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Vertical distribution of soil chemical properties under different land use systems of Biligirirangana Hills, Karnataka

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ABSTRACT

Abstract*Globally, efforts are being made to identify land use types that could potentially improve carbon sequestration and soil fertility to ensure sustainable agriculture. Secondary nutrients and micronutrients in soil are crucial for improved crop output and require a detailed understanding of their status and sources of variation. Therefore, in order to evaluate the changes in soil chemical properties of soils, an experiment was conducted in Biligirirangana hills with soil samples from three soil depths i.e. 0-15, 15–30, and 30–45 cm of six prominent land-use systems viz. natural forest, a forest plantation, pure coffee system, coffee multi-storeyed system, agriculture mono, and mixed cropping systems. Among different land use systems (LUSs), significantly higher mean soil organic carbon and available nitrogen content were recorded in surface soils of natural forest (37.09 g kg^{-1}) and pure coffee system (414.99 kg ha^{-1}), respectively. The cation exchange capacity and percent base saturation were significantly higher in natural forest (28.22 cmol (p+) kg^{-1} soil and 76.56 % respectively) and lower in agriculture mono-cropping (13.83 cmol (p+) kg^{-1} soil and 39.50 %, respectively). The exchangeable calcium, magnesium, available sulfur and DTPA extractable micronutrients were higher in natural forest and tree-based LUSss compare to agriculture LUSss. The correlation analysis revealed that soil SOC had a positive effect on the availability of available secondary and DTPA extractable micronutrients in soils.*

***Keywords-** Soil organic carbon, available nitrogen, Soil secondary and micronutrients, land use systems.*

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1. INTRODUCTION

The increasing population and its corresponding demand for food in the midst of changing climate require the identification of land use types and management practices that can promote carbon sequestration and retention for agricultural sustainability and food security (Okolo et al, 2019). Globally, land-use changes associated with forestry and agriculture, such as deforestation and subsequent conversion to agriculture, are estimated to be responsible for 25 percent of the accumulated GHG (greenhouse gas) emissions (Achard et al., 2014). Despite 37% of total land globally being used for agriculture (Chen et al 2018, and World Bank 2019), the world still grapples with food production on a sustainable basis due to soil and land degradation, rising sea levels, climate change, and increasing population growth (F.A.O, 2016, and Trendov, et al, 2019). This could affect the soil properties of a given land when it is changed from natural to converted LUSs or vice versa.

In the Indian context, around 275 million people rely on forests for their livelihood or means of subsistence (World Bank 2006). Of these, around 89 million people belong to the marginalized communities known as Adivasis or Scheduled tribes. Soligas, an Adivasi community residing in the Biligirirangana Hills located in South-Western Karnataka are the unique extension of the Western Ghats. Shifting cultivation and more recently settled agriculture have historically been important sources of subsistence for these communities (Mundoli *et al.,* 2016). The Soliga community relocated to a stable agricultural area where the same plot of land was maintained and farmed continuously when this place was designated as a Sanctuary in 1974. One of the main causes of changes in land use and livelihood in the tropical forests is due to government policies that supported settled agriculture, combined with an ever-increasing demand for forest products from international markets, a changing climate, limited access to markets, and rising wildlife depredation, have increased rates of conversion of forests to plantation crops (Mundoli *et al.*, 2016).

The land use type could be determined by the need of the producer, the environmental condition (soil, climate, rainfall, altitude, etc.), socioeconomic status (landlord, tiller, or peasant), and political (tenure, land policy, and ownership) and cultural manners (beliefs, norms, and bylaws on the land) of the given area (DeFries et al., 2004). Land use changes affect basic processes such as erosion, soil structure, nutrient recycling, and carbon sequestration (Yoseph et al. 2017) and it greatly influences physicochemical properties (Paz-Kagan, et al. 2014) and affects the nutrient dynamics and supply (Agniva et al. 2018). Secondary (Ca, Mg, and S) and Micronutrients (Fe, Mn, Zn, and Cu) plays a vital role in the growth and production of crops through their involvement in regulating enzyme, cell wall formation, synthesis of chlorophyll, proteins, lipids, nucleic acids, carbohydrates metabolism and tolerance to stress, etc (Barker and Pilbeam, 2015). Soil secondary nutrients and micronutrient cycling and their distribution in soils have been known to be varied with a shift in the land use from forest to cultivated systems and differences in land use patterns and depth of soil (Han, *et al*, 2017, Paul *et al.*, 2018). The status of available micronutrients in soils depends on soil properties such as pH, EC, OC, clay and calcium carbonate ($CaCO_3$) content, land use patterns, and soil depths (Shukla *et al.*, 2014). Information soil secondary and micronutrient status when natural forest converted to different LUSss at different soil depths. We get the chance to acquire a deeper understanding of the aforementioned subject in forest-dwelling Adivasi farmers situated within a protected tiger reserve (Biligirirangana Hills). Our major objectives of the current study were to investigate 1) soil available secondary and micronutrients for different land use systems during the conversion of natural forest to agricultural fields.

2. MATERIALS AND METHODS

2.1. Description of the study site

Biligirirangana Hills is located in South-Western, Karnataka and it is the unique extension of the Western Ghats. The region constitutes a live bridge between the Eastern and Western Ghats. The region extends between 11^0 40′ – 12^0 06′ N latitude and 76^0 24′ – 77^0 46′ E longitude and the altitude ranges from 1400 – 1800 m above MSL. A location map of the study area is presented in Figure. 1. The Biligiris are Charnockite hills, covered with tropical dry broadleaf forest, part of the South Deccan Plateau dry deciduous forests ecoregion. The forests range from scrub forests at lower elevations, degraded by over-use, to the tall deciduous forests typical of the ecoregion, to stunted shola forests and montane grasslands at the highest elevations, which exceed 1800 meters. The region receives an annual rainfall of 1099 mm with the highest precipitation occurring in the month of September. The maximum and minimum temperature varied from 13.6 to 21.3^0 C and 28.3 to 36.3 ^{0}C, respectively (Figure 2).

