichment compared to regular crop removal in mono crop sugarcane system (Somasundaram *et al*. 2009). Contrarily, similar trend with respect to sampling season for enhancing the macro and micronutrients concentrations in soil were also observed (Fig. 5b). The DTPA extractable Zn and Mn were 20 and 37 per cent greater in September 2013 sampling compared with March 2013 sampling (Fig. 5b). Litter fall and favorable environmental conditions may facilitate the decomposition and consequently increase the concentration of available micro nutrients (Swaminathan 2001). Furthermore, on decomposition organic matter produce organic molecules which form chelates of micronutrient and increase their availability in soils.

Vertical distribution of SOC and MBC

For *eucalyptus*, within 0.6 m of soil depth, around 67-74% of WBC (out of 105 cm soil depth) was allocated. Greater amount of ether soluble

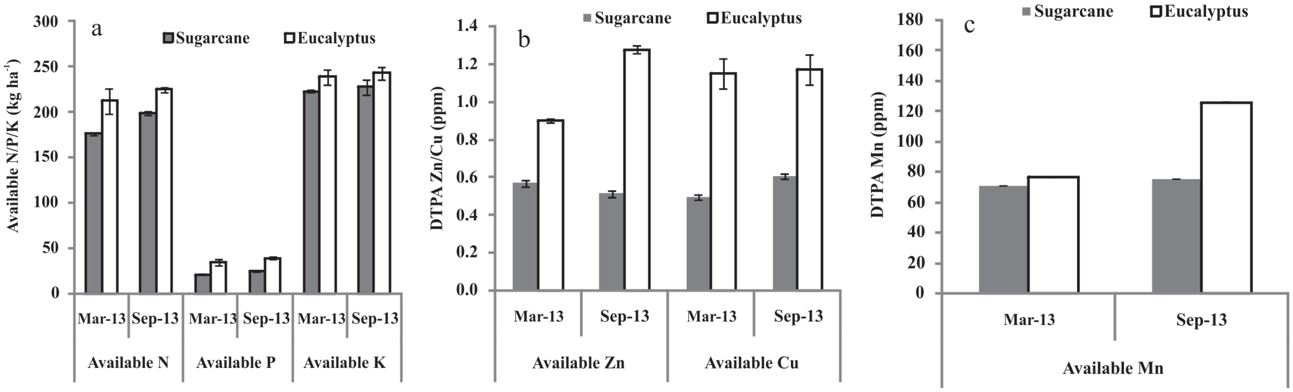

Fig. 5. Changes in available macro (a) and micronutrient (b and c) for monocropped sugarcane and *eucalyptus* based agroforestry system in the average across soil layer of 105 cm depth; bars represent ±standard errors of mean

extractives like fat and waxes, alcohol soluble extractives like resin, water soluble extractives (like free sugars) in the *eucalyptus* residues (Pande 1999) may contribute such a higher quantity of organic C. In *eucalyptus*, subsoil (30-105 cm) contained appreciable amount of WBC (60-62%, WBC 0-105 cm soil layers) of 0-105 cm soil layer, signifying the importance of subsoil horizons for C storage. This may be ascribed to relatively higher resistance C to oxidation in lower soil layers, indicating the turnover time of C was higher in sub-surface horizons (Gaudinski *et al*. 2000). Soil organic C in deeper horizons for forest soils may due to deposition of dissolved organic C and leaking of suberin from roots (Lorenz and Lal 2005).

In general, soil TOC stock and MBC declined with increasing soil depth. Averaged across soil depths (0-105 cm) TOC-stock for *eucalyptus* plantation was 23 and 14 per cent greater than monocropped sugarcane in March and September 2013 samplings (Fig. 6a and 6b). The increase in SOC was attributed to greater soil biological activities and greater C-input by litterfall, bark deposition, dead roots, and root exudates. The increment in SOC at subsoil layers could be ascribed to addition of organic matter through fine and coarse roots and their fast

