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Land Use Change Alters Soil Physico-Chemical Properties in Manipur, Northeast India

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ABSTRACT

Land-use change is a major driver of soil degradation in tropical ecosystems, influencing soil organic carbon (SOC), nutrients and ecosystem productivity. This study evaluated the effects of five contrasting land-use systems, namely natural forest (NF), degraded forest (DF), fallow land (FL), pine plantation (PP), and paddy field (PF), on soil physico chemical properties in Manipur, Northeast India. Soil samples were collected from all land use types to a depth of 1 m and divided into four layers (0–15, 15–30, 30–60, and 60–100 cm). Soil samples were analyszd for soil bulk density, moisture content, texture, texture, pH, SOC, available nitrogen (N_{avail}), phosphorus (P_{avail}), and exchangeable potassium (K^+), calcium (Ca), and magnesium (Mg). Two-way ANOVA revealed significant effects of land-use type, soil depth, and their interaction on most soil properties ($p < 0.001$). Natural forest soils maintained the highest SOC, N_{avail}, and moisture content. Fallow land exhibited soil properties comparable to those of NF, indicating substantial recovery of soil fertility during secondary succession. In contrast, pine plantation soils showed the lowest SOC and available P, associated with acidic conditions and slow decomposition of conifer litter. Paddy fields were characterised by higher pH, K^+, Ca, and Mg due to prolonged flooding and management practices. Soil nutrient concentrations and moisture content declined significantly with increasing depth, whereas bulk density increased. Principal Component Analysis explained 73.28% of the total variance and clearly distinguished land-use systems based on their soil properties. The findings demonstrate that land-use conversion substantially alters soil physicochemical properties and highlight the importance of maintaining natural forests and promoting fallow-based restoration strategies to sustain soil fertility and ecosystem functioning in tropical landscapes.

Keywords Land use change, Soil properties, Soil organic carbon, Available nitrogen, Available phosphorus, Exchangeable potassium, Soil moisture, Soil pH.

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INTRODUCTION

Forests regulate the climate and support the livelihood of many people around the globe by providing a number of ecosystem services (Jackson *et al.* 2005, McKinley *et al.* 2011). Tropical forests support over 1.5 billion people for their food, medicine, timber and livelihood (Lewis *et al.* 2015). Forests act as a major sink of carbon (C) and play an important role in regulating the climate by storing 662 gigatons of C globally (FAO 2020, Monsang *et al.* 2024). Thereby, they play a central role in regulating the C, nutrient, and hydrological cycles, providing provisioning services (such as food and timber) and aesthetic services to society (Lewis *et al.* 2015, Upadhyay *et al.* 2026). Forest soil is a major storehouse of C, nutrients, and microorganisms that drive the growth of aboveground vegetation, all of which are key to providing ecosystem services (Chanda and Tripathi, 2026a, 2026b). Of the total C stored in forests, over two-thirds is stored in the soil, while the remaining is stored in aboveground vegetation (Dixon *et al.* 1994). However, anthropogenic activities, such as deforestation, have led to diverse land-use systems and altered forest functioning (Chanda *et al.* 2024, Tripathi *et al.* 2026). This leads to changes in soil physical properties, loss of soil nutrients and C stocks, and increased atmospheric greenhouse gas accumulation (Manpoong and Tripathi 2021, Yinga *et al.* 2022, Wungshap *et al.* 2023). There has been a rapid change in global land-use systems (Global Forest Resources Assessment 2025) and has degraded the physical and chemical properties of the soils, and alters how ecosystems function (Lindenmayer *et al.* 2012, Tripathi *et al.* 2006).

Rapid landscape transformations from natural forests to a multitude of ecosystem types are occurring in tropical regions due to expanding population pressure, altering soil ecological functioning (Devi *et al.* 2025, Moirangthem *et al.* 2026a, 2026b). The ability of forest soils to provide ecosystem services depends largely on their physical, chemical (Obalum *et al.* 2017), and biological properties (Ovsepyan *et al.* 2019), as well as their intricate interactions (Chanda *et al.* 2026). When aboveground biomass is removed due to land-use change, soil health is degraded by increased soil erosion (Khodadadi *et al.* 2023), which, in turn, affects soil structure and reduces biodiversity and soil organic carbon (SOC) (Davari *et al.* 2020). Moreover, soil erosion following deforestation decreases soil nutrients and water-holding capacity, reducing soil fertility and moisture content. This lowers productivity and soil organic C stocks, reducing the regulating and provisioning services that soil provides. Soil chemical properties, including SOC, soil moisture, available nitrogen (N), phosphorus (P), exchangeable potassium (K^+), exchangeable magnesium (Mg), exchangeable calcium (Ca), and soil pH, as well as soil physical properties such as bulk density and soil texture, are all affected.

Land-use change directly affects soil C stocks and other soil properties. In stable ecosystems, soils contain organic matter occluded within aggregates, which physically protects it from microbial decomposition, making it more resistant to decomposition (Ao *et al.* 2023). However, when land-use changes, these aggregates break down and become more susceptible to microbial decomposition (Tripathi *et al.* 2008, Tripathi *et al.* 2012), leading to the release of C into the atmosphere. Moreover, they become more vulnerable to further breakdown as above-ground vegetation is removed, soils become more exposed to sunlight, and organic matter input (from litter and roots) is reduced. The impact, however, can vary across land-use systems due to differences in land-use intensity and management practices. For instance, soil organic C can be reduced by 30% when natural forests are converted to a plantation forest (Vanlalfakawma *et al.* 2014, Padbhushan *et al.* 2022) and by 25% when they converted to agricultural cropland (Don *et al.* 2011).