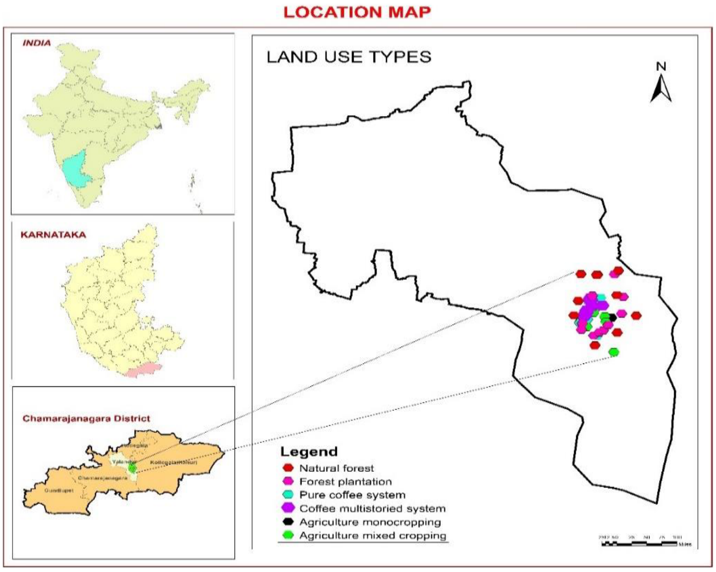


Figure 1. Location map of the study area

2.2. Selection of land use types

The dominant land use types selected were natural forest, a forest plantation, pure coffee system, coffee multi-storeyed system, agriculture mono, and mixed cropping systems. The details of the land use types have been described in Table 1.

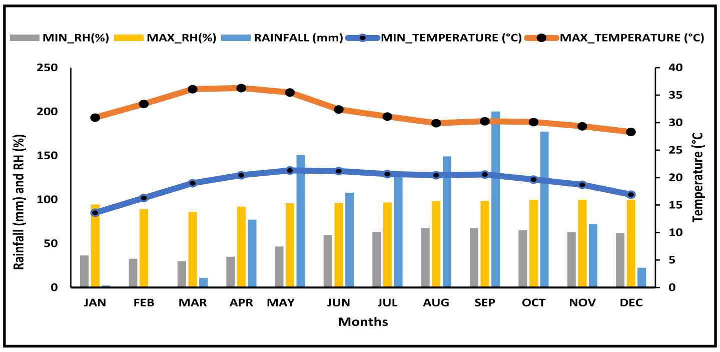


Figure 2. The climatic data of study area

Table 1 Description of land use types used in the study

Land use	Type of system Natural/Man made	Site characteristics	Source of external nutrient input	Other management practices
Natural forest	Natural	The research area is part of a type of dry deciduous forest (61.1%), which includes significant deciduous species including *Adina cardifolia, Anagesus latifolia, Bombax malabarica, Gemelina arborea, Terminalia tomentosa, and Terminalia Billericaetc.*	Nill	No tillage and letting litter fall to the ground to decompose.
Forest plantation	Man made	The study focused on teak plantations with aged 12 to 15 years.	Nill	In the plantation, soil conservation techniques included no tillage and letting litter fall to the ground to decompose.

Pure coffee plantation	Man made	Predominantly robusta coffee (*Coffeea canephora*) was grown under native tree species of *Terminalia tomentosa, Terminalia billerica, Syzygium cumini, Pteerocarpus marsupium, Cassia fistula and Grevilia robusta.*	Fertilizer + FYM	In the plantation, soil is minimal disturbance by adapting zero tillage, non-removal of cleared weed and punned plant parts, and left-to-rot litter fall from coffee and shade trees.
Coffee multi-storeyed system	Man made	Predominantly Robusta coffee (*Coffeea canephora*) was grown under native tree species along with pepper and other fruit trees (mango, citrus, Indian gooseberry etc.).	Fertilizer + FYM	In the plantation, soil conservation practices included zero tillage, non-removal of cleared weed, and left-to-rot litter fall.
Agriculture mono-cropping system	Man made	The area has been used for agriculture since 1990. A few of the crops grown are ragi, maize, cotton, and sorghum.	Fertilizer + FYM	Stubbles and roots residue, frequent tillage, sporadic pesticide use, crop residue clearance, and others.
Agriculture mixed cropping system	Man made	The agriculture land has been under cultivation since 1985. The crops cultivated Ragi + cowpea, maize with pulses,	Fertilizer + FYM	Stubbles and roots residue, frequent tillage, sporadic pesticide use, crop residue clearance, and others.

2.3. Land demarcation and soil sampling

Garmin eTrex 30x (global positioning system (GPS) device was used to record the boundary coordinates of the entire study site and each land use type. A stratified random sampling technique was used for soil sampling where GPS coordinates were recorded at each sampling point. In each LUS, ten mini pits were randomly dug and marked at 0–15 cm, 15–30 cm, and 30–45 cm depths. At each fixed soil depth, 1 soil sample were randomly collected resulting in a total soil sample of 180 (1 sample x 3 soil depths x 10 pits × 6 land use types) and then kept in labeled transparent plastic zip lock bags and sealed for laboratory analysis. These samples collected across the entire field were used for the determination of the spatial variation and vertical distribution of soil chemical properties.

2.4. Laboratory analysis of soil samples

Plant materials and clods were removed from the air-dried soil samples, crushed using a mortar with a pestle, and sieved through a 2 mm mesh sieve. The chemical properties analyzed in the laboratory soil organic carbon, cation exchange capacity, secondary and micronutrient contents. The determination of soil organic carbon was carried out by wet oxidation method (Walkley and Black, 1934), and available nitrogen by Subbaiah and Asija (1956). The neutral normal ammonium acetate extract was used to determine exchangeable calcium and magnesium content (Page et al., 1982). Sulfur was extracted using a 0.15 percent calcium chloride solution, and the amount of sulfur in the extract was determined using turbidimetry as described by Black (1965). The available micronutrients in soil were extracted with DTPA-extractant (0.005 M Diethylene Triamine Penta Acetic acid + 0.01 M $CaCl_2$ + 0.1 M Triethanol Amine) at a 1:2 soil-to-extractant ratio as described by Lindsay and Norvell (1978). The concentrations of zinc, iron, manganese, and copper in the extract were determined by an Atomic Absorption Spectrophotometer (AAS) under suitable measuring conditions (Page et al., 1982). The cation exchange capacity of the soil was estimated by the neutral normal ammonium acetate method Jackson (1973).

2.5 Statistical analysis

The statistical analysis of the experimental data gathered during the study was performed using the suitable analysis of variance (ANOVA) approach to examine the significance of the overall differences across treatments using the "F" test as described by Gomez and Gomez (1984). Using SPSS software, the data was statistically examined for different soil properties using a factorial approach (version 1.2.5042). When the "F" value was found to be significant, the Tukey HSD process was used to compare the means of different land uses and soil depths (Steel and Torrie, 1960). At the (P 0.05) level of significance, differences in land use mean were judged statistically significant.

