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Profile distribution of phyto-available nutrients as influenced by land use systems of dominant soil orders in north-west India

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ABSTRACT

Changes in land use practices affect the distribution of nutrients in soil and their availability to plants, thus necessitating for sound understanding of their status in the soil profile and causes of variability. The primary challenges faced in this study were addressing the considerable variation in soil nutrients caused by different land uses and soil orders while also distinguishing the specific impacts of these factors from other influencing environmental and management conditions. Therefore, this study aims to investigate the nutrient dynamics in soil profiles of forest and agriculture/horticulture land use systems across four prominent soil orders i.e. Inceptisols, Entisols, Aridisols and Alfisols, existing in north-west India. Soil samples were collected from five depths (0-20, 20-40, 40-60, 60-80 and 80-100 cm) of each land use system prevailing under soil orders. Results revealed that among various soil orders, overall pH, EC and SOC ranged from 7.60 to 9.04, 0.05-0.96 dS m^{-1} and 0.15-0.79 %, respectively. The DTPA extractable Zn varied from 0.26-1.56, 0.19-2.42, 0.16- 1.27 and 0.18-1.04 mg kg^{-1}; Fe from 4.90-14.94, 1.94-11.84, 0.73-3.40 and 2.94-12.56 mg kg^{-1}; Mn from 2.79-8.50, 2.58-10.27 1.80-7.54 and 2.44-7.98 mg kg^{-1} and Cu from 0.58-1.63, 0.42-1.21, 0.18-0.35 and 0.33-2.01 mg kg^{-1} in Inceptisols, Entisols, Aridisols and Alfisols, respectively. Micronutrient concentration generally exhibited a decreasing trend with increasing soil depth. Under both land use systems, organic carbon showed a significant positive correlation with DTPA extractable micronutrients. The findings underscore the importance of understanding nutrient dynamics to soil profile characteristics and land use systems. This study offer a foundation for developing precise soil management strategies aimed at enhancing sustainable farming and preserving soil quality.

Keywords: *Micronutrients, secondary nutrients, soil order, soil profile, forest, agriculture, horticulture and land use.*

1. INTRODUCTION

The Green Revolution primarily aimed to achieve self-sufficiency in food grain production to meet the demands of an ever-increasing population. This initiative was characterized by the introduction of high-yielding varieties and the extensive use of nitrogen, phosphorus, and potassium (NPK) fertilizer. However, the prolonged reliance on chemical fertilizers, coupled with insufficient micronutrient inputs, has led to a significant decline in the native pool of micronutrients in soils [1]. This disruption has resulted in multi-nutrient deficiency that adversely affects crop yield and quality. Additionally, intensive cropping systems, soil with low clay content and poor organic carbon content led to diminished soil microbial populations, further exacerbating the decline in soil health and nutrient availability [1]. Micronutrients are essential for plant growth and play a crucial role in vital processes such as photosynthesis and enzyme activation.

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Micronutrient availability in soil is markedly influenced by the parent material including rocks and minerals as well as other soil forming processes and factors [2]. Generally, micronutrients in soil profile increase with increased organic carbon (OC) content and cation exchange capacity (CEC) whereas, their content decreases with increasing pH, calcium carbonate and sand content in soil [3]. The presence of organic matter as well as organic residues and manure applications, plays a vital role in regulating the availability of micronutrient cations and the vertical distribution of essential nutrients. Furthermore, understanding factors that can enhance the nutrient availability in various agro-forestry settings has resulted in shoot up agricultural production –[4]. In northwestern India, mainly three predominant land use systems exist: cropland, forest, and horticulture. However, the increasing pressure to produce more food from limited land has resulted in significant changes in land use patterns, particularly the conversion of forest land into agricultural land. This shift has adversely affected the nutrient status and overall quality of the soil [5], [6]. The availability and distribution of micronutrients within the soil profile are influenced by the variability of land use, which affects key soil properties such as organic carbon content, pH, and clay content –[7], [8].

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Notably, significant alterations in these properties due to changes in land use have drastically impacted soil fertility and productivity. Micronutrient cycling differs noticeably among diverse terrestrial ecosystems, showcasing the intricate relationship between land use dynamics and soil quality [9], [10]. Land uses have a substantial impact on biogeochemistry and consequently, soil characteristics, soil organic carbon pools, and phyto-availability of soil nutrients –[10]. The impact of different land use systems on soil properties has been reported by different researchers over time [11], [12].

Research on the distribution of micronutrients in soil profiles remains limited, particularly when compared to macronutrients across various soil orders and land use systems. There is a notable deficiency of studies examining micronutrients beyond the surface soil layer. Furthermore, comparative research investigating the interactions between diverse soil orders and their respective land use systems regarding micronutrient dynamics is lacking. Addressing these gaps is essential for a comprehensive understanding of soil nutrient management and its implications for agricultural productivity and sustainability. The objective of this research is to investigate the distribution and dynamics of micronutrients across various soil orders and land use systems, specifically focusing on forest and agriculture/horticulture contexts. The scope encompasses a comprehensive analysis of micronutrients at different soil depths, comparative studies among diverse soil orders, and the evaluation of land use changes on micronutrient availability. However, the research may face constraints such as limited historical data on micronutrient profiles, variability in soil sampling methods, challenges in accessing diverse land use sites, and time and resource limitations that may restrict longitudinal studies necessary for understanding long-term trends. Addressing these gaps is crucial for enhancing soil nutrient management and promoting sustainable agricultural practices. This multifaceted approach positions this study as a significant contribution to understanding sustainable land management practices that can enhance both crop quality and ecosystem vitality for future generations.

2. MATERIAL AND METHODS

2.1. Site description

Haryana extends between 27.39° to 30.55°N latitude and 74.27° to 77.36°E longitude with an altitude ranging between 200 to 300 m above the mean sea level. Most of Haryana has a semi-arid to sub-humid climate characterized by hot summers, cool winters, and a short monsoon season. The average temperature of this region during the summer months (May to June) is around 40-45°C, while in the winter months (December to January) it can drop to around 5-10°C. The maximum temperature during the summer months can go up to 48°C in some parts of the state. Average annual rainfall of the area is around 500-600 mm, with most of the rainfall occurring during the monsoon season (July to September). However, the distribution of rainfall across the state is uneven, with some areas receiving more rainfall than others. Most prominent soil types found in these regions is alluvial, arid, desert soils. The dominant soil orders existing in region are Inceptisols (58%), Entisols (29%), Aridisols (9%) and Alfisols (2%).