When forests are converted to other land-use systems, such as plantations or agriculture, soil organic matter and nutrients (e.g., N, P, and K) are substantially reduced due to reduced litter inputs (Hauchhum and Tripathi 2019, Singha *et al.* 2020, Singh *et al.* 2025a). This overall reduces the fertility and productivity of the ecosystem. Land-use change also increases bulk density and reduces microporosity and water-retention capacity, thereby reducing soil moisture content (Davari *et al.* 2020). Soil acidity is an important soil chemical property that regulates the availability of essential nutrients to plants and influences nutrient cycling processes in terrestrial ecosystems (Brady and

Weil 2017). It is affected by land-use change through changes in leaching capacities. A lower pH value (higher acidity) is often observed in more intensive land-use systems, such as cropland, due to greater leaching losses of soil nutrients (Devi *et al.* 2018).

Although numerous studies have been conducted across different sites and land-use types, no clear conclusions have been drawn on how land-use change affects soil properties. Moreover, there is still a need to document SOC under different land-use types in the state (Devi *et al.* 2025). This study examines how different land-use types affect soil physicochemical properties that determine both their climate change mitigation potential and ecosystem productivity. We hypothesize that a) SOC and nutrients (N, P, K, Ca, Mg) will be higher in natural forest than other land uses (fallow lands, plantations and croplands) due to higher litter inputs, b) soil bulk density, moisture content, and pH will be higher in other land uses (fallow lands, plantations and croplands) compared to natural forests due to disturbance.

MATERIALS AND METHODS

Study site

The study was conducted in three districts (Thoubal, Imphal West, and Kamjong) of Manipur, India (Fig. 1). The state of Manipur is characterized by four distinct seasons: spring, monsoon, autumn and winter. The total annual rainfall in the state ranged from 1, 200 to 2,700 mm, the highest rainfall was observed in Kamjong district, and the mean annual temperature ranged from 21.51 to 32.80 °C, while the relative humidity ranged from 42.2 to 88.9% (Fig. 2). A total of 5 major land-use types of the state of Manipur were selected from three districts to examine the effects of land use on soil properties. Among different land-use types, a Natural Forest (NF) approximately 100 years old and fallow land (FL) approximately 10 years old were selected from Lungtoram village in Kamjong district. Similarly, a disturbed forest (DF) of approximately 30 years old was selected from Lanthungching village in Imphal West district. In addition, a pine plantation (PP) about 25 years old from Chakama village and a paddy field (PF) about 60 years old from Nambashi Horton village in Thoubal district were selected. Soil samples were selected from five land-use types (Table 1).

Soil sampling

To study the effects of different land uses on soil phys-

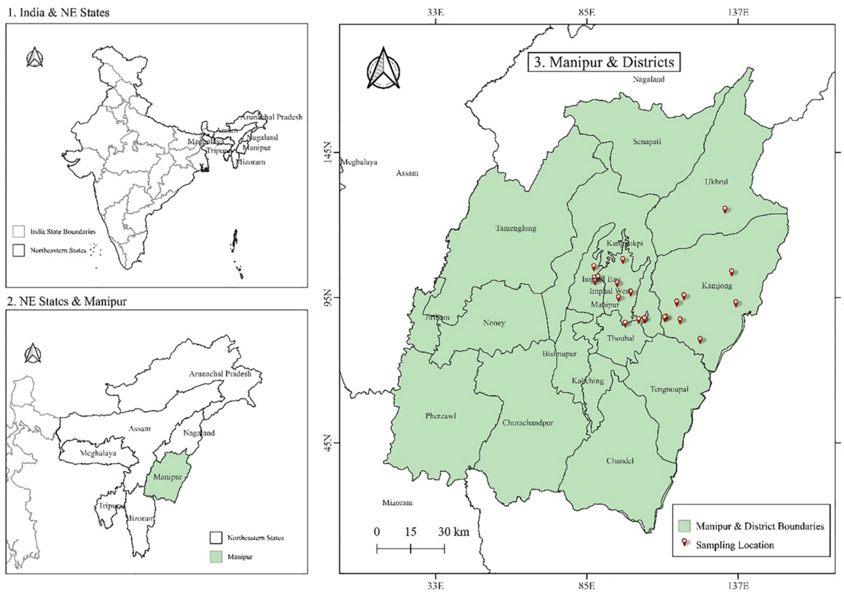

Fig 1. Figure showing three study regions with different land-use types and data-collection sites. Data were collected from three districts in Manipur.