3 Result and discussion

3.1 Chemical properties of soils under different land use systems

3.1.1 Soil organic carbon

The results of soil organic carbon (SOC) content of soil at different depths under different LUSs are presented in Table 2. The soil organic carbon content differed significantly with LUSs and depth. The soil organic carbon content of the surface soil was significantly higher (29.84 $g\ kg^{-1}$) than the lower soil layer (17.33 $g\ kg^{-1}$). Among different LUSs, the mean SOC content under the natural forest system (37.09 $g\ kg^{-1}$) was significantly high followed by forest plantation (31.82 $g\ kg^{-1}$). The mean SOC content in soils under a coffee multi-storeyed system (26.03 $g\ kg^{-1}$) was statistically on par with the pure coffee system (25.55 $g\ kg^{-1}$) but significantly higher than agricultural LUSs (Table 2). The interaction between the land use system and depth was found to be significant. A significantly higher SOC content of 45.9 $g\ kg^{-1}$ was recorded in the surface soil layer under natural forest type than the values found in the surface soil layer of other systems. Similarly, a significantly lower SOC content of 10.24 g kg^{-1} was found in agriculture mono-cropping systems.

Higher SOC content in natural forest, forest plantation, and coffee LUSs was mainly attributed to addition of larger amounts of litter biomass on surface soil and low oxidation process as the soils are less disturbed. Similar, higher SOC content in forest soils has been reported by Nagaraja (1997) and Yao *et al*. (2010). Sainepo *et al*. (2018) revealed different land use types had significantly different SOC where shrubland exhibited high levels of SOC which could be attributed to higher litter deposition, soil moisture content, C: N ratio and grazing management.

The higher SOC content in soils under coffee could be attributed to the addition of litter and pruned plant materials from shade trees and coffee plants and other management practices involving the addition of organic manures and fertilizers over the years helps to maintain the higher organic carbon level than other agriculture LUSs. Whereas, significantly lower SOC content was recorded in soils under the agriculture mono-cropping system (8.5 g kg^{-1}) than all other systems. The variation in SOC content among agriculture LUSs compared to other land uses could be attributed to variations in litter input and amount of FYM used, root growth, the extent of surface cover and soil erosion, type and time of tillage operation and addition of biomass and intensive cultivation practices (Doran 2002). The accumulation of organic matter in soils is the result of a balance between residue input rates and net decomposition rates as affected by soil temperature and moisture conditions (Murage *et al*., 2007). These results are corroborated by the findings of Shivakumar *et al*. (2020). Islam and Well (2000) reported that lower SOC in soil under paddy might be attributed to an imbalance in C input and output in the system. A decrease in soil organic carbon is observed as the impact of conversion from natural forest to coffee plantation (Karthika*et al.* 2020;; Dariah *et al.,* 2008).

The variation in soil organic carbon content may be attributed to variation in potential carbon returned to soil through the litter. This was evident in the significant positive correlation observed in the present investigation among litter C content and SOC content which suggest that as the plant carbon in litter increases the soil organic carbon. Takele *et al.* (2014) reported that the SOC decreases with increasing soil depth, with more accumulation on the upper surface soil layer. Toru and Kibret (2019) found that soil organic carbon and total nitrogen were significantly ($p<0.05$) affected by soil depth and land use under four major land uses *viz*., natural forest, coffee agroforestry, grazing land, and cropland in Hades sub-watershed, eastern Ethiopia.

3.1.2 Available nitrogen

The data on the available nitrogen status of soils as influenced by different LUSs at different depths are presented in Table 2. The difference in available nitrogen content with depth was significant. The soil available nitrogen content in surface soil was significantly higher (424.41 kg ha^{-1}) than that of subsurface soil (275.97 kg ha^{-1}). Among LUSs, the available nitrogen content was significantly higher in the pure coffee system (414.99 kg ha^{-1}) followed by coffee multi-storeyed system (410.81 kg ha^{-1}), natural forest (393.04 kg ha^{-1}) than other systems. Similarly, the lowest available N content of 263.42 kg ha^{-1} was recorded in the agriculture mono-cropping system and it was statistically on par with agriculture mixed cropping system (270.74 kg ha^{-1}). The interaction between depth and land use was significant. Thus, the maximum value of 495.49 kg ha^{-1} was recorded in surface soil of the coffee multi-storeyed system and the minimum value (185.02 kg ha^{-1}) was recorded in the subsurface layer (30-45 cm) of the agriculture mono-cropping system.

Soil organic matter (SOM) acts as a storehouse and supplier of N to plant roots and microorganisms, almost 95 percent of the total soil N is closely associated with SOM. The higher available N content in manmade systems especially under coffee plantations might be attributed to the application of very high dose of N fertilizers along with very high level of FYM. Similarly, the higher available N content under natural forest and forest plantation system might be attributed to the variation in quality and quantity of litter input and rate of mineralization. Secondly, the leguminous tree species in the natural forest might have fixed atmospheric N. Thus, the higher available N content was observed under natural forests. The amount so fixed along N derived from mineralization might be sufficient to replace the N removed through the litter. These results are in accordance with Shivakumar *et al.* (2020) who reported that higher available N content under natural systems namely evergreen and semi-evergreen compared to forest plantation systems *viz.,* teak and acacia might be attributed to the variation in quality and quantity of litter as it is derived from mixed vegetation type under natural system.

Further, the removal of vegetation by livestock grazing and exposure of soil surface may impact on the surface runoff due to direct drop of rainfall under agricultural land use system, which can remove the animal and plant residues from the surface soil layer thereby causing nitrogen depletion. Similarly, Nigussie and Kissi (2012), Ufot *et al*. (2016), Tufa *et al*. (2019) and Chemada *et al.* (2017) stated that the higher total N was obtained under forest land compared to the adjacent grazing and cultivated lands.

The soil available nitrogen content in surface soil was significantly higher (424.41 kg ha^{-1}) than that of subsurface soil (275.97 kg ha^{-1}) which may be attributed to the accumulation of more organic matter on the surface layer and its subsequent decomposition than the subsurface soil layer. These results are in conformity with the results obtained by Shivakumar (2020) explaining the presence of higher available nitrogen content in the surface layer than that of the subsurface layer of different LUSs. The contents of available nitrogen were strongly associated ($r = 0.875^*$) with soil organic carbon in all the depths and decreased consistently with increasing soil depth under all LUSs (Table 6). The results of the present study agree with the findings of many other workers Malo *et al*. (2005) and Heluf and Wakene (2006) reported that the decrease in available nitrogen with increasing depth was due to a decline in humus content with depth.