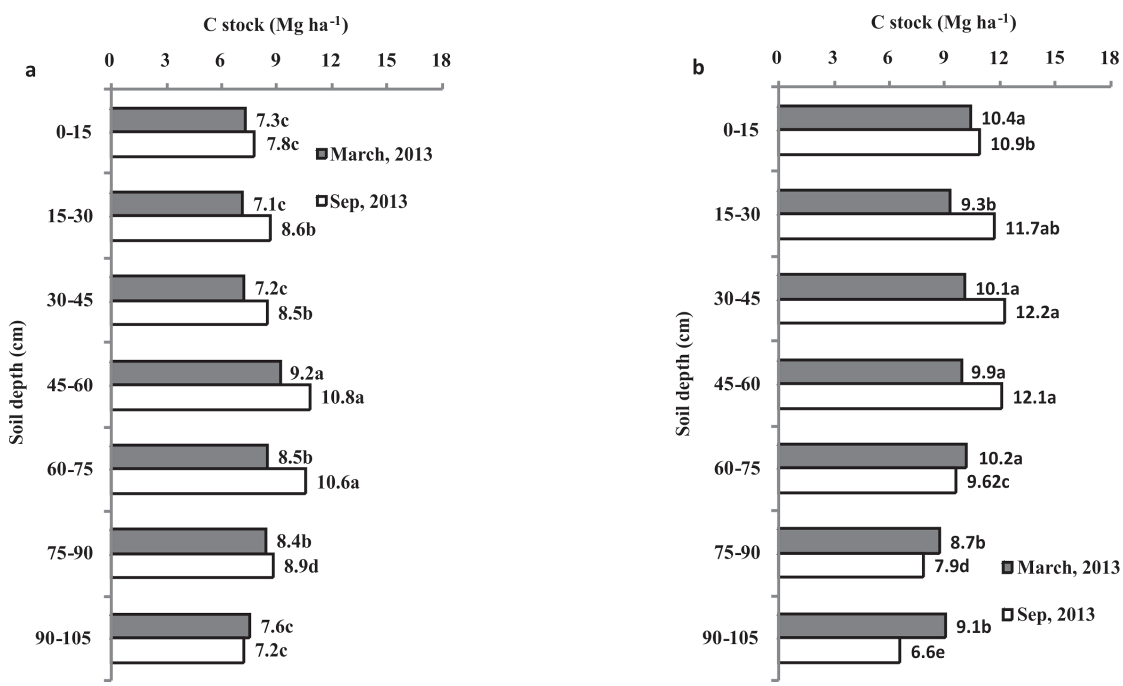

Fig. 6. Periodic changes in vertical distribution of C stock for monocropped sugarcane (a) and *eucalyptus* based agroforestry systems (b); different lowercase within the bar show the significant difference at $p < 0.05$ according to DMRT for separation of mean