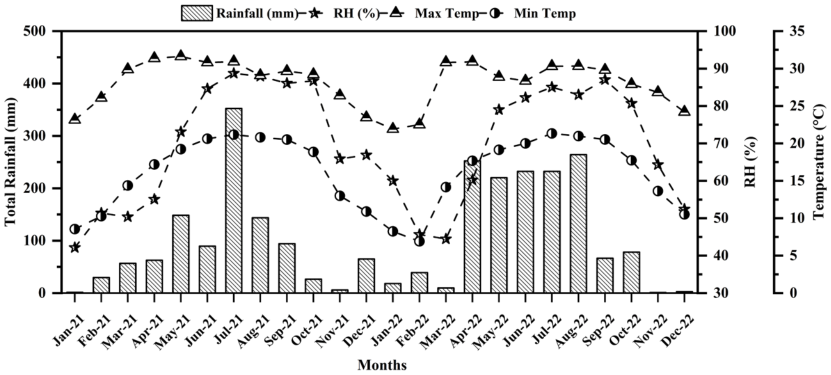

Fig. 2. Climatogram of the study area. Rainfall data were obtained from NASA's Global Precipitation Measurement (GPM), and temperature and Relative humidity data were obtained from NASA's MERRA-2 project.

icochemical properties, soil samples were collected at three randomly selected locations to a depth of 1 meter using a soil auger from five land uses across three districts (Fig. 1) in the state of Manipur, India (23.8372° N, 93.5701° E). To study the differences in soil physicochemical properties (texture, bulk density, soil moisture content, pH, SOC, available nitrogen (N_{avail}), available phosphorus (P_{avail}), K^+, Ca and Mg at four different depths (0-15, 15-30, 30-60, 60-100 cm) at different land use types was analyzed. The collected soil samples were transferred to polybags with tags or label numbers for future identification. A total of 60 soil samples were collected from 5 study sites in triplicate, with 12 per land-use type. The collected soil samples were analyzed for various soil parameters at the Indian Council of Agricultural Research (ICAR) in Imphal, Manipur.

Laboratory analysis of soil physicochemical properties

The collected soil samples were analyzed following standard laboratory protocols. Bulk density was determined using undisturbed core samples collected in volumetric cylinders, with values calculated as the oven-dry mass at 105 °C divided by the sample volume (Blake and Hartge 1986). The Bouyoucos hydrometer method (Bouyoucos 1962) was used to

Table 1. Site descriptions of the five different land use types used in the study, including their geographical locations, slopes, and management practices.

Land use	GPS coordinates	Altitude (msl)	Slope (degree)	Management/Characteristics
Natural Forest (NF)	24.684 N 94.201 E	1520	12^0	An undisturbed natural forest preserved by the villagers as the hydrological regulator of the water source for more than 100 years.
Degraded Forest (DF)	24.842 N 93.894 E	748	9^0	The disturbed forest has been declared a reserved forest for its preservation and has been protected by the local community and he Forest Department for the past 30 years.
Pine Plantation (PP)	24.677 N 94.087 E	916	11^0	Planted by the villagers on community land to produce timber for the rotation period, in existence for the past 25 years.
Fallow Land (FL)	24.687 N 94.207 E	1314	14^0	Hilly terrain where shifting cultivation has been practised and kept fallow with its natural regeneration for the past 10 years
Paddy Field (PF)	24.680 N 94.113 E	835	4^0	*Kharif*, *Rabi*, and *Zaid* crops have been grown on this patch of land for the past 60 years for domestic consumption.

separate the soil's sand, silt, and clay fractions based on sedimentation rates.

Among the soil chemical properties, pH was measured using a 1:2.5 soil-to-water suspension with a glass calomel electrode as per Jackson (1973), while soil moisture content was determined gravimetrically by oven-drying fresh samples at 105 °C until constant weight. The SOC was estimated using the Walkley–Black wet oxidation method (Walkley and Black 1934). Available nitrogen (N_{avail}) was determined by the Kjeldahl digestion, distillation, and titration procedure (Bremner and Mulvaney 1982), whereas available phosphorus (P_{avail}) was extracted with 0.5 M sodium bicarbonate solution (pH 8.5) following the Olsen method (Olsen *et al.* 1954) and quantified calorimetrically. K^+ was measured by extracting soil with neutral 1 N ammonium acetate and analyzing the extract using a flame photometer (Richards 1954). Finally, exchangeable calcium and magnesium were extracted with 1 N ammonium acetate (pH 7) and quantified using atomic absorption spectrophotometry (Buck Scientific Model 210).

Statistical analysis

We evaluated the effect of land-use change on soil properties by comparing soil properties across land-use types. Differences in soil properties (SOC, N_{avail}, P_{avail}, K^+, pH, and soil moisture) across land-use types were evaluated using a two-way ANOVA. Land-use types differed significantly for all soil properties (Table 2). For each significant result ($p < 0.05$), a Dunn's pairwise test was performed to determine group differences in each soil property between land use types. Results of the pairwise comparisons for each soil property across land-use types are visualized using a jitter plot (data points), the media, and the data range. For physical properties (Bulk density, total sand, silt, and clay content), mean values across land-use types and four soil layers were estimated (Table 3). Principal Component Analysis (PCA) was performed using OriginPro 2021 (OriginLab Corporation, Northampton, MA, USA) to evaluate relationships among soil physicochemical properties and land-use systems. The analysis was conducted on standardized data, and the first two principal components (PC1 and PC2) were used for interpretation and visualization through PCA biplots. All statistical analyses were conducted at a significance level of p < 0.05. All analyses in the study, except PCA, were performed using R (version 4.4.1; A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