3.1.3 Cation exchange capacity

The data presented in Table 3 indicates that among different LUSs mean cation exchange capacity (CEC) values of soil were higher in natural forest (28.22 cmol (p+) kg^{-1} soil) and lower in agriculture mono - cropping (13.83 cmol (p+) kg^{-1} soil), while CEC of pure coffee and coffee multi-storeyed system was on par with each other. Among different soil depths, cation exchange capacity of surface soil depth (0-15 cm) were significantly higher (23.38 cmol (p+) kg^{-1} soil) than lower soil depth (30-45 cm) (18.72 cmol (p+) kg^{-1} soil). The CEC of soil differed significantly with land use (Table 3). Higher CEC of soil was recorded in the surface depth of natural forest and tree-based LUSs compare to agricultural LUSs, which might be due to high exchangeable bases and organic carbon resultin in the dissociation of its functional groups which providing more negative charges (Das et al., 2023: Karthika et al. (2020)). Shivakumar *et al*. (2020) reported that CEC of soil under the coffee system was significantly higher as compared to paddy LUSs. Das et al., 2023 and Shivakumar *et al*. (2020) observed a decline of CEC with soil depth along with a decline in SOM but unchanged clay content and composition.

Table 3: Cation exchange activity [cmol (p+) kg^{-1} soil] as influenced by different land use systems of Biligirirangana Hills

Land use systems	**CEC [cmol (p+) kg^{-1} soil]**				**Base saturation (%)**			
	Depth (cm)				**Depth (cm)**			
	0-15	**15-30**	**30-45**	**Mean**	**0-15**	**15-30**	**30-45**	**Mean**
Natural forest	30.65	29.27	24.71	28.22	73.26	76.70	79.72	76.56
Forest plantation	28.05	26.22	21.64	25.31	62.44	62.83	66.17	63.81
Pure coffee system	25.71	23.25	19.41	22.79	65.25	58.91	66.60	63.59
Coffee multistoried system	23.81	22.11	19.23	21.72	69.59	67.24	60.51	65.78
Agriculture mono-cropping system	14.60	13.59	13.27	13.83	42.39	43.13	32.97	39.50
Agriculture mixed cropping system	17.44	15.77	14.05	15.76	48.33	42.15	45.64	45.37
Mean	23.38	21.70	18.72		60.215	58.49	58.60	
Factors	**C.D.**	**SE (d)**	**SE (m)**		**C.D.**	**SE (d)**	**SE (m)**	
Land use	0.89	0.45	0.32		5.151	2.605	1.842	
Depth	0.63	0.32	0.22		NS	1.842	1.302	
Land use × Depth	1.55	0.78	0.55		NS	4.511	3.19	

NS: Non significant,

3.1.4 Base saturation (%)

The percent base saturation (PBS) values of soils were significantly affected by land use types but not among soil depths (Table 3). The PBS values range from 39.50 to 76.56 % from all the LUSs. The study site is situated in high rainfall area and these soils are basically derived from granite and granite gneiss which are silica-saturated igneous and metamorphic rocks, as a result the soils shows lower PBS (Anonymous, 2005). The highest mean value of PBS was found in natural forest (76.56 %) which was on par with forest and coffee plantations, and the lowest was observed in agriculture mono-cropping system (39.50 %). In all the LUSs, the PBS is significantly increased with increasing depths and the highest was recorded in surface soil depth (60.25 %). Natural forest and tree-based LUSs' surface soil depths recorded greater percentages of base saturation; these results were comparable to those of the soil's CEC and soil organic carbon content. Bouajila, *et al.* (2023) reported that FYM and Sulla amendment resulted in PBS increased up to 73.3% and 63.8% respectively compared to the soil control (50.6%). Relatively lower percent base saturation was recorded in agricultural LUSs because of nutrient removal resulting from forest clearance and less organic input with intensive tillage operation (Chimdie and Gurmessa, 2023).

3.1.5 Calcium and magnesium saturation (%)

Conversion of natural forest to different LUSs had a significant influence on the calcium and magnesium saturation in soil. The highest calcium and magnesium saturation were recorded in the surface depth of pure coffee (61.61%) and coffee multi storeyed systems (18.04%) when compared to other LUSs (Figure 3 and 4). Coffee and forest plantations, natural forest recorded higher Ca and Mg saturation values compare to agricultural LUSs, which might be due to the organic carbon of soil which increase cation holding capacity by increasing the CEC of soil (Chimdie and Gurmessa, 2023).

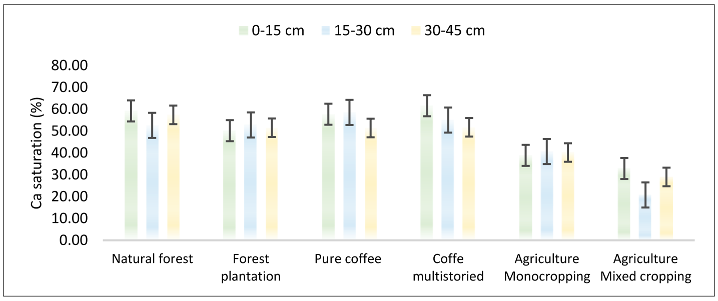


Figure 3: Calcium saturation (%) as influenced by different land use systems of Biligirirangana hills

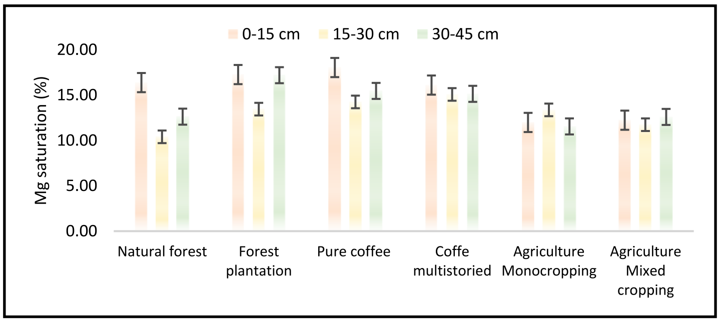


Figure 4: Magnesium saturation (%) as influenced by different land use systems of Biligirirangana hills

3.2 Secondary nutrients

3.2.1 Exchangeable calcium

The data on exchangeable-Ca content in soils under different LUSs are presented in Table 4. Calcium content in soils differed significantly due to the land use system. The significantly higher calcium content (10.62 cmol (p+) kg^{-1}) was recorded in natural forest soils and which was on par with the coffee multi-storeyed system (10.38 cmol (p+) kg^{-1}). The highest exchangeable calcium content (10.62 cmol (p+) kg^{-1} was recorded in natural forests (Table 5) compare to agriculture, pure coffee system may be attributed to higher turnover of organic matter having higher