2.2. Soil sampling and analysis

Soil profile samples were collected from each existing distinct soil order possessing both land use systems, as a systematic approach to capture the inherent variability within the soil profiles. Soil sample from 5 different sites of both (forest and agriculture/horticulture) land use were collected from the dominating orders of Haryana (Fig. 1). These different sample sites under a particular land use system were selected randomly. The forest land use system dominated with *eucalyptus spp.*, *Azadirachta indica*, *Acacia nilotika* and agriculture land use system mainly follow rice-wheat, cotton-wheat, bajra-wheat cropping system and horticulture land use system had mango, guava and citrus plantations. Profile samples of Inceptisols having forest and agriculture/horticulture land use systems were collected from areas falling in Jind and Yamuna Nagar districts of Haryana, while for soil order Entisoils from areas of Ambala, Sirsa and Fatehabad districts. For order Aridisols occupied with forest land use was taken from Hisar, Bhiwani and Mahendragarh, whereas, agriculture/horticulture land use samples were collected from Hisar, Bhiwani, Rewari and Mehendragarh districts. Profile soil samples under forest land use of Alfisols order, collected from Karnal whereas, under agriculture/horticulture land use system, samples were collected from Karnal, Bhiwani, Hisar, Rewari and Mahendragarh districts. Soil samples were collected from 0-20, 20-40, 40-60, 60-80 and 80-100 cm soil depth from each location and their geographical coordinates were recorded on a global positioning system (GPS) device. Sample site map was prepared using ArcGIS 10.4. Samples were air dried in shade and ground to pass through 2mm sieve for further analysis of chemical properties.

Soil pH and electrical conductivity (EC) were estimated by using potentiometric and conductivity method, respectively by taking soil:water suspension of 1:2 ratio. Organic carbon was determined by wet digestion method developed by [12], Available S was estimated using $CaCl_2$ (0.15%) as extractant and measured on spectrophotometer (Model: Spectronic-20). Available Zn, Fe, Cu and Mn were analyzed using DTPA as extractant and concentration was measured using AAS (PerkinElmer Model: PinAAcle 900T). Calcium and magnesium were determined by using method of versenate titration. Available B was estimated by extracting with hot water and color intensity was measured by adding Azomethene-H at spectrophotometer (Model: Spectronic-20)

2.3. Statistical analysis

Soil properties were analysed statistically in a factorial randomised block design and three-way analysis of variance was performed using IBM SPSS Statistics version 26 to determine statistically significance of soil order and pertaining land use effects on profile distribution of nutrients. Dunken's multiple range test was applied to test the significant difference between the means at p-value < 0.05. Karl Pearson's correlation coefficient was workout with *metan* package in R software and other graphs were prepared using OriginPro 2024b software.

3. RESULTS

3.1. Soil properties

Soil properties (pH, EC and OC) help to trace the status of the nutrients in the soil. Soil pH effect the solubility of the nutrients hence, their availability to the plants. Among both land uses, agriculture/horticulture land use had significantly ($p < 0.05$) higher pH (3.12%) over forest land use system. Inceptisols reported the lowest pH value, whereas, highest pH was found in Alfisols which was statistically at par with pH value of Aridisols. Significantly higher pH was recorded in 40-60 cm soil depth as compared to lower soil depths (Table 1).

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Significant higher EC was observed in agriculture/horticulture land use over forest with the increment of 27.28% (Table 1). The EC differ significant in all the soil orders and it followed the sequence: Entisols > Aridisols > Alfisols > Inceptisols. There was no specific trend of EC with depth was observed, highest EC was observed in 60-80 cm soil depths and it was about 68.42% higher EC as compared to 0-20 cm depth. Soil organic carbon (SOC) is considered as key factor controlling the availability and supply of nutrients from soil to plants. The SOC content in forest land use systems was found 22.58% higher as compared to agriculture/horticulture land use systems (Table 1). Among orders, SOC varied from 0.31 to 0.38% and follows the trend: Entisols > Aridisols > Alfisols > Inceptisols having value of 0.38, 0.36, 0.33 and 0.31%, respectively. Among different soil depths, the SOC content ranging from 0.31 – 0.37% Although, no significant variation in SOC was observed with depth.

3.2. Interactive effect of soil orders and land use systems on soil properties

Interactive effect of soil orders and land use systems on soil properties were represented in Fig. 2. It indicated that soil pH did not follow specific trend across various soil depths. However, maximum pH at all the soil depths was observed in agriculture/horticulture land use system of Aridisols. While soil pH was found minimum at all soil depths (except at 0-20 cm, it was minimum in forest land use system of Entisols) in forest land use system of Inceptisols order (Fig. 2a). The EC decreased with depth and highest EC across depth was recorded in agriculture/horticulture land use of Entisols (Fig. 2b). At all the soil depths, highest value of SOC were recorded in Entisols under forest land use system. The SOC content in both the land uses under different soil orders decreased with increasing soil depths. Among different soil orders the SOC varied from 0.14 to 0.79%. (Fig. 2c)

3.3. Micronutrients

The concentration of Zn, Fe and Mn differ significantly in both the land use system (Table 2). Relatively higher concentration of all the micronutrients were reported in forest land use system than Agriculture/horticulture land use system with increase of 49.02, 88.26, 15.87, 10.29 and 3.68% for Zn Fe, Mn, Cu and B respectively. Significantly higher concentration of Zn was recorded in Entisols however, its relative trend of distribution among different soil order following the sequence of Entisols > Inceptisols > Alfisols > Aridisols. Although, no significant change in Zn concentration was reported with soil depth but, Soil layer 80-100 cm reported 29.63, 16.67, 1.45 and 7.69% higher Zn concentration over 0-20, 20-40, 40-60 and 60-80 cm soil layer, respectively. Among different soil orders, the concentration of Fe differ significantly and its concentration was reported significantly highest in Inceptisols (8.29 mg kg^{-1}) followed by Alfisols (6.95 mg kg^{-1}) > Entisols (4.87 mg kg^{-1}) > Aridisols (1.51 mg kg^{-1}). The Fe concentration decreased in all the depths (except in 20-40 cm, where it increased) and lowest Fe concentration was reported in 0-20 cm soil depths which was 24.58, 22.07, 20.11 and 17.29% lower than its concentration in 20-40, 40-60, 60-80 and 80-100 cm soil layer, respectively. Likewise Fe, Manganese concentration varied significantly among different soil orders and follows the trend of Inceptisols > Entisols > Alfisols > Aridisols. The Mn concentration was 15.64, 33.47, 89.08% higher in Inceptisols than Entisols, Alfisols and Aridisols, respectively.