Effects of land-use type and soil depth on soil physicochemical properties

Soil organic carbon (SOC), available nitrogen (N_{avail}), available phosphorus (P_{avail}), exchangeable potassium (K+), magnesium (Mg), calcium (Ca), soil pH, and moisture content varied significantly among land-use systems and across soil depths (Tables 2 and 3). In general, surface soils (0-15 cm) contained greater concentrations of SOC and nutrients than subsurface layers, with values declining progressively with increasing depth. Natural forest and fallow land maintained comparatively higher SOC concentrations than plantation forest and permanent farmland. SOC decreased markedly with soil depth, ranging from 4.28 ± 0.04% in the surface layer of natural forest to 1.47 ± 0.01% at 60–100 cm depth (Table 2). Similar depth-dependent declines were observed for N_{avail}, $P_{avail,}$ K^+, and moisture content (Table 3). Exchangeable Mg and Ca also differed significantly among land-use systems, reflecting differences in vegetation

Table 2. Depth-wise per cent soil organic carbon (SOC) under different land uses. Values are means ± 1SE. Different lowercase letters denote significant differences among the land uses.

Depth (cm)	NF	DF	FL	PP	PF
0–15	4.28 ± 0.04[a]	3.11 ± 0.04[b]	4.02 ± 0.03[a]	1.35 ± 0.04[c]	0.77 ± 0.01[d]
15–30	3.02 ± 0.01[a]	2.10 ± 0.01[b]	1.57 ± 0.04[c]	0.88 ± 0.02[d]	0.75 ± 0.00[d]
30–60	1.51 ± 0.01[a]	1.60 ± 0.01[a]	0.93 ± 0.00[b]	0.69 ± 0.00[c]	0.93 ± 0.00[b]
60–100	1.47 ± 0.01[a]	1.05 ± 0.01[b]	0.50 ± 0.01[c]	0.65 ± 0.01[c]	0.78 ± 0.00[bc]

Table 3. Variation in soil organic carbon (SOC), nutrient concentrations, pH, moisture content, and bulk density across land-use types and soil depths.

Land_use	Depth	SOC	N %	P %	K%	Mg cmol kg^{-1}	Ca cmol kg^{-1}	pH	Moisture	Bulk density
	0-15	4.28	0.03	0.01	0.02	0.05	0.28	4.81	31.48	0.95
NF	15-30	3.02	0.02	0.01	0.02	0.05	0.14	4.58	27.62	1.01
	30-60	1.51	0.01	0.01	0.01	0.04	0.11	4.88	22.05	1.07
	60-100	1.47	0.01	0.01	0.01	0.04	0.05	4.96	20.78	1.07
	0-15	3.11	0.02	0.01	0.02	0.05	0.29	4.91	29.73	0.94
DF	15-30	2.10	0.01	0.01	0.02	0.04	0.29	4.98	23.62	1.03
	30-60	1.60	0.01	0.01	0.01	0.04	0.29	4.91	22.20	1.11
	60-100	1.05	0.01	0.00	0.01	0.04	0.28	4.99	20.37	1.18
	0-15	1.35	0.01	0.00	0.02	0.04	0.08	4.13	16.03	0.90
PP	15-30	0.88	0.01	0.00	0.02	0.04	0.08	4.26	14.12	1.03
	30-60	0.69	0.01	0.00	0.02	0.05	0.13	4.33	15.62	0.97
	60-100	0.65	0.01	0.00	0.02	0.04	0.15	4.40	17.22	0.79
	0-15	4.02	0.02	0.01	0.02	0.05	0.29	4.83	34.87	0.94
PL	15-30	1.57	0.01	0.01	0.02	0.05	0.28	4.79	28.18	1.04
	30-60	0.93	0.01	0.01	0.02	0.05	0.20	4.89	26.30	1.06
	60-100	0.50	0.01	0.00	0.01	0.04	0.18	5.03	26.85	1.19
	0-15	0.77	0.01	0.01	0.02	0.05	0.29	5.62	17.22	0.99
PF	15-30	0.75	0.01	0.00	0.02	0.05	0.29	5.69	17.38	1.01
	30-60	0.93	0.01	0.01	0.02	0.05	0.28	5.01	18.93	1.01
	60-100	0.78	0.01	0.01	0.02	0.05	0.29	5.22	19.20	1.04

cover and nutrient cycling. Soil pH varied among land-use categories, with plantation forest generally exhibiting higher pH values than the other systems. Two-way ANOVA confirmed significant main effects of land-use type and soil depth on SOC ($F_{4,\ 40}$ = 5805.30, p < 0.001; $F_{3,40}$ = 8432.46, p < 0.001, respectively). Moreover, the significant interaction between land-use type and soil depth ($F_{12,\ 40}$ = 1240.69, p < 0.001) indicated that the magnitude of SOC changes with depth differed among land-use systems. Similar significant effects of land-use type, soil depth, and their interaction were observed for N, P, K, Mg, Ca, pH, and moisture content (all p < 0.001, Table 4). Bulk density exhibited a different pattern. Although significant effects of land-use type ($F_{4,\ 40}$ = 3.02, p = 0.0288) and soil depth ($F_{3,40}$ = 3.05, p = 0.0393) were detected, the interaction between land-use type and depth was not significant ($F_{12,\ 40}$ = 1.35, p = 0.2286), indicating a relatively consistent depth-related re-

Table 4. Two-way ANOVA results for soil physicochemical properties under different land-use systems and soil depths.