Ca, and its mineralization was the cause for the higher available Ca in soils. The recycling of litter having a higher amount of Ca keeps this element in continuous circulation in the system. These results are in accordance with the findings of Geetha (2005) reported that the exchangeable calcium content in surface soils under high rainfall areas was highest in evergreen forest vegetation followed by moist deciduous forest. However, the quantity of calcium content in soils under plantations such as teak systems is comparable with each other. In coffee plantations, the exchangeable calcium content was higher may be attributed to the recycling of higher litter and the application of agricultural lime and dolomite ($CaCO_3MgCO_3$) in coffee plantations might have enhanced exchangeable (Shivakumar *et al*. 2020) and Karthika *et al.* (2020) found that coffee soils recorded relatively exchangeable Ca and Mg than forest soils in all the profiles. The calcium content in soil was positively correlated with SOC (r = 0.296), CEC (r = 0.418) and PBS (r = 0.629) in all the soil depths (Table 6).

The lowest (3.88 cmol (p+) kg^{-1}) value exchangeable-Ca was recorded in the agriculture mixed cropping system which was on par with the agriculture mono-cropping system (4.46 cmol (p+) kg^{-1}) which might be due to erosion loss and variation in litter input and rate of decay and leaching. Secondly, the soils in the hill zone are predominantly kaolinitic and consequently had low negative charge density to hold cation in exchange surface. Further, these cations are not adsorbed; they are susceptible for leaching in high-rainfall areas. Besides, the variation may also be attributed to management practices adopted to grow these crops. Lima et al. (2022b), analyzing the forest-to-pasture conversion, also found low levels of Ca2+, Mg2+ and K+ in the first layers of soil in cultivated areas. Prabhudev (2011) has also opined that leaching is the main cause of low availability.

Calcium content in soils differed significantly with depth. Surface (0-15 cm) soil had higher NH_4OAC - Ca content (9.34 cmol (p+) kg^{-1}) than subsurface (30-45 cm) soil (7.15 cmol (p+) kg^{-1}). The variation in depth could be attributed to low-activity clay and organic matter content in the subsurface soil. Arevalo *et al.* (2009) stated that the increase in exchangeable Ca and Mg with soil depth were likely to have been brought about by weathering and leaching. Constant mixing of the soil by ploughing and disking of the soil surface release more exchangeable Ca and Mg, which are leached to subsurface layers with precipitation and infiltration. Salve *et al.* (2018) reported that exchangeable Ca (5.52 mg/100g) was significantly higher in agri–the horti-silviculture system and at 0–15 cm depth (6.03 mg/100g). Interaction between depth and land use showed a significant difference and the highest value of 11.90 cmol (p+) kg^{-1} was recorded in the surface soil of natural forest followed by coffee multi-storeyed system (11.79 cmol (p+) kg^{-1}).

3.2.2 Exchangeable magnesium

The data relating to exchangeable Mg in soils under different LUSs is presented in Table 4. The concentration of NH_4OAC-Mg varied significantly between LUSs, ranging from 3.11 to 5.54 cmol (p+) kg^{-1}. Soils under the forest plantation had a higher Mg content of 5.54 cmol (p+) kg^{-1}, which was significantly higher than soils under natural forest (3.94 cmol (p+) kg^{-1}), agriculture mono-cropping (3.28 cmol (p+) kg^{-1}), and agriculture mixed cropping (3.11 cmol (p+) kg^{-1}), and other systems were comparable. There was no significant variation in exchangeableMg with depth, but surface soils (4.62 cmol (p+) kg^{-1}) contained higher exchangeableMg than subsurface (30-45 cm) samples (4.12 cmol (p+) kg^{-1}). Furthermore, there was no significant variation between land use and depth.

Higher exchangeableMg content was recorded in forest and coffee plantations compared to agricultural LUSs. This kind of variation was mainly attributed to management practices being practiced and the quantity and quality of litter input added to the particular land use. Application of dolomite ($CaCO_3MgCO_3$), for instance, in coffee plantations might have enhanced exchangeableMg content in soil under these crops. Similar observations were also reported by Prabhudev (2011). While agriculture's land use system has a lower amount of organic matter, intensive cultivation, leaching and erosion loss of exchangeable Mg through percolating water might have reduced Mg content (Shivakumar *et al*., 2020: Lima et al. (2022b).

3.2.3 Available sulphur

The data on depth-wise changes in the available sulphur status of soils under different LUSs are presented in Table.4.

The available sulfur content differed significantly with depth, so the available sulphur value (49.62 mg kg^{-1}) of surface soil was higher than that of subsurface (30-45 cm) layer soil (25.73 mg kg^{-1}). Similarly, the available sulfur content differed significantly among LUSs. The available sulfur content in soils under multi-storeyed coffee soils was significantly higher (49.31 mg kg^{-1}) than in pure coffee system (46.79 mg kg^{-1}), natural forest (43.62 mg kg^{-1}), forest plantation (39.12 mg kg^{-1}), agriculture mixed system (25.21 mg kg^{-1}) and agriculture mono-cropping system (18.81 mg kg^{-1}).

In the interaction of land use and depth, a maximum available sulfur content of 62.96 mg kg^{-1} was observed in the surface soil layer of natural and a minimum available sulphur content of 12.26 mg kg^{-1} was observed in the subsurface (30-45 cm) layer of an agriculture mono-cropping system.

When compared to agricultural mono and mixed systems, the available sulfur level in soils under coffee plantations was much higher, followed by natural forest (Table 4). The reason for this could be due to increasing soil organic carbon content (Table 4), which reduces sulfate ion leaching. Second, the use of S-containing fertilizers (single super phosphate or ammonium

Table 4: Secondary nutrients status as influenced by different soil depths and land use systems of Biligirirangana Hills

Land use systems	**Exchangeable Ca (cmol (p+) kg^{-1})**				**Exchangeable Mg (cmol (p+) kg^{-1})**				**Available S (mg kg^{-1})**			
	Depth (cm)				**Depth (cm)**				**Depth (cm)**			
	0-15	**15-30**	**30-45**	**Mean**	**0-15**	**15-30**	**30-45**	**Mean**	**0-15**	**15-30**	**30-45**	**Mean**
Natural forest	11.90	10.32	9.64	**10.62^{a}**	3.70	4.20	3.92	**3.94^{bc}**	62.96	39.72	28.18	**43.62^{b}**
Forest plantation	11.39	10.83	8.17	**10.13^{ab}**	5.50	6.50	4.61	**5.54^{a}**	52.27	37.75	27.35	**39.12^{c}**
Pure coffee system	11.32	8.53	8.14	**9.33^{b}**	6.20	5.24	4.89	**5.45^{ab}**	60.59	45.86	33.92	**46.79^{ab}**
Coffee multistoried system	11.79	9.86	9.48	**10.38^{a}**	5.23	5.04	5.76	**5.35^{ab}**	60.71	49.33	37.88	**49.31^{a}**