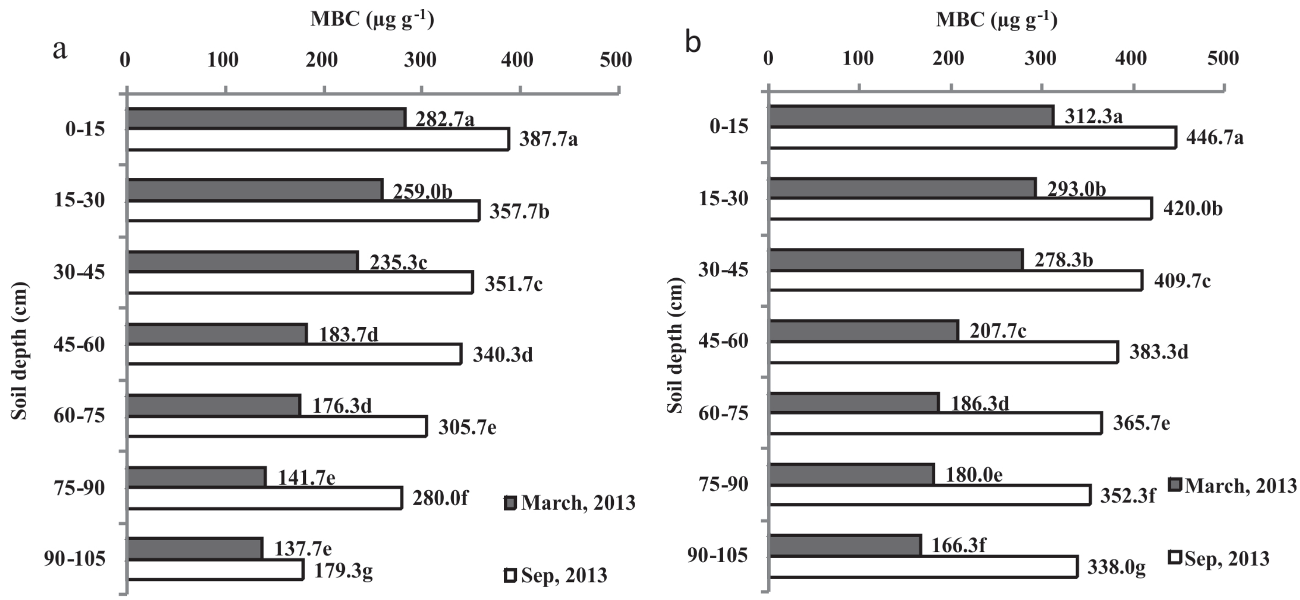

Fig. 7. Periodic changes in vertical distribution of MBC under monocropped sugarcane (a) and *eucalyptus* based agroforestry systems (b); different lowercase within the bars of the same parameter indicate significant differences at $p < 0.05$ according to Duncan Multiple Range Test (DMRT) for separation of mean

turn over (Chaudhari *et al*. 2015). Increased inputs of lignin and lipids from root litter at deeper horizons may resist the oxidation of organic C and more hoarding of C (Lorenz and Lal 2005). In addition, roots of the aged *eucalyptus* plantations secrets considerable amount of lignin or other recalcitrant compounds that contribute to minimal oxidation of SOC in deep soil layers compared to annual sugarcane crop (Datta *et al*. 2015).

Nearly 15 and 23 per cent greater value of MBC in the month of March 2013 and September 2013 samplings were found in soils under *eucalyptus* based agroforestry system than sugarcane (Fig. 7a and 7b). The difference in the quantity and quality of substrate inputs *via*. varying litter and root types and associated nutrients can be crucial drivers to influence the soil microbial biomass for land uses (Jin *et al*. 2010). The significant positive correlations ($r = 0.63^{**}$, $p < 0.01$) between MBC and SOC in the present study can support this. Fresh litter increases the soil microbial biomass and activity. The monsoon rain generally occurs in northwestern India during June to August. Naturally MBC might have altered by the sampling event before and after rainfall. Soils in sugarcane and *eucalyptus* had ~100 and 88 per cent more MBC in March 2013 in the 0-15 cm soil layer than the deep soil layer (Figs. 7a and 7b). Similarly, in September 2013, ~200 and 32 per cent increment in MBC in the surface soil layer was recorded compared to the deep soil layer, for the two cultivated systems. These findings corroborated with those of Silva *et al*. (2012) who observed higher values of MBC in surface layer of Haplic Acrisols in Brazil for 20-years-old regenerated forest than sugarcane grown crop land. Seasonal variations of soil microbial biomass reflected the degree of immobilization-mineralization of soil C and N. Decreased soil microbial biomass can result in mineralization of nutrients, whereas increased microbial biomass may lead to immobilization of nutrients.

In sugarcane, MBC/TOC ratio during March and September 2013 samplings were 63 and 25 per cent more in surface soil layer than deep soil layer. Whereas, in *eucalyptus* MBC/TOC ratio in upper soil depth increased by 20 and 5 per cent during March 2013 and September 2013 samplings than the lower depth (45-60 cm) (Fig. 8a and 8b). But, this ratio again increased for only *eucalyptus* plantation after 60 cm soil depth. Furthermore, this ratio was greater for *eucalyptus* (6.2) compared to monocropped sugarcane (5.9), irrespective of collection of samples for different soil depths and sampling seasons. Inhibition of microbial immobilization and production of more diversified organic substrate by cultivation of mixed species may indicate greater MBC/TOC ratio in the *eucalyptus* based agroforestry system compared with monocropped sugarcane.