While considering soil depth as a sole factor no specific trend in Mn concentration was observed and its concentration was recorded lowest 4.74 mg kg^{-1} at 40-60 and highest to 5.68 mg kg^{-1} at 80-100 cm soil depth. Copper concertation effected significantly in different soil orders and followed the trend as: Alfisols > Inceptisols > Entisols > Aridisols. Highest concentration of Cu was recorded in 80-100 cm soil depth with increase of 38.81% over surface soil layer (0-20 cm). Significant change in B concentration among different soil order was recorded and it followed the trend Inceptisols > Alfisols > Entisols >Aridisols. No significant change was reported in B concentration with depth except at 20-40 cm soil depth.

3.4. Interactive effect of soil orders and land use systems on micronutrients status

The Interactive effect of soil orders and land use systems on concentration of DTPA extractable micronutrients (Zn, Fe, Mn and Cu) and hot water soluble B at various soil depths were presented in Fig. 3. The overall, Zn, Fe, Mn, Cu and B concentration under different land uses and soil orders varied from 0.08 – 4.08, 0.50 - 19.40, 0.52 - 11.82, 0.03 – 4.90 and 0.77-3.72 mg kg^{-1}, respectively. Interactive effect of different land uses system and orders indicated decreasing trend of Zn concentration with depth (Fig. 3a). At all soil depths, comparatively higher concentration of Zn was observed in forest land use system of Entisols order than rest of land use system under different soil orders. Likewise Zn, concentration of Fe also follows similar trend of decreasing Fe concentration with depth. Highest Fe concentration at each soil depth was observed in forest land use system of Inceptisols followed by forest land use system of Alfisos and forest land use system of Entiosls as compared to Fe concentration in remaining land use systems of different soil orders (Fig. 3b). The Mn concentration also decreased with increasing soil depth. At all soil depths (except at 60-80and 80-100 cm), its concentration was recorded highest in forest land use system of Entisols order and lowest in Forest land use of Arisols (Fig. 3c). Likewise, Zn, Fe and Mn, the Cu concentration also decreased with increasing soil depth (Fig. 3d). However, among all the soil orders and land uses, the highest Cu concentration was reported in 0-20 and 20-40 cm in agriculture/horticulture land use system of Alfisols and in 40-60 and 60-80 cm in forest land use of Inceptisols while at 80-100 cm soil depth highest Cu concentration was observed in forest land use of Entisols. At all soil depths, B concentration was highest in agriculture/horticulture land use system of Inceptisols and lowest in agriculture/horticulture land use system of Aridisols (Fig. 3e).

3.5. Secondary nutrients

Effect of land use, soil orders and depths on the concentration of secondary nutrients was presented in table 3 indicated that significantly higher concentration of S in forest land use system with increase of 28.47% over agriculture/horticulture land use system (Table 3). Although, the results of Ca and Mg concentration in respect to land use systems found contrary to S concentration where 24.76 and 27.57% higher concentration was recorded in agriculture/horticulture land use systems compared to Forest land, respectively. The S concentration in different soil orders followed the sequence of: Entisols > Aridisols > Alfisols > Inceptisols whereas, the Ca and Mg concentration followed similar trend of: Alfisols > Entisols > Aridisols > Inceptisols order. However, with depth no significant variation in S concentration was observed.

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The increase in concentration of Ca and Mg at 80-100 cm soil depth was 18.75 and 20.51% over surface layer (0-20 cm), respectively.

Interactive effect of land uses under different soil orders on S concentration indicated that highest concentration of S was recorded at all soil depths (except at 0-20 cm) in forest land use system of Entisols and lowest in agriculture/horticulture land use system of Inceptisols order (Fig. 4a). Similarly, highest concentration of Ca and Mg was recorded at all soil depths (except at 0-20 cm) in agriculture/horticulture land use system of Alfisols (Fig. 4b and Fig. 4c).

4. DISCUSSION

4.1. Influence of soil factors on chemical properties

The soil chemical properties were significantly influenced by land use and soil order. For instance, in Aridisols, soil pH tends to increase with depth. This may be due to the presence of translocated silicate clays, calcium carbonate, gypsum, and other soluble salts, along with the leaching of bases to lower depth [13]. In contrast, Inceptisols show lower pH values, although no significant difference was observed across depths. This could be due to the continuous addition of organic residues from forest trees, which decompose and produce organic acids [14], [15].

Higher soil EC values was observed in 0-20 cm soil depths in both the land use systems under all the soil orders. The elevated EC in Entisols under agriculture/horticulture land use system may result from fertilizer application and surface salt accumulation due to evaporation [15]. Fertilizers applied to the soil contribute to the accumulation of nutrient ions, leading to an increase in EC at the surface, which gradually decreases with depth due to reduced salt concentration at lower levels[16].

Land use system significantly influence soil organic carbon status. Although Entisols generally exhibit low fertility due to limited development time, land use and duration also impact their SOC concentration [17], [18], [19]. The higher SOC concentration in Entisols compared to other soil orders might be due to forest cover, which adds organic matter through leaf litter and root biomass, contributing to SOC upon decomposition [20], [21], [22].

4.2. Micronutrient concentration as influenced by soil factors

Micronutrient concentration, particularly Zn, Fe, Mn, and Cu, vary significantly with land use, soil order, and depth. Zinc concentration is generally higher in surface soils and decreases with depth across soil orders and land use systems. This may be due to the mineralization of organic litter from trees, which adds nutrients upon decomposition [23], [24]. The highest Zn levels were found in Entisols under forest land, possibly due to arbuscular mycorrhizal associations with tree roots and organic matter decomposition ––[25], [26]. Lower Zn concentration in forest-covered Aridisols may be attributed to $CaCO_3$ presence, which promotes Zn fixation, even after Zn is released through litter mineralization [27]. Iron (Fe) concentration is generally higher throughout Inceptisols profiles, while Aridisols have lower Fe levels, especially in forest land use. The availability of Fe is largely influenced by pH and redox conditions, which affect Fe precipitation and dissolution. Additionally, organic molecules can enhance Fe availability through complexation and adsorption-desorption processes[28].