Variable	Source of	*df*	F-value	p-value
SOC	Land use	4	5805.30	<0.001
	Depth	3	8432.46	<0.001
	Land use × Depth	12	1240.69	<0.001
N (%)	Land use	4	276.98	<0.001
	Depth	3	253.74	<0.001
	Land use × Depth	12	27.04	<0.001
P (%)	Land use	4	5779.39	<0.001
	Depth	3	11751.05	<0.001
	Land use × Depth	12	1523.73	<0.001
K (%)	Land use	4	50671.24	<0.001
	Depth	3	1235868.00	<0.001
	Land use × Depth	12	289944.10	<0.001
Mg (cmol kg^{-1})	Land use	4	3294.41	<0.001
	Depth	3	1254.94	<0.001
	Land use × Depth	12	1251.11	<0.001

Table 4. Continued.

Variable	Source of	*df*	F-value	p-value
Ca (cmol kg^{-1})	Land use	4	1044557.00	<0.001
	Depth	3	121804.00	<0.001
	Land use × Depth	12	111838.50	<0.001
pH	Land use	4	7674.98	<0.001
	Depth	3	138.30	<0.001
	Land use × Depth	12	457.26	<0.001
Moisture (%)	Land use	4	5756.22	<0.001
	Depth	3	1317.50	<0.001
	Land use × Depth	12	396.63	<0.001
Bulk density (g cm^{-3})	Land use	4	3.02	0.0288
	Depth	3	3.05	0.0393
	Land use × Depth	12	1.35	0.2286

Note: *df* = degrees of freedom. Significant effects were considered at p < 0.05. Significant interaction terms indicate that the effect of soil depth varied among land-use systems.

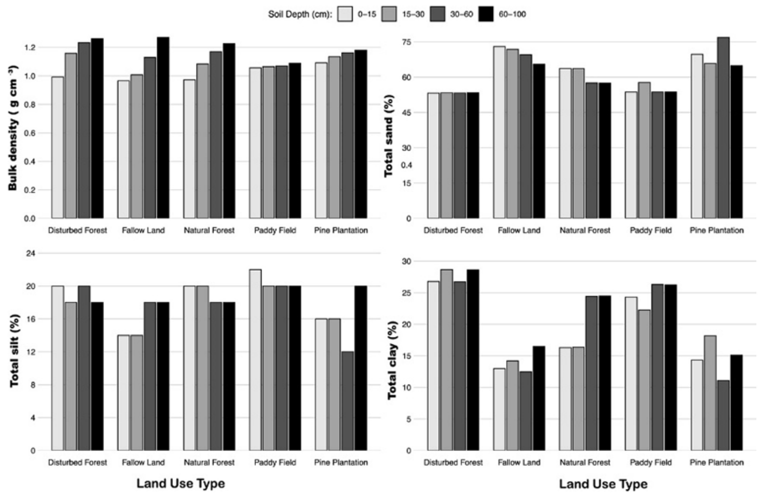

Fig. 3. Bar graph showing the variation of bulk density, total sand, total silt, and total clay content across different land use types and different soil depths.

sponse across land-use systems (Table 4).

Soil physical properties (bulk density and texture) across depths and land uses

Fig. 3 illustrates the variation in bulk density, total sand, total silt, and total clay across four soil depths (0–15, 15–30, 30–60, 60–100 cm) and five land use types (disturbed forest, fallow land, natural forest, paddy field, pine plantation). Bulk density increased consistently with depth under all land uses, ranging from 1.0 g cm^{-3} (0–15 cm, natural forest) to 1.6 g cm^{-3} (60–100 cm, disturbed forest and fallow land). Total sand content was lowest in the surface layer under natural forest (≈45%) and highest in the deepest layer under fallow land and disturbed forest (≈70%), with sand increasing progressively in depth across all land uses. Total silt content showed the opposite trend, peaking in the topsoil of natural forest (≈35%) and paddy field (≈30%) and decreasing to <15% at 60–100 cm for all uses. Total clay content in the 0–15 cm layer was highest under natural forest and paddy field (≈20–25%), intermediate under pine plantation (≈15%), and lowest under disturbed forest and fallow land (≈10–12%); clay decreased with depth under natural forest and paddy field but showed a slight increase between 30–60 cm under pine plantation and disturbed forest, indicating possible clay illuviation.

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was performed to assess relationships among soil physicochemical properties and their influence on sample distribution across different forest types. The first two principal components explained 73.28% of the total variance, with PC1 accounting for 49.76% and PC2 accounting for 23.52% (Fig. 4), indicating that these axes adequately captured variation in soil properties across the study sites. The PCA biplot revealed that K^+, P_{avail}, moisture (M), N_{avail}, and soil organic carbon (SOC) contributed positively to PC1, whereas bulk density (BD) showed a negative association with this axis. Along with PC2, soil pH, Ca, and Mg showed strong positive loadings, whereas SOC and N_{avail} showed negative loadings. The loading vectors indicated a strong positive relationship between SOC and N_{avail}, as reflected by their close alignment. Likewise, pH, Ca, and Mg were positively correlated and clustered together in the ordination space. In contrast, the opposite orientation of the SOC–N_{avail} and pH–Ca–Mg vectors suggested an inverse relationship between these groups of soil variables. The score distribution showed clear separation among forest types. PF samples were predominantly located in the positive region of PC2 and were associated with higher pH, Ca, and Mg concentrations. NF samples were distributed toward the positive end of PC1 and the negative end