Agriculture mono-cropping	4.99	4.43	3.97	**4.46**^{c}	3.79	3.31	2.73	**3.28**^{c}	27.14	17.02	12.26	**18.81**^{e}
Agriculture mixed cropping	4.64	3.52	3.47	**3.88**^{c}	3.28	3.24	2.81	**3.11**^{c}	34.05	26.75	14.81	**25.21**^{d}
Mean B	**9.34**	**7.92**	**7.15**		**4.62**	**4.59**	**4.12**		**49.62**	**36.07**	**25.73**	
Factors	**C.D.**	**SE(d)**	**SE(m)**		**C.D.**	**SE(d)**	**SE(m)**		**C.D.**	**SE(d)**	**SE(m)**	
Land use	0.48	0.24	0.17		0.85	0.43	0.30		2.02	1.02	0.72	
Depth	0.34	0.17	0.12		NS	0.30	0.21		1.43	0.72	0.51	
Land use * Depth	0.83	0.42	0.30		NS	0.74	0.53		3.50	1.77	1.25	

NS: Non significant, Mean followed by the same letter are not significantly different based on Tukey's HSD ($P<0.05$).sulfate) and $CuSO_4$ (bordeaux mixture) could be contributing to the elevated S levels in that system. In coffee plantations, Shivakumar *et al*. (2020) and Prabhudev (2011) observed comparable results in terms of S availability. Herojith Singh *et al*. (2007), with the higher available sulfur content ascribed to higher organic matter content.

3.4 DTPA extractable micronutrients (mg kg^{-1})

3.4.1 DTPA-Fe

DTPA extractable Fe content in soils differed significantly with depth and LUSs (Table 5). The surface soil layer had significantly higher DTPA-Fe levels (33.38 mg kg^{-1}) than the subsurface soil layer (30-45 cm) (24.24 mg kg^{-1}). While the amount of DTPA-Fe was significantly higher in soils under forest plantation (42.32 mg kg^{-1}) than in soils under natural forest (36.80 mg kg^{-1}), coffee multi-storeyed system (31.98 mg kg^{-1}), pure coffee system (28.85 mg kg^{-1}), agriculture mixed cropping (15.92 mg kg^{-1}). The amount of DTPA-Fe was significantly lower in agriculture mono-cropping (15.13 mg kg^{-1}) compare to other land uses. Kumar *et al.* (2009) showed that DTPA–extractable Fe and Mn (but not Zn and Cu) in soil declined from their respective initial values as a result of intensive cropping for more than three decades in long-term experiments in New Delhi, India. The interaction effect of depth x land use was non-significant, thus the higher value of 46.88 mg kg^{-1} DTPA-Fe was recorded in surface soils of forest plantation and lower value was recorded in subsurface soils under agriculture mono-cropping (11.22 mg kg^{-1}).

3.4.2 DTPA-Mn

The data presented in Table 5 revealed that DTPA-Mn content in soils differed significantly with depth and LUSs. However, the effect of the season was non-significant.

Significantly lower (20.17 mg kg^{-1}) DTPA-Mn content was recorded in the subsurface (30–45 cm) soil layer as compared to the surface soil layer (25.76 mg kg^{-1}). However, the amount of DTPA-Mn was significantly higher in soils under forest plantation (28.33 mg kg^{-1}), which was on par with natural forest (27.98 mg kg^{-1}) and pure coffee systems (26.12 mg kg^{-1}) followed by the coffee multi-storeyed system (22.99 mg kg^{-1}). A significantly lower amount of 14.86 mg kg^{-1} was recorded in soils under the agriculture mono-cropping system, which was on par with the agriculture mixed cropping system (16.27 mg kg^{-1}).

The interaction effect of depth and land use was non-significant. However, a numerically higher value of 31.68 mg kg^{-1} DTPA-Mn was recorded in surface soils of pure coffee plantations and lower value was recorded in subsurface (30-45 cm) soils under agriculture mono-cropping (12.04 mg kg^{-1}).

3.4.3 DTPA-Zn

The data on the DTPA-Zn content of soils under different LUSs are presented in Table 5. The soil DTPA-Zn showed a significant difference among LUSs. The highest mean DTPA-Zn content was found in the coffee multi-storeyed system (2.71 mg kg^{-1}), followed by the pure coffee system (2.60 mg kg^{-1}), and forest plantation (2.43 mg kg^{-1}). A significantly lower amount of mean DTPA-Zn was found in the soil of agriculture mixed cropping (1.18 mg kg^{-1}), which was on par with agriculture mono-cropping (1.31 mg kg^{-1}). Similarly, the available zinc content decreased with depth. A significantly higher amount of DTPA-Zn was found in surface soil (2.69 mg kg^{-1}) as compared to the subsurface (30–45 cm) soil layer (1.47 mg kg^{-1}). The interaction effect of depth x land use was significant, thus the higher value of 3.52 mg kg^{-1} DTPA-Mn was recorded in surface soils of pure coffee plantations and the lower value was recorded in subsurface (30-45 cm) soils under agriculture mixed cropping (0.85 mg kg^{-1}). These results were in line with Shivakumar,(2013) who reported that the highest DTPA zinc availability was found in the coffee system (1.81mg kg^{-1}) followed by paddy (1.51 mg kg^{-1}), areca nut (1.36 mg kg^{-1}) and banana (1.27 mg kg^{-1}). Significantly, a lower amount of available Zn was found in the soil of the grassland system (0.93 mg kg^{-1}).

3.4.4 DTPA-Cu

The data on DTPA-Cu content in soils, as influenced by depth and LUSs, are presented in Table 5. The mean DTPA-Cu content of soil varied significantly among LUSs and depths. Soils under pure coffee (1.74 mg kg^{-1}) had the highest mean DTPA-Cu content, which was on par with natural forest (1.72 mg kg^{-1}), coffee multi-storeyed system (1.69 mg kg^{-1}) and forest plantation (1.62 mg kg^{-1}). In soils under agricultural mono-cropping systems, significantly lower levels of DTPA-Cu (1.16 mg kg^{-1}). With increasing depth, the mean DTPA-Cu content reduced significantly, and a higher amount of DTPA-Cu was found in surface soil (1.63 mg kg^{-1}) as compared to the subsurface (30–45 cm) soil layer (1.45 mg kg^{-1}).