In Inceptisols, higher organic matter and finer textures (clay) may promote Fe solubilization by converting Fe from its oxidized (Fe^{3+}) to reduced (Fe^{2+}) form, with a strong correlation between pH and organic matter[29]. Forest cover in Inceptisols, along with continuous addition of organic matter, may also increase Fe concentration –[29], [30], [31]. The solubility of Fe decreases by a factor of 1000 for each unit increase in soil pH from 4 to 9, while Mn, Cu, and Zn solubility drop by a factor of 100[32]. In Aridisols, Fe availability decreases due to fixation by high carbonate levels, typical of calcareous soils[33]. Higher Mn concentration was observed in Entisols at 0–60 cm depth and in Inceptisols at 60–100 cm depth under forest land use. This may be due to the continuous addition of organic matter from forest litter at shallower depths and the production of root exudates and mineralization of dead roots by microbes at lower soil depths ''[34], [35]. Soil pH and moisture are critical factors influencing Mn availability [40]. Organic residues in Entisols may shield micronutrients from oxidation and precipitation, providing soluble chelating agents and aiding micronutrient solubilization through moisture retention [35], [36]. Copper concentration is generally higher in Inceptisols between 20–80 cm depth, while Aridisols tend to have lower Cu levels across all depths, especially under forest land use. The increased Cu in Inceptisols may be attributed to exogenous carbon inputs, which enhance microbial biomass and activity. This microbial activity accelerates decomposition and the release of micronutrients from organic matter [37]. In Aridisols under forest cover, the low Cu levels may be due to similar factors as seen with Zn, Fe, and Mn, where high pH and $CaCO_3$ presence favour micronutrient fixation. The higher Cu levels in Inceptisols are likely due to sufficient organic matter, which stimulates microbial activity and promotes micronutrient release upon decomposition[37], [38].

4.3. Secondary Nutrients and soil factors

Secondary nutrient concentrations varied significantly under the influence of land use systems, soil orders and depth. Sulfur (S) concentration tends to increase with depth across most soil orders and land use systems, except in Inceptisols. The observed increase in S with depth may result from higher root biomass, root exudates, and reduced oxidation in deeper layers[38] . Lower S levels in surface soils could be due to low soil carbon levels, which, combined with lighter soil texture, lead to increased microbial oxidation. No specific trend was observed in the profile distribution of calcium (Ca) across different land use systems. However, higher Ca levels were noted in agricultural/horticulture land use systems of Alfisols, potentially due to increased organic matter from manure or crop/tree litter, which decomposes and releases cations [39] . Alfisols, which are mineral-rich soils found in sub-humid to humid climates, are less acidic and have high fertility with elevated cation levels, including Ca, Mg, K, and Na. The increased $CaCO_3$ concentration observed at lower depths is thought to be related to the downward leaching of calcium, which precipitates as carbonate in these deeper layers. In contrast, Entisols generally exhibit lower magnesium (Mg) levels, particularly under forest cover across all depths (except at 0-20 cm). The subsoils of base-rich parent materials or those with limited weathering and leaching often show accumulated exchangeable Ca, Mg, and K, partly due to the formation of argillic horizons. Alfisols, by contrast, typically have higher cation levels (Ca and Mg) due to the composition of their parent materials[40].

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4.4. Pearson correlation coefficient of micronutrients with other soil properties

Pearson's correlation matrix was drawn to understand the degree of relation among different soil properties in soil profile (Fig. 5). Under forest (Fig. 5a) and agriculture/horticulture (Fig. 5b) land use significant positive correlation was observed between SOC and Zn (r = 0.62*** and 0.67***), Fe (r = 0.25* and 0.56***), Mn (r = 0.49*** and 0.66***) and Cu (r = 0.34*** and 0.48***), respectively.

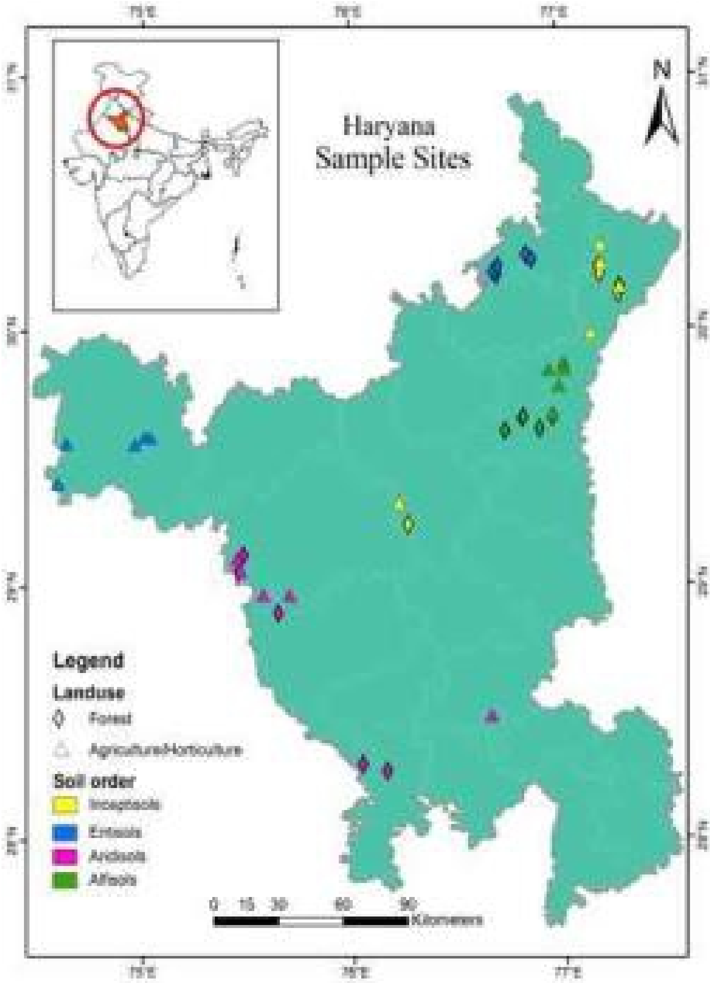
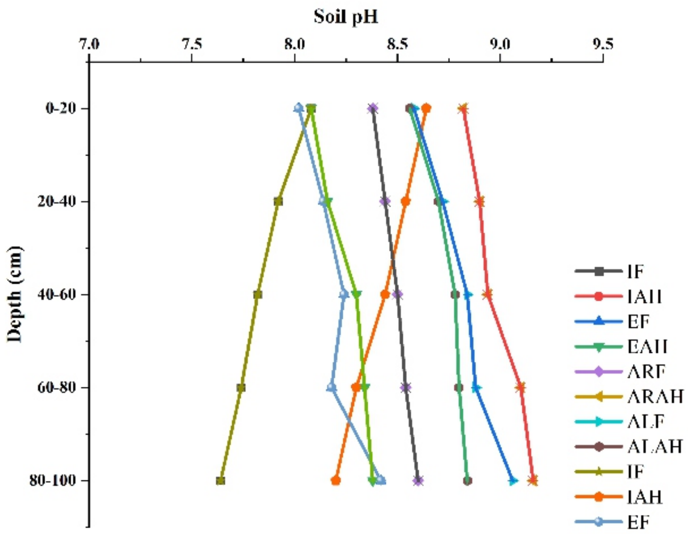
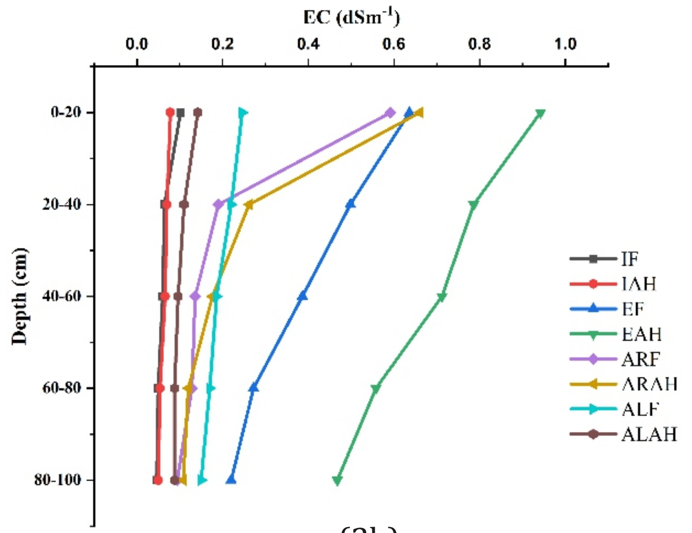