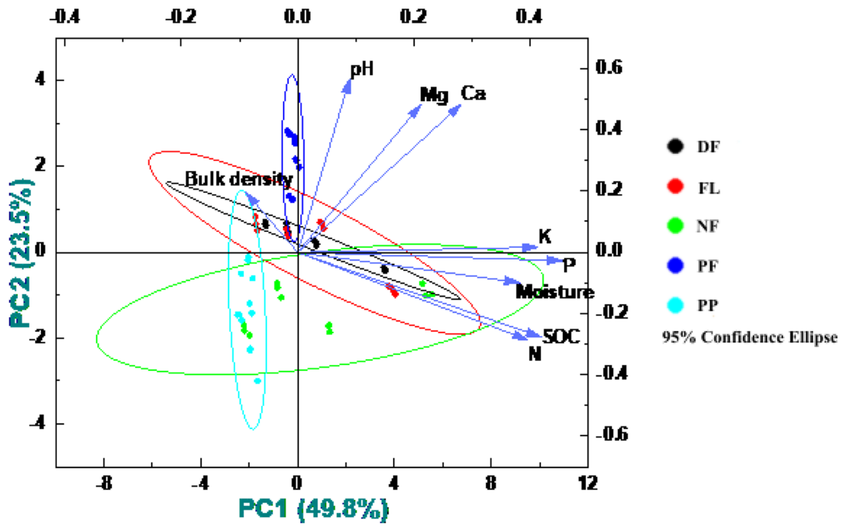

Fig 4. PCA ordination of soil physicochemical properties across different forest types (NF, PF, FL, and PP) in Manipur.

of PC2, indicating an association with higher SOC and N contents. FL samples occupied intermediate positions and showed affinity towards P and K, while PP samples were mainly concentrated on the negative side of PC1 and PC2, suggesting comparatively lower nutrient concentrations. The distinct clustering of samples demonstrates substantial variation in soil properties among the studied forest ecosystems.

DISCUSSION

Influence of land-use type and soil depth on soil properties

The significant differences among land-use systems highlight the strong influence of vegetation cover and management practices on soil properties. Natural forest soils exhibited higher SOC and nutrient concentrations, likely due to minimal disturbance and continuous litter inputs from leaves and roots (Murty *et al.* 2002, Guo and Gifford 2002). Fallow land also maintained relatively high SOC and nutrient levels in the upper depth, indicating the role of regenerating vegetation in restoring soil fertility through organic matter accumulation and enhanced biological activity (Aweto 1981, Brown and Lugo 1990). The decline in SOC, N_{avail}, P_{avail}, and soil moisture with increasing depth reflects the concentration of organic matter inputs and biological activity in surface soils, where litter decomposition and root density are greatest (Jobbágy and Jackson 2000). Similar depth-related trends have been widely reported in forest ecosystems and are attributed to reduced incorporation of organic matter into deeper soil layers (Jobbágy and Jackson 2000). Land-use conversion from natural forest to managed systems resulted in lower SOC and nutrient availability, which may be attributed to reduced litter inputs, biomass removal, and increased soil disturbance (Murty *et al.* 2002, Guo and Gifford 2002). Significant variation in exchangeable Ca and Mg among land-use systems further suggests differences in nutrient cycling and vegetation composition. Likewise, variations in soil pH likely reflect differences in litter quality, organic matter decomposition, and nutrient dynamics (Juo and Manu 1996). Higher soil moisture content in natural forest and fallow land indicates improved water retention associated due to greater organic matter content and better soil structure (Celik 2005). Although bulk density showed comparatively smaller responses to land-use change, its increase with depth reflects reduced organic matter content and greater soil compaction in subsurface layers (Celik 2005). The significant land-use × depth interactions observed for several soil properties indicate that land-use change influences not only soil nutrient status but also the vertical distribution of soil nutrients within the soil profile.

Edaphic N_{avail} Pools and Mineralization Constraints

The spatial variations in N_{avail} closely match the trends observed in SOC, confirming that soil organic matter functions as both the primary substrate for mineralization and the main energy source for N-transforming microorganisms. The NF ecosystem showed the highest N_{avail} concentration (376 kg ha^{-1}), driven by abundant organic matter pools and an undisturbed soil matrix that hosts a diverse, active microbial community. This stable environment maintains high extracellular enzyme activity, ensuring a consistent flux of plant-available inorganic N_{avail} (Carrara *et al.* 2018). When these stable forest ecosystems are altered, the N_{avail} concentration declines sharply to a lower, consistent baseline across PP (172 kg ha^{-1}), PF (188 kg ha^{-1}), and FL (220 kg ha^{-1}). In degraded or agricultural land-use systems, reduced canopy cover increases the likelihood that bare soil will be exposed to direct sunlight and higher surface temperatures (Leal *et al.* 2023). These microclimatic changes accelerate the leaching of highly mobile nitrate ions (NO^{3-}) and can inhibit specialized nitrifying bacterial communities, thereby greatly reducing mineral N_{avail} retention. Moreover, this N_{avail} limitation is especially severe in conifer plantations, which exhibit the lowest Navail level. In conifer forests, needle litter is notoriously poor in N_{avail} and rich in defensive compounds, such as polyphenols and lignin. Whereas the decomposing microorganisms need a balanced supply of nutrients, when decomposing high-lignin substrates, they often immobilize inorganic N_{avail} from the surrounding soil solution to meet their metabolic needs (Manzoni *et al.* 2021). This microbial sequestration effectively deprives the soil solution of inorganic N_{avail}, creating a significant nutrient bottleneck that limits overall plant productivity.