Table 6: DTPA extractable micronutrients status as influenced by different land use systems of Biligirirangana Hills

Land use systems	**Fe (mg kg^{-1})**				**Mn (mg kg^{-1})**				**Zn (mg kg^{-1})**				**Cu (mg kg^{-1})**			
	Depth (cm)				**Depth (cm)**				**Depth (cm)**				**Depth (cm)**			
	0-15	**15-30**	**30-45**	**Mean**	**0-15**	**15-30**	**30-45**	**Mean**	**0-15**	**15-30**	**30-45**	**Mean**	**0-15**	**15-30**	**30-45**	**Mean**
Natural forest	44.11	36.16	30.11	**36.8^{b}**	29.30	27.65	26.99	**27.98^{a}**	2.57	1.75	1.52	**1.947^{b}**	1.78	1.65	1.73	**1.72^{a}**
Forest plantation	46.88	42.16	37.93	**42.32^{a}**	30.65	27.01	27.35	**28.33^{a}**	3.24	2.46	1.60	**2.43^{a}**	1.58	1.85	1.43	**1.62^{a}**
Pure coffee system	33.93	29.42	23.20	**28.85^{c}**	31.68	24.27	22.41	**26.12^{ab}**	3.52	2.49	1.81	**2.60^{a}**	1.88	1.51	1.83	**1.74^{a}**
Coffee multistoried system	36.71	30.42	28.82	**31.98^{c}**	26.89	23.83	18.24	**22.99^{b}**	3.28	2.82	2.06	**2.71^{a}**	1.97	1.66	1.42	**1.69^{a}**
Agriculture mono-cropping	18.31	15.86	11.22	**15.13^{d}**	16.96	15.59	12.04	**14.86^{c}**	1.82	1.13	1.00	**1.31^{c}**	1.18	1.22	1.08	**1.16^{b}**
Agriculture mixed cropping	20.31	13.28	14.18	**15.92^{d}**	19.06	15.78	13.98	**16.27^{c}**	1.72	0.99	0.85	**1.18^{c}**	1.37	1.17	1.22	**1.25^{b}**
Mean	**33.38**	**27.88**	**24.24**		**25.76**	**22.36**	**20.17**		**2.69**	**1.94**	**1.47**		**1.63**	**1.51**	**1.45**	
Factors	**C.D.**	**SE(d)**	**SE(m)**		**C.D.**	**SE(d)**	**SE(m)**		**C.D.**	**SE(d)**	**SE(m)**		**C.D.**	**SE(d)**	**SE(m)**	
Land use	2.39	1.21	0.85		2.07	1.05	0.74		0.25	0.13	0.09		0.13	0.07	0.05	
Depth	1.69	0.85	0.60		1.47	0.74	0.52		0.18	0.09	0.06		0.09	0.05	0.03	
Land use * Depth	NS	2.09	1.48		NS	1.82	1.28		0.43	0.22	0.15		0.23	0.11	0.08	

NS: Non significant, Mean followed by the same letter are not significantly different based on Tukey's HSD ($P<0.05$).DTPA-extractable micronutrients (Fe, Mn, Zn, and Cu) were found to be above critical levels in both surface and subsurface soils under a different of LUSs (Tables 5). Higher content over the threshold level could be due to low soil pH, as the solubility of certain micronutrients increases as pH falls (Brady and Weil, 1996). Second, increased intensity of OM in forest soils developed through higher litterfall and root biomass that elevated the aeration status of soils, prevent oxidation and precipitation of micro-nutrients in bound forms along with supplementation of chelating agents that enhanced solubility and availability of micronutrients in soils. (Dhaliwal, et al. 2023). Lindsay and Norwell (1978) found that soil reactivity and organic matter concentration were the two most critical factors controlling micronutrient availability. Soil organic carbon showed a positive and significant correlation with all the micronutrient cations (Zn, Fe, Mn, and Cu), being the highest correlation (r = 0.887) with DTPA Cu (Table 7).

The soil DTPA-Fe and Mn content was found to be higher in forest plantations, followed by natural forest and coffee plantations. The increased concentration could be related to increased litter recycling and chelation processes in forest soils (Dhaliwal, et al. 2023:). Coffee soils contained higher levels of DTPA-Fe and Mn among coffee crops (22.74 and 8.29 mg kg^{-1}). Higher litter turnover and the application of external organic inputs such as FYM, leftover pruning materials, coffee processing waste, and compost could be ascribed to this (Shivakumar *et al.,* 2020). Extractable DTPA Cu and Zn followed the same trends as Fe and Mn, but their content was maximum in the coffee multistoried system (Zn) and pure coffee system (Cu). Copper and Zn concentrations were substantially higher in a coffee-based land-use system. Higher Cu and Zn content in coffee plantation systems due to the frequent application of Bordeaux mixture, Zn, and Cu-fungicides, as well as the high organic carbon content. DTPA extractable micronutrient concentration significantly decreases with increases in soil depth from 0–45 cm, which might be due to decreasing organic carbon content and increasing soil pH with increasing soil depth.

The increased rates of agricultural and tillage practices that lead to a faster rate of OM decomposition, loss of soil nutrients, and increased nutritional demands with lower use efficiencies by plants may be associated with a lower content of DTPA-extractable micronutrients under agricultural LUSs (Dhaliwal, et al. 2023). The decreased input of organic carbon to soils and the ongoing removal of nutrients through nutrient agglomeration by crops in cultivated soils may also be responsible for the decline in micronutrients observed with the conversion of natural forest to agricultural land.

Correlation and regression analysis

Irrespective of different LUSs and soil depths, available N, secondary, and micronutrients of soil were found significantly well-correlated (Table 6) with SOC (P=0.01). The available sulfur showed the highest positive correlation with SOC (r = 0.909, P = 0.01) followed by Cu (r=0.887, P= 0.05) available nitrogen (r=0.876, P= 0.01), Mn (r=0.757, P= 0.01), Fe (r= 0.743, P= 0.01) and exchangeable Ca exhibited least (r= 0.296, P= 0.01). In all six LUSs, available N, S (Figure 5c), and micronutrients Zn, Cu (Figure 5a) Fe, Mn (Figure 5b) exhibited a positive linear relationship with SOC. The regression analysis showed a trend of nitrogen (R = 0.87) > Fe (R = 0.84) > Cu (R = 0.0.81) > Mn (R = 0.79) > S (R = 0.0.73) > Zn (R = 0.67) regarding their relationship with SOC under different LUSs. The aggradation of SOC under different LUSs is reflected by increasing the concentration of all soil nutrients.