Fig 1. Sampling site map of soil orders and pertaining land use systems



(2a)



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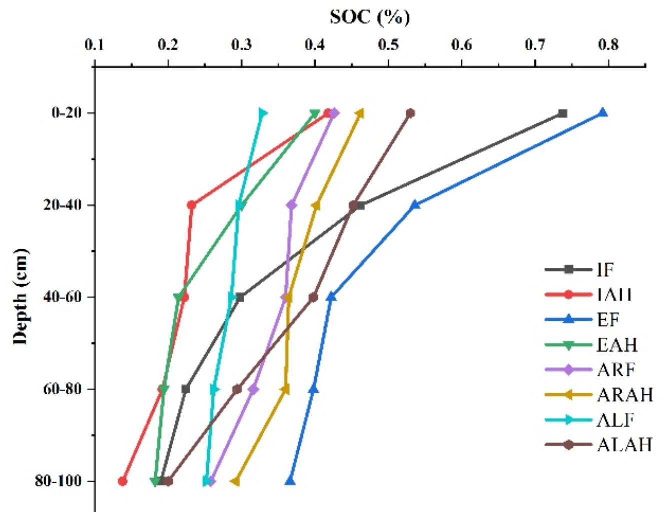
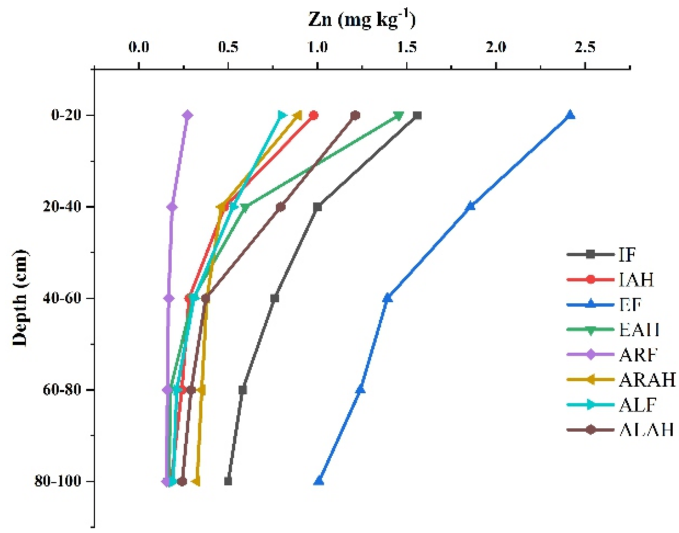


(2c)

Fig 2 (2a to 2c). Depth wise variation in soil pH; EC, electronic conductivity and SOC, soil organic carbon among different combinations of soil orders and land use systems. IF indicates Inceptisols Forest; IAH, Inceptisols agriculture/horticulture; EF, Entisols forest; EAH, Entisols agriculture/horticulture; ALF, Alfisols forest; ALAH, Alfisols agriculture/horticulture; ARF, Aridisols forest; ARAH, Aridisols agriculture/horticulture



(3a)

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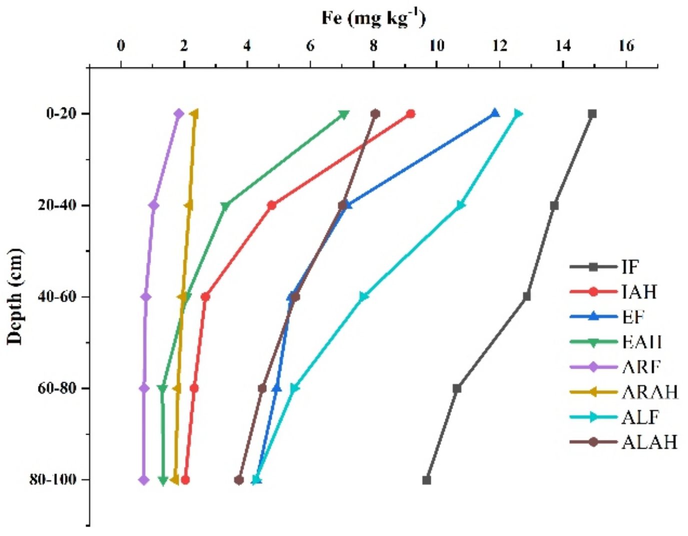