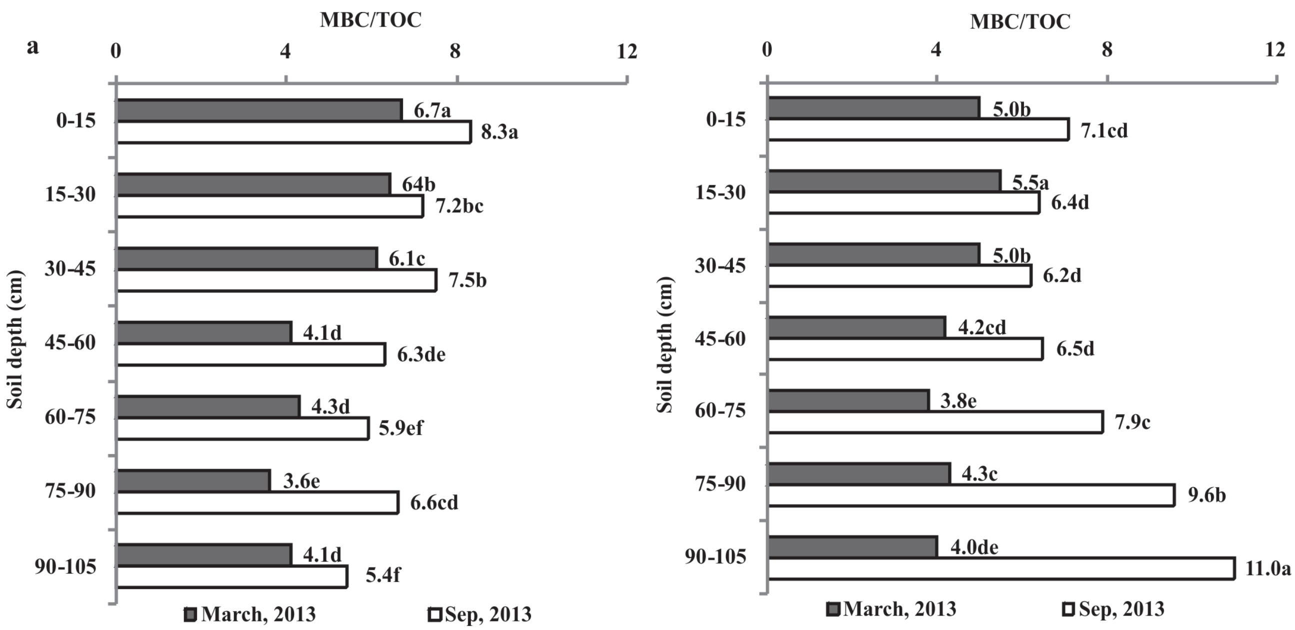

Fig. 8. Periodic changes in vertical distribution of MBC/TOC ratio under monocropped sugarcane (a) and *eucalyptus* based agroforestry system (b); different lowercase within the bars of the same parameter indicate significant difference at $p < 0.05$ according to Duncan Multiple Range Test (DMRT) for separation of mean

Vertical distribution of macro and micronutrient

Litter fall is an important component for the transfer of nutrients from plants to soil, and the litter layer is critical for nutrient retention in some ecosystems. In general, available N, P and K decreased with soil depth across the land use and sampling seasons (Table 3). Surface soil (0-15 cm layer) contained 200 per cent higher available N and P and 31 per cent higher K compared with lower depth (90-105 cm) for sugarcane. Whereas, such values were increased by 200 and 300 per cent for available N and P; and 43 per cent for K in surface soil depth compared to lower soil depth in September sampling. Similarly, in *eucalyptus* based agroforestry system, at surface soil (0-15 cm layer) available N, P and K increased by 27, 400 and 200 per cent, respectively in March 2013 sampling season compared to those in the deep soil layer (90-105 cm). Whereas, in September 2013 sampling, the increment in available N, P and K were 53, 500 and 70 per cent, respectively in surface soil layer over the deep soil layer (Table 3). Patterns of appreciable concentration of these nutrients in surface layer were attributed to greater uptake, scavenge from deeper soil layers and return to the soil surface through litter fall (Pinho *et al*. 2012).