Geochemical Regulators of P_{avail} and K

Unlike N_{avail}, the changes of P_{avail} across the studied land-use types are primarily influenced by local chemical fixation and pH-dependent solubility, rather than organic matter accumulation alone. The P_{avail} in the PP (2.86 kg/ha) showed severe depletion, less than half the value reported in all other ecosystems. This significant P_{avail} deficiency results directly from geochemical processes driven by intense soil acidification caused by the accumulation and decomposition of conifer needles. As these needles break down, they release low-molecular-weight organic acids, reducing soil pH (> 4.3) and creating an acidic environment (Attiwill and Adams 1993). In these strongly acidic soils, soluble orthophosphate ions (H_2PO_4-) react with active iron (Fe) and aluminium (Al) oxides, forming highly insoluble complexes that bind P_{avail} to Fe and Al minerals. This chemical fixation, along with the slow rate of decomposition and high microbial immobilisation of P_{avail} within conifer soils, renders the plantation highly deficient in P.

In contrast, the P_{avail} value was higher in PF (6.59 kg/ha), showing that natural ecosystems are supported by entirely different mechanisms. In the waterlogged, anaerobic ecosystem of PF, ferric iron (Fe^{3+}) complexes are reduced to more soluble ferrous iron (Fe^{2+}), thereby breaking down insoluble iron phosphate minerals and releasing bound orthophosphate back into the soil solution (Richardson 1985). In NF, DF, and FL plots, the release of various organic ions by diverse broadleaf species competes for fixation sites on clay. P_{avail} is maintained by the steady return of broadleaf litter, which releases organic anions that compete for fixation sites on clay minerals, thereby keeping P_{avail} available to plants.

The primary influence of potassium (K^+) changes is due to intensive management practices rather than to natural soil weathering. Soils under paddy cultivation had the highest K^+ concentration (378 kg ha^{-1}), significantly higher than in other land uses. This increase is driven by two main factors: the regular application of chemical potassium fertilizer to maximize crop yields and the physical effects of prolonged flooding (Lalitha and Dhakshinamoorthy 2015). In PF, waterlogged, anaerobic conditions induce ammonium (NH^{4+}) and ferrous ions to displace potassium from exchange sites in clay interlayers, thereby increasing K^+ levels. In contrast, land use types such as NF, DF, FL, and PP maintain a uniform K^+ level (323–345 kg ha^{-1}) because they rely primarily on the slow weathering of K^+-bearing minerals and the cyclic recycling of plant biomass.

Mechanistic Drivers of Soil pH and Exchangeable Cations

The observed pH gradient across the landscape, from intense acidity in conifer (PP) stands to a more neutral profile in PF, illustrates how different land uses alter fundamental soil chemical equilibria. The extreme acidity of the PP soil (pH = 4.30) is directly linked to the slow decomposition of its recalcitrant litter. This slow breakdown releases complex organic acids (such as oxalic acid) that are saturated with the soil matrix and release free hydrogen ions (H^+). Moreover, the heavy accumulation of acidic needles creates a steady source of H+ ions that strip exchangeable bases from clay surfaces, worsening soil acidity (Attiwill and Adams 1993).

In contrast, the PF ecosystem buffers this acidity, reaching the highest pH (5.42). Prolonged waterlogging pushes the soil into a highly reduced state. This reductive process consumes large amounts of hydrogen ions during the reduction of iron and manganese oxides, acting as a natural chemical buffer that temporarily raises the soil pH toward neutrality (Garrido-Benavent *et al*. 2020).

This managed waterlogged environment also explains the higher levels of exchangeable Mg and Ca in PF soils. PF benefits from the deposition of mineral-rich sediments carried by irrigation water, as well as from the direct application of synthetic fertilizer. Moreover, exchangeable Ca values are also high in DF (0.288 c mol kg^{-1}) and FL (0.237 c mol kg^{-1}), far surpassing the values found in undisturbed NF (0.124 c mol kg^{-1}). This enrichment indicates that moderate soil disturbances or rapid vegetative changes during early secondary succession can accelerate the weathering of parent rocks, revealing hidden reserves of exchangeable bases in the upper soil horizons (Uhlig and Blancjenburg 2019).

Hydrological and Physical Restructuring of the Soil Matrix

The steady increase in BD with depth across all land-use types is a typical physical profile, caused by decreasing organic matter, less root penetration, and the weight of overlying soil compacting lower horizons (Van Der *et al.* 2023). However, clear differences appear in the topsoil horizon (0–15 cm), where the PP (1.091 g cm-3) and PF (1.055 g cm-3) show advanced compaction compared to the NF (0.972 g cm-3). In PF, this compaction is an intentional result of traditional tillage and puddling, which deliberately break down soil macroaggregates, forming a dense, impermeable plough pan that prevents water loss (Rahman and Amin 2023). In PP, the high BD results from a lack of active macro-organic matter and root-driven bioturbation in the mineral soil layer, allowing soil particles to settle into a more compacted matrix.