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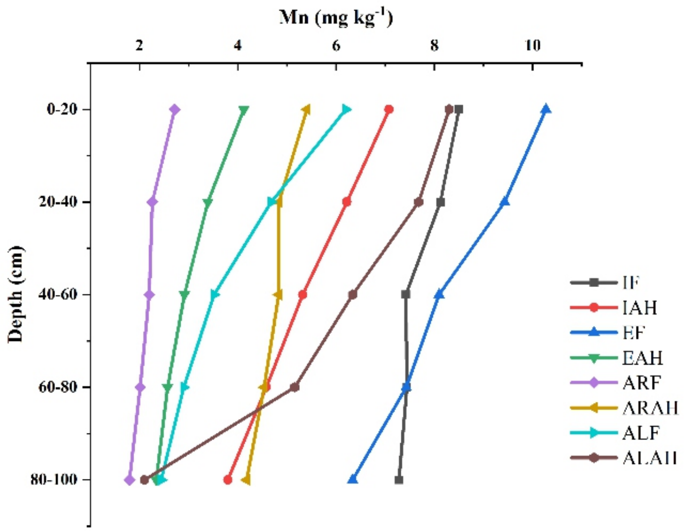

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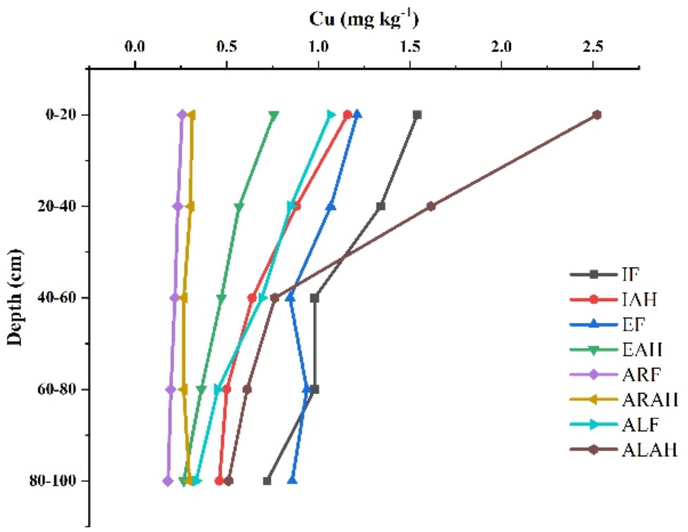

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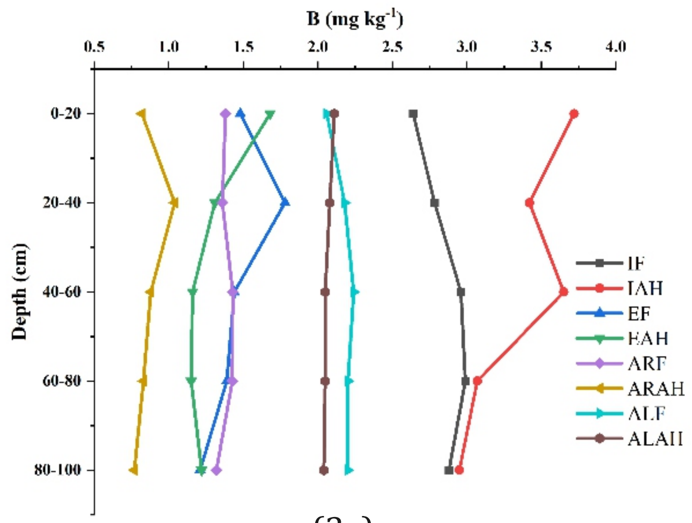
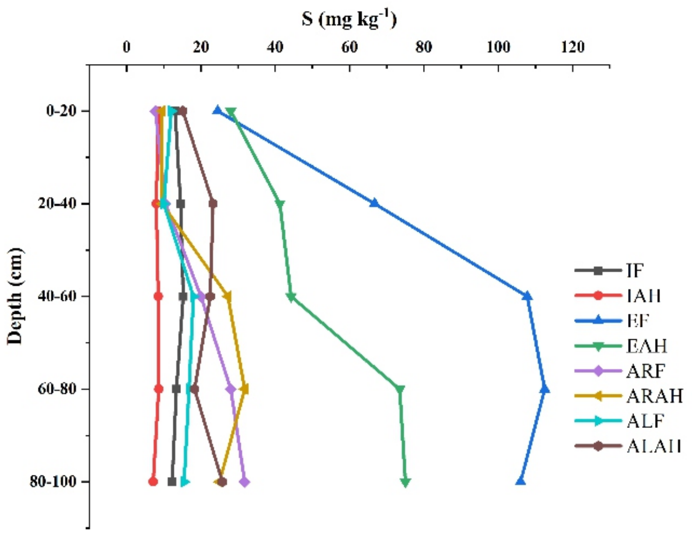
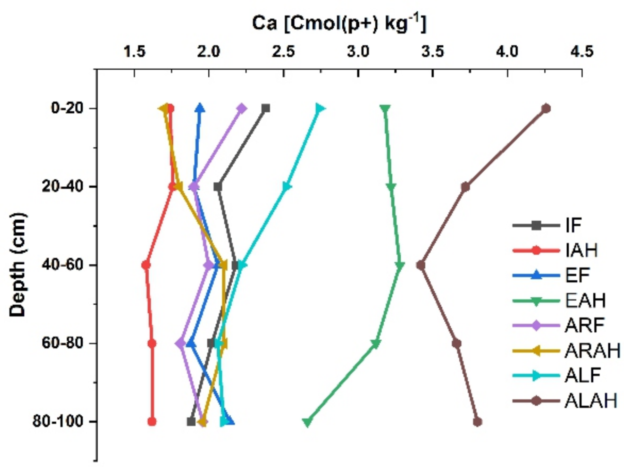


(3e)

Fig 3 (3a to 3e). Variation in micronutrient concentration along soil depth. IF, Inceptisols Forest; IAH, Inceptisols agriculture/horticulture; EF, Entisols forest; EAH, Entisols agriculture/horticulture; ALF, Alfisols forest; ALAH, Alfisols agriculture/horticulture; ARF, Aridisols forest; ARAH, Aridisols agriculture/horticulture



(4a)



(4b)