For the sugarcane system, the increment in available P and K concentrations were ~20 and 14 per cent greater in September 2013 sampling compared with March in 2013. In the *eucalyptus* based agroforestry system, available P and K increased in September 2013 by 26 and 13 per cent compared to March 2013 sampling (Table 3). The marked increase in available N, P and K concentrations were directly related to the organic matter content. This was also evident from the correlation (r = 0.71**, r = 0.84** and r = 0.73*, $p< 0.01$) between WBC and available N, WBC and available P and WBC and available K (Table 5). The increase in available K concentration may be due to release of K from the K-bearing minerals and partly due to recycling of K on account of litter decomposition. In addition, the organic acids released during decomposition of residues and organic matter enhanced P release by reducing metal ions binding phosphates through chelation as well as by competing for exchange sites (Basak *et al*. 2016). However, the release of nutrients on decomposition varies with seasonal variability and would be less during winter because of low temperature. Contrarily, increased temperature and soil moisture during March to September 2013 favour the availability of P.

The inconsistency of micronutrients, particularly DTPA extractable Cu and Zn, with respect to soil depth had been reported by Sharma *et al*. (2009). But results of the current study were in contrast, indicated a decreasing trend with soil depth in both land uses

Table 4. Distribution of micronutrients (mg kg^{-1}) within the soil profile in the land uses between the sampling seasons

Soil depth (cm)	DTPA-Zn		DTPA-Cu		DTPA-Mn	
	Sugarcane	*Eucalyptus*	Sugarcane	*Eucalyptus*	Sugarcane	*Eucalyptus*
March 2013						
0-15	0.80[a]	1.38[a]	0.85[a]	1.99[a]	80.1[a]	87.9[a]
15-30	0.77[a]	1.40[a]	0.77[b]	1.72[ab]	77.3[b]	80.8[a]
30-45	0.70[b]	1.26[b]	0.66[c]	1.41[b]	81.8[a]	76.1[a]
45-60	0.54[c]	1.18[c]	0.50[d]	0.84[c]	68.4[c]	71.5[a]
60-75	0.43[d]	0.43[d]	0.33[e]	0.76[c]	57.1[e]	76.5[a]
75-90	0.43[d]	0.35[e]	0.25[f]	0.69[c]	61.1[d]	72.4[a]
90-105	0.33[e]	0.30[f]	0.10[g]	0.64[c]	68.9[c]	67.0[a]
September 2013						
0-15	0.89[a]	2.16[a]	0.93[a]	2.03[a]	84.0[a]	210.4[a]
15-30	0.65[b]	2.05[b]	0.92[a]	2.01[a]	77.0[c]	146.1[ab]
30-45	0.58[c]	1.75[c]	0.86[b]	1.21[b]	81.3[b]	139.5[ab]
45-60	0.43[d]	1.33[d]	0.75[c]	0.90[bc]	73.6[d]	81.8[b]
60-75	0.42[d]	0.76[e]	0.42[d]	0.77[c]	75.0[cd]	96.5[b]
75-90	0.34[e]	0.58[f]	0.24[e]	0.66[c]	69.5[e]	119.8[ab]
90-105	0.28[f]	0.31[g]	0.10[f]	0.61[c]	65.2[f]	84.3[b]

Values with the same lowercase letters within land use in a column denote no significant difference at $p < 0.05$ according to DMRT for separation of mean throughout the soil depth

and sampling events, except Mn for the *eucalyptus* based agroforestry system. The increment in DTPA extractable Zn and Cu for sugarcane was 11 and 9 per cent higher in September 2013 sampling than in March 2013 in the surface layer. Whereas, for surface layer, the *eucalyptus* based agroforestry system had ~56, and 200 per cent higher DTPA extractable Zn and Mn in September 2013 than in March 2013 sampling (Table 4). Nigussie and Kissi (2012) reported similar findings in Ethiopia while assessing the impact of four land uses namely, coffee, *eucalyptus* plantation, grazing and cultivated lands. The increase in these nutrients from March to September sampling may be attributed to favourable conditions, such as high temperature and soil moisture that fasten the decomposition of litter fall and sugarcane trash. Besides, the formation of chelates of micronutrient cations by the organic molecules have enhanced the availability of micronutrients in soils. Such an increase from April to October was also observed by Singh *et al*. (2007) under *Populus deltoides* based agroforestry systems in Punjab state of north-west Indian subtropical environment.