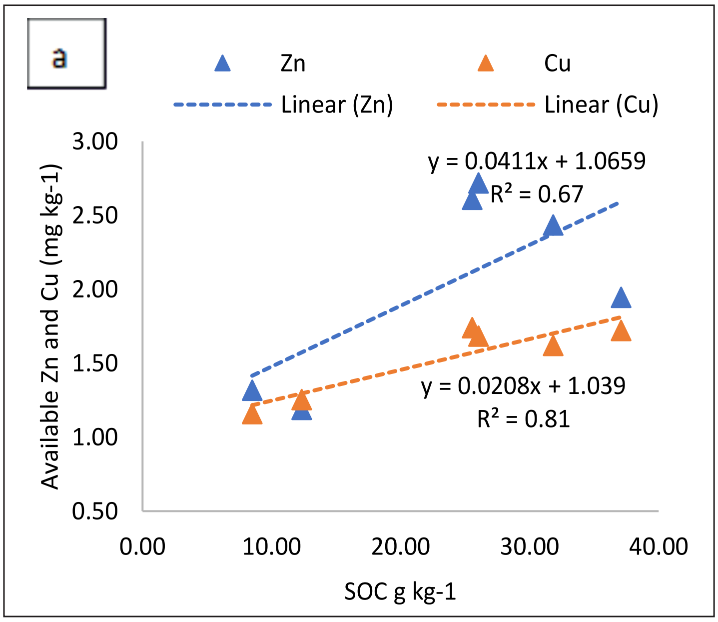
Conclusion

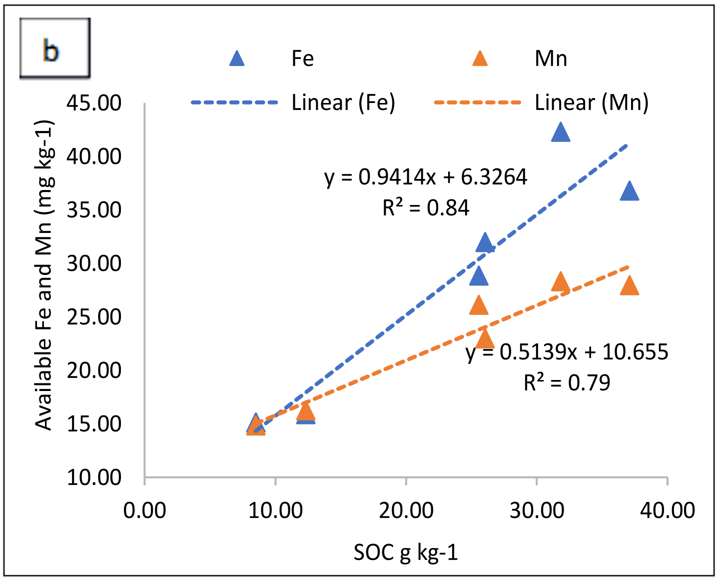
LUSs play an important role in the distribution of carbon stock, nitrogen stock, secondary and micronutrients in soils. The study concluded that among different LUSs viz. natural forest, coffee plantations, and agricultural land, the forest land use was the most eco-friendly and sustainable system followed by the coffee land use system. Natural forest conversion to coffee-based LUSs results in losses of 23-32, 30-37, and 30-39 percent carbon stock at soil depths of 0-15, 15-30 and 30-45 cm, respectively. Similarly, 58-72, 60-74, and 70-71 percent loss of C stock from 0-15, 15-30, and 30-45 cm soil depths, respectively after conversion from natural forest to agriculture LUSs. The natural forests had the highest levels of soil CEC, PBS, secondary nutrients, and micronutrients followed by coffee land use and the least in agricultural LUSs. The correlation study showed that SOC had a favorable impact on the availability of secondary nutrients and DTPA-extractable micronutrients in soils. The present study's findings had a key impact in soil and crop productivity, which is useful for farmers in implementing appropriate land use selection and nutrient management techniques.

Table 6 Linear correlation (Pearson) coefficient between soil chemical properties of different land use systems in the Biligirirangana hills

	SOC	**CEC**	**PBS**	**N**	**Ca**	**Mg**	**S**	**Fe**	**Mn**	**Zn**	**Cu**
SOC	1										
CEC	0.531*	1									
PBS	0.524	0.774*	1								
N	0.876*	-0.588^{NS}	-0.824*	1							
Ca	0.296	0.418*	0.629**	-0.949**	1						
Mg	0.560*	-0.292^{NS}	0.549^{NS}	-0.895*	0.840*	1					
S	0.909**	-0.672^{NS}	-0.811^{NS}	-0.933**	0.843*	0.822*	1				
Fe	0.743**	-0.072^{NS}	-0.904*	-0.919**	0.437^{NS}	0.945**	0.932**	1			
Mn	0.757**	-0.214^{NS}	-0.882*	-0.930**	0.513^{NS}	0.965**	0.972**	0.922**	1		
Zn	0.521	-0.491^{NS}	-0.654^{NS}	-0.920**	0.911*	0.688^{NS}	0.665^{NS}	0.721^{NS}	0.937**	1	
Cu	0.887*	-0.557^{NS}	-0.863*	-0.951**	0.756^{NS}	0.906*	0.902*	0.946**	0.988**	0.458^{NS}	1

**Correlation is significant at the 0.05 level, **Correlation is significant at the 0.01 level.*





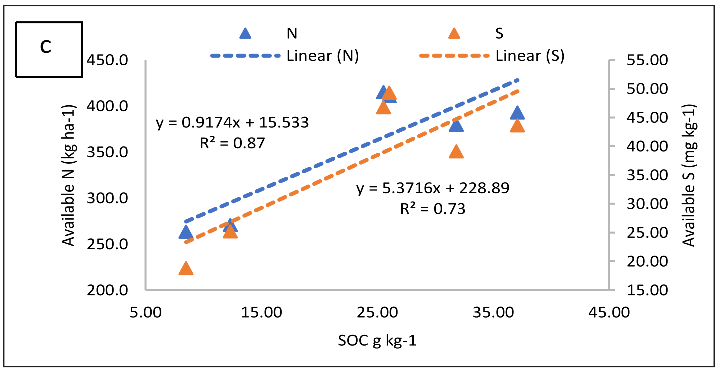


Figure 5: Relationship between SOC and available N, S, and micronutrients (Zn, Cu, Mn, and Fe) under different LUSs at 0-45 cm soil depth

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