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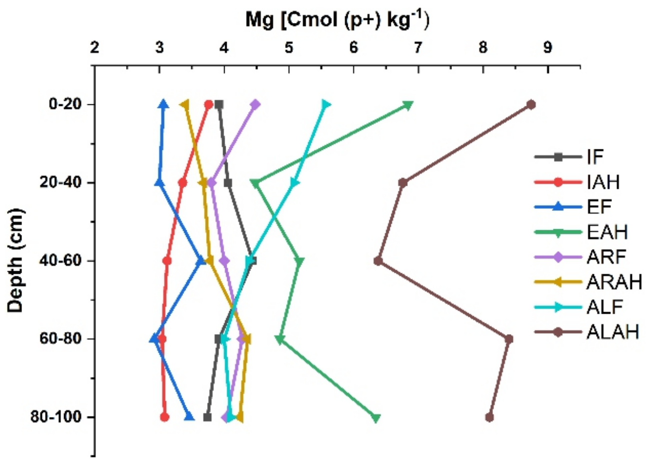
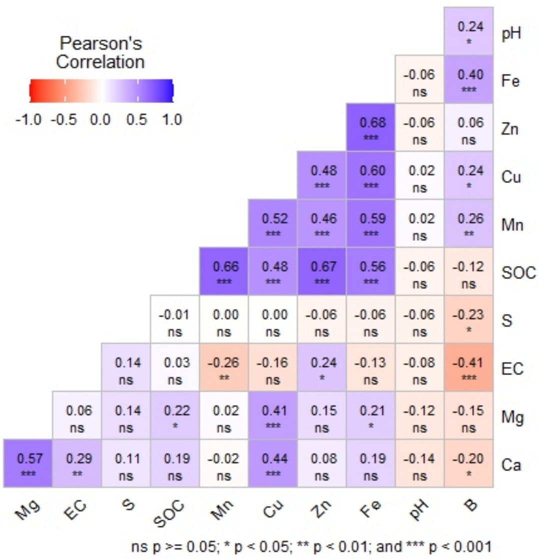
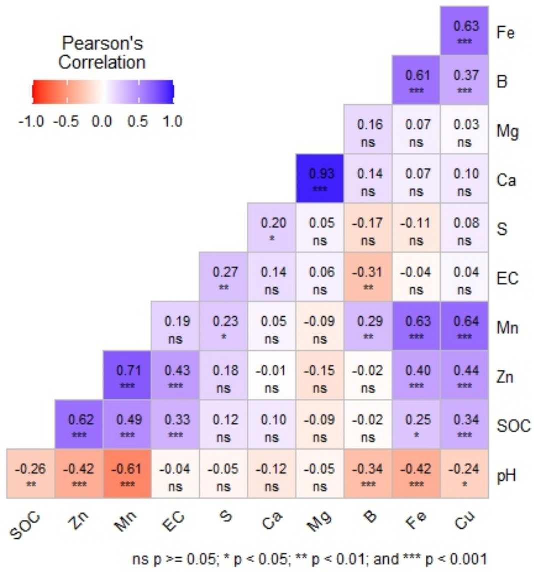


(4c)

Fig 4 (4a to 4c). Variation in secondary nutrient concentration in different sampling depths. S, sulfur; Ca, calcium; Mg, magnesium. IF, Inceptisols Forest; IAH, Inceptisols agriculture/horticulture; EF, Entisols forest; EAH, Entisols agriculture/horticulture; ALF, Alfisols forest; ALAH, Alfisols agriculture/horticulture; ARF, Aridisols forest; ARAH, Aridisols agriculture/horticulture



(a) Forest land use system



(b) Agriculture/horticulture land use system

Fig 5. Pearson correlation coefficient among soil properties in the soil profile of different land use systems and soil orders. pH; EC, electrical conductivity; SOC, soil organic carbon; Zn, zinc; Fe, iron; Mn, mangamese; Cu, copper: B, boron; S, sulphur; Ca, calcium; Mg, magnesium.

Land Use	**pH**	**EC (dS m^{-1})**	**SOC (%)**
Forest	8.34 (±0.04)^{b}	0.22 (±0.02)^{b}	0.38 (±0.02)^{a}
Agri/horti	8.60 (±0.04)^{a}	0.28 (±0.03)^{a}	0.31 (±0.01)^{b}
F value	113.65	4.97	11.66
Soil Order			
Inceptisols	8.13 (±0.06)^{c}	0.06 (±0.00)^{c}	0.31 (±0.03)^{b}
Entisols	8.23 (±0.03)^{b}	0.55 (±0.05)^{a}	0.38 (±0.03)^{a}
Aridisols	8.74 (±0.04)^{a}	0.25 (±0.04)^{b}	0.36 (±0.02)^{ab}
Alfisols	8.78 (±0.03)^{a}	0.15 (±0.00)^{c}	0.33 (±0.02)^{ab}
F value	187.21	62.61	2.51
Soil Depth (cm)			
0-20	8.51 (±0.05)^{ab}	0.19 (±0.03)^{b}	0.34 (±0.03)^{a}
20-40	8.47 (±0.07)^{ab}	0.24 (±0.04)^{ab}	0.31 (±0.02)^{a}
40-60	8.52 (±0.08)^{a}	0.23 (±0.03)^{ab}	0.35 (±0.02)^{a}
60-80	8.42 (±0.07)^{b}	0.32 (±0.07)^{a}	0.36 (±0.03)^{a}
80-100	8.41 (±0.06)^{b}	0.27 (±0.05)^{ab}	0.37 (±0.03)^{a}
F value	3.15	2.60	1.01

Values in the parenthesis represent standard error of mean. Different letters in same column denote significant difference

Table 2. Micronutrient concentration in soil profile as influenced by different land use and soil orders