Correlation matrix

Soil $pH_{1:2}$ had significantly negative ($p< 0.01$) correlations with available N, MBC and MBC/TOC, whereas, significantly weaker negative ($p< 0.05$; n=84) correlations with DTPA extractable micronutrients (Zn, Mn and Cu) in irrespective soil layers (Table 5). The TOC and TOC stock showed significantly positive correlation ($p< 0.05$) with other soil properties, except $pH_{1:2}$ and $EC_{1:2}$. Similarly, MBC was positively ($p< 0.01$) correlated with all soil properties, except $pH_{1:2}$ and $EC_{1:2}$. Soil available macronutrients (N, P and K) had significantly positive correlations with MBC, TOC and DTPA extractable Zn, Mn Cu. Further, DTPA extractable micronutrients concentration in soils were enhanced with increasing MBC, WBC and TOC content. This might be due to the favour of organic chelating extracting agent (DTPA) to extract micronutrients from different organic pools (Sharma *et al.* 2003; Somasundaram *et al*. 2009). Significantly negative correlation between $pH_{1:2}$ and N (r = -0.35**), $pH_{1:2}$ and P (r = -0.19) and $pH_{1:2}$ and MBC/TOC ratio were observed (Table 5).

Conclusions

Land use change, sampling season, and soil depth had significant impacts on soil properties. Organic C content in monocropped sugarcane was 10 per cent higher in September 2013 sampling compared with March 2013 sampling. In addition, the *eucalyptus* based agroforestry system contained 22 and 13 per cent greater total organic C stock in March and September 2013 sampling compared with the monocropped sugarcane. Carbon stock, MBC, soil available macro and micronutrients status decreased with increasing soil depth. The current study will help to understand soil C build-up, redistribution of nutrients, microbial biomass carbon along the land uses and soil depth.

Table 5. Correlation matrix among different soil parameters irrespective sampling seasons

Soil properties	$pH_{1:2}$	WBC	TOC	BD	TOC stock	Available N	Available P	Available K	DTPA-Zn	DTPA-Mn	DTPA-Cu	MBC	MBC/TOC
$EC_{1:2}$	0.105	0.06	-0.036	-0.145	-0.107	0.097	0.072	0.114	0.162	0.275*	0.066	0.249*	0.336**
$pH_{1:2}$		-0.087	-0.215*	-0.027	-0.249*	-0.354**	-0.189	0.023	-0.247*	-0.259*	-0.262*	-0.457**	-0.404**
WBC			0.901**	-0.843**	0.644**	0.706**	0.838**	0.734**	0.815**	0.442**	0.813**	0.633**	-0.035
TOC				-0.596**	0.900**	0.613**	0.747**	0.607**	0.814**	0.435**	0.772**	0.597**	-0.137
BD					-0.197	-0.778**	-0.729**	-0.685**	-0.655**	-0.305**	-0.732**	-0.535**	-0.112
TOC Stock						0.340**	0.479**	0.369**	0.616**	0.335**	0.514**	0.429**	-0.249*
Available N							0.654**	0.481**	0.644**	0.392**	0.708**	0.670**	0.276*
Available P								0.737**	0.873**	0.638**	0.924**	0.598**	0.083
Available K									0.708**	0.366**	0.670**	0.465**	0.043
DTPA-Zn										0.607**	0.859**	0.634**	0.067
DTPA-Mn											0.535**	0.561**	0.281**
DTPA-Cu												0.604**	0.11
MBC													0.693**

**Correlation is significant at $p < 0.01$ level (2-tailed); *Correlation is significant at $p < 0.05$ level (2-tailed)

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