These structural changes directly influence SMC, which is lowest in PP (15.8%) and PF (18.2%). In PP, this dryness results from two mechanisms: high transpiration rates from the conifer canopy year-round and the highly hydrophobic nature of conifer litter. As conifer needles decay, they form a coating of water-repellent, non-polar organic compounds on soil particles, creating a hydrophobic barrier that significantly reduces rainfall infiltration and leaves the underlying soil dry (Molina *et al.* 2019).

In PF, low moisture content occurs when fields are drained between crop cycles. Tillage breaks down structural aggregates, transforming a complex, well-pored soil into a homogeneous matrix directly exposed to sunlight and wind. This exposure accelerates evaporation and greatly reduces the soil's natural water-holding capacity (Singh *et al.* 2024).

In contrast, the high, stable moisture levels maintained across NF, DF, and FL demonstrate the vital protective role of consistent organic matter and plant covers. These natural structures shield the soil surface from solar radiation, reduce evaporation rates, and enhance rainfall infiltration. The fact that the 10-year-old FL has regained moisture levels comparable to those of NF highlights how quickly soil physical and hydrological properties can recover when land is left to regenerate naturally, supporting the use of fallowing as an effective tool for restoring degraded landscapes.

Multivariate Relationships Among Soil Properties (PCA)

The PCA revealed considerable variation in soil physicochemical properties among the forest types, with PC1 and PC2 explaining 49.76% and 23.52% of the total variance, respectively (73.28% cumulative variance). This indicates that the selected soil variables effectively captured the major environmental gradients influencing soil quality across the study sites (Jolliffe and Cadima 2016). The close association between SOC and N_{avail} suggests a strong positive relationship between soil organic matter accumulation and nitrogen availability, reflecting the role of litter decomposition and nutrient mineralization in forest nutrient cycling (Prescott 2010, Lal 2004). Similarly, the grouping of pH, Ca, and Mg indicates that these variables are closely linked through soil buffering processes and base cation dynamics, which regulate soil fertility and nutrient availability (Brady and Weil 2017). The opposite orientations of the SOC–N and pH–Ca–Mg vectors suggest an inverse relationship between organic matter accumulation and soil reaction, a pattern commonly observed in forest soils, where organic matter decomposition contributes to soil acidification (Augusto *et al.* 2002, Singh *et al.* 2025b). The positive association of P and K with PC1 further highlights their importance in differentiating soil fertility status among the forest types, likely reflecting variations in litter quality, weathering, and nutrient cycling processes (Vitousek 2004). The distinct clustering of forest types in the ordination space demonstrates clear differences in soil characteristics. PF was associated with higher pH and Ca and Mg concentrations, whereas NF was more closely associated with higher SOC and N_{avail} contents, indicating contrasting nutrient dynamics between forest ecosystems. Similar patterns of forest-type differentiation based on soil nutrient status have been reported in tropical and subtropical forests (Paudel and Sah 2003). Overall, the PCA highlights the importance of nutrient availability, organic matter accumulation, and soil chemical properties in shaping soil variability and ecosystem functioning across the forest types of Manipur.

CONCLUSION

This study demonstrates that land-use change profoundly influences soil physicochemical properties in tropical ecosystems of Manipur. Significant variations in SOC, available nutrients, exchangeable cations, soil moisture, pH, and bulk density among the five land-use systems indicate that both vegetation type and management intensity play critical roles in determining soil quality. Natural forests consistently maintained the highest SOC, available nitrogen, and soil moisture, highlighting the importance of undisturbed ecosystems for sustaining nutrient cycling, C sequestration, and soil fertility. The strong positive association between SOC and nutrient availability further emphasises the central role of organic matter in maintaining soil productivity. Fallow land exhibited soil characteristics that closely resembled those of natural forest, particularly in terms of SOC and nutrient status, suggesting that natural regeneration can effectively restore soil quality within a relatively short period. This finding underscores the ecological importance of fallow systems as a viable restoration strategy for degraded landscapes. In contrast, pine plantation soils were characterized by low SOC, reduced phosphorus availability, high acidity, and lower moisture content, indicating that monoculture plantations may not adequately replace the ecological functions of natural forests. Paddy fields showed elevated pH and concentrations of potassium, calcium, and magnesium, reflecting the influence of flooding, sediment deposition, and agricultural management practices on soil chemistry. The PCA further confirmed distinct soil property patterns among land-use systems, revealing clear separation of natural forest, fallow land, pine plantation, and paddy field ecosystems based on nutrient status and soil chemical characteristics. Overall, the results indicate that intensive land-use conversion can diminish soil fertility and alter nutrient dynamics, whereas conserving natural forests and promoting fallow-based restoration can enhance soil recovery and ecosystem resilience. These findings provide valuable insights for sustainable land management, soil conservation, and climate change mitigation strategies in Northeast India and other tropical regions experiencing rapid land-use transformation.

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