Land Use	**Zn (mg kg^{-1})**	**Fe (mg kg^{-1})**	**Mn (mg kg^{-1})**	**Cu (mg kg^{-1})**	**B (mg kg^{-1})**
Forest	0.76 (±0.08)$_{a}$	7.06(±0.52)^{a}	5.55 (±0.29)^{a}	0.75 (±0.06)^{a}	1.97 (±0.07)^{a}
Agri/horti	0.51 (±0.04)^{b}	3.75(±0.30)^{b}	4.79 (±0.23)^{b}	0.68 (±0.07)^{a}	1.90 (±0.11)^{a}
F value	14.75	70.60	13.58	1.33	1.46
Soil Order					
Inceptisols	0.66 (±0.07)^{b}	8.29(±0.78)^{a}	6.58 (±0.24)^{a}	0.92 (±0.08)^{ab}	3.11 (±0.09)^{a}
Entisols	1.06 (±0.13)^{a}	4.87(±0.56)^{c}	5.69 (±0.43)^{b}	0.74 (±0.06)^{b}	1.38 (±0.068)^{c}
Aridisols	0.34(±0.04)^{c}	1.51 (±0.19)^{d}	3.48 (±0.34)^{d}	0.25 (±0.02)^{c}	1.13 (±0.05)^{d}
Alfisols	0.50 (±0.05)^{bc}	6.95 (±0.46)^{b}	4.93 (±0.33)^{c}	0.94 (±0.11)^{a}	2.12 (±0.04)^{b}
F value	22.00	55.82	39.76	26.64	252.34
Soil Depth (cm)					
0-20	0.54 (±0.07)^{a}	4.45 (±0.55)^{a}	4.95 (±0.39)^{ab}	0.67 (±0.07)^{bc}	2.02 (±0.16)^{a}
20-40	0.60(±0.08)^{a}	5.90 (±0.83)^{a}	5.19 (±0.43)^{ab}	0.83 (±0.09)^{ab}	1.68 (±0.14)^{b}
40-60	0.69 (±0.09)^{a}	5.71 (±0.72)^{a}	4.74 (±0.41)^{b}	0.53 (±0.06)^{c}	1.98 (±0.15)^{a}
60-80	0.65(±0.12)^{a}	5.57 (±0.74)^{a}	5.29 (±0.46)^{ab}	0.61 (±0.07)^{bc}	1.96 (±0.14)^{a}
80-100	0.70 (±0.12)^{a}	5.38 (±0.77)^{a}	5.68 (±0.42)^{a}	0.93 (±0.15)^{a}	2.03 (±0.13)^{a}
F value	0.80	1.63	2.34	5.80	5.27

Values in the parenthesis represent standard error of mean. Different letters in same column denote significant difference

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Table 3. Effect of land uses and soil orders on profile distribution of Secondary nutrients

Land Use	S (mg kg^{-1})	Ca cmol (p+) kg^{-1}	Mg cmol (p+) kg^{-1}
Forest	32.81 (±4.89)^{a}	2.10 (±0.07)^{b}	3.99 (±0.14)^{b}
Agriculture/horticulture	25.54 (±3.56)^{b}	2.62 (±0.12)^{a}	5.09 (±0.26)^{a}
F value	3.24	28.13	25.78
Soil Order			
Inceptisols	10.94(±0.61)^{b}	1.88 (±0.08)^{c}	3.64 (±0.16)^{c}
Entisols	67.95 (±9.48)^{a}	2.54 (±0.16)^{b}	4.38 (±0.32)^{b}
Aridisols	20.10 (±3.85)^{b}	1.96 (±0.07)^{c}	4.01 (±0.15)^{bc}
Alfisols	17.72 (±1.41)^{b}	3.05 (±0.17)^{a}	6.15 (±0.37)^{a}
F value	41.89	31.58	26.33
Soil Depth (cm)			
0-20	29.32 (±5.90)^{a}	2.24 (±0.14)^{b}	4.34 (±0.29)^{b}
20-40	30.94 (±6.08)^{a}	2.23 (±0.15)^{b}	4.20 (±0.33)^{b}
40-60	22.65 (±3.64)^{a}	2.17 (±0.11)^{b}	4.33 (±0.28)^{b}
60-80	29.22 (±5.62)^{a}	2.48 (±0.18)^{ab}	4.63 (±0.27)^{ab}
80-100	33.74 (±10.75)^{a}	2.66 (±0.20)^{a}	5.23 (±0.46)^{a}
F value	0.81	3.68	2.91

Values in the parenthesis represent standard error of mean. Different letters in same column denote significant difference

5. CONCLUSIONS

The study provides an in-depth knowledge of soil properties encompassing different land uses and soil orders, highlighting significant variations in soil pH, EC, SOC, micronutrient concentration and secondary nutrient levels. This emphasizes the role of forest ecosystems in maintaining higher organic matter content, which is crucial for soil fertility and structure. The SOC content did not vary significantly with depth, suggesting that organic matter distribution might be more influenced by the land use system than soil depth. Results indicate that forest ecosystems may provide better nutrient profiles for plant uptake compared to agricultural systems. Notably, the concentration of Fe showed a considerable increase with depth in certain soil orders, which could have implications for nutrient management practices in agriculture. Sulfur concentration was higher in forest lands, while calcium and magnesium were more abundant in agricultural lands. This study highlights the need for tailored fertilization strategies depending on the land use type. The novelty of this study lies in its comprehensive approach to analysing how different land uses and soil orders interact to influence soil quality parameters. The examination of nutrient variation with depth adds a critical dimension to understanding nutrient dynamics beyond surface-level assessments. The detailed comparison of soil properties across various soil orders (Entisols, Aridisols, Alfisols, Inceptisols) offers valuable insights for regional agricultural practices and ecological conservation strategies. The findings can help guiding sustainable land management practices by identifying which systems promote better nutrient retention and availability, thus informing future agricultural policies and practices aimed at enhancing soil health. This study not only contributes valuable data on soil properties but also emphasizes the importance of considering both ecological and agricultural perspectives when managing soils for optimal productivity and sustainability.

FUTURE SCOPE OF THE STUDY

Future studies should prioritize continuous long-term monitoring of nutrient fluctuations to understand temporal changes and the effects of climate change on soil characteristics. Moreover, investigating the relationships between soil microbial populations and nutrient availability across various land uses and soil types could offer valuable insights for improving soil fertility management. Tailoring nutrient management strategies to specific sites and crops, informed by these findings, will significantly advance precision agriculture and support effective ecosystem conservation.

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COMPLIANCE WITH ETHICAL STANDARDS

The article does not present any primary research involving human subjects conducted by the authors.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTION

Rohtas Kumar: Conceptualization; investigation; formal analysis; writing– original draft; methodology; writing– review and editing; data curation; visualization. Vikas Kumar: Writing– original draft; methodology; writing– review and editing validation; investigation. H.K. Yadav: Conceptualization; resources; validation; data curation; investigation. Arvind Kumar Shukla: Conceptualization and supervision. Sanjib Kumar Behera: Conceptualization and supervision. Anurag: Identification of data points and preparation of maps.

SUPPLEMENTARY INFORMATION

The data will be made available on reasonable request to corresponding author.

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