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Research Article

Soil fertility stratification in a fragile ecosystem: Depth-wise gradients of nitrogen, phosphorus, potassium and pH in Chure hills Nepal

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ABSTRACT
The Chure region of Nepal, an ecologically fragile landscape, faces severe degradation, threatening its soil fertility and ecosystem services. Conducted in 2024, this study aimed to assess the vertical and spatial variations of key soil fertility indicators, total nitrogen (TN), available phosphorus (AP), available potassium (AK), and pH, in the forest soils of this understudied region. Soil samples were collected from 29 permanent sample plots across six districts (Bara, Parsa, Rautahat, Mahottari, Sarlahi, Siraha) in Madhesh Province. Stratified random sampling was employed to collect samples from three depth intervals (0–10, 10–20, and 20–30 cm). TN was determined using the Kjeldahl method, AP by Olsen's method, AK by flame photometry, and pH using a digital pH meter. A two-way ANOVA tested main effects of depth and district ($p< 0.05$). The results revealed significant vertical gradients for all parameters. TN decreased markedly with depth (0.034% at 0–10 cm to 0.012% at 20–30 cm), while AP, AK, and pH showed a significant increase with depth. This subsoil enrichment is attributed to the region's specific pedogenic processes, including leaching in coarse-textured soils, fixation in alkaline subsoils, and weathering of the calcareous/sandstone parent material. Spatially, Rautahat district consistently exhibited the highest levels of TN (0.034%), AP (106.46 kg/ha), AK (20.67 kg/ha), and pH (7.69), whereas Siraha had the lowest AP (99.84 kg/ha), AK (19.38 kg/ha), and pH (7.21), and Mahottari had the lowest TN (0.010%).These findings provide a critical scientific baseline for designing targeted soil conservation, sustainable forest management, and land rehabilitation strategies in this vulnerable ecosystem.

Keywords: Chure hills, nutrient leaching, soil depth, soil fertility stratification, Terai forests.

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INTRODUCTION
In the Chure region of Nepal, the Siwalik Hills are an Example of geologically young, fragile, and environmentally susceptible land. The region consists of loose sediments of sedimentary rocks, and the monsoon patterns have strong, seasonal rains, contributing to the highest

susceptibility to large-scale soil erosion in the region. Natural conditions are greatly aggravated through increased deforestation, the cultivation of land using unsustainable methods, and the unbridled extraction of natural resources in the region. Erosion selectively removes fine particles rich in nutrients, which alters depth profiles (Morgan, 2005; Ghimire et al., 2013). Notably, the above conditions contribute greatly to the accelerated loss of nutrients in the region and the degradation of the land itself, and the direct effect of all these conditions remains the threat to the livelihood of the people, who depend on agricultural production and natural resources in the region, as stated in the findings by Chalise et al. (2019). The soil is no more alike at a place two feet beneath the surface than it is a mile beneath. It differs extensively in depth and geographical location. Soil nutrient distribution with depth is governed by plant uptake, organic matter inputs, microbial decomposition, and long-term pedogenic processes (Jobbágy & Jackson, 2001; Batjes, 1996)." On a global scale, the presence of organic matter and the nitrogen fixed in it is greatest in the topsoil because the plant litter continues to feed the top layer, and their concentration drops abruptly when measured deeper because of the fewer inputs (Jobbágy & Jackson, 2001). Phosphorus and potassium, however, could be entirely different. In the case of forests, land with a considerable leaching process could see the accumulation of these two components in the subsoil because of the leaching process attributed to the solubility of their ions, or the result of the decomposition of the primary material present in the topsoil. It is significant to note here how the land use affects the topsoil's fertility, and undisturbed forests could be more efficient in retaining the topsoil's fertility than the degraded one (Binkley & Fisher, 2019).

Conceptually, the research connects the concepts of variability in soil nutrients and the processes of erosion, geomorphology, and degradation occurring within the Chure region. The nature of the sedimentary rock, monsoon climate, and human activity create an environment wherein the nutrients on the top soil are easily removed by erosion, whereas leached ions and weathered minerals may deposit beneath. An understanding of the three-dimensional nature of the nutrient variability is vital for predicting the fertility levels after erosion events, for choosing the appropriate biologically deep-rooted plants for re-plantation, and for formulating the necessary region-specific plans for conservation efforts.

Despite the established significance of the Chure region in terms of ecological and economical concerns, there is a remarkable deficiency in the in-depth analysis related to the soil nutrients in the Madhesh Province's forests. As a general pattern for Nepalese study, the analysis is mostly focused on the top layer of the soil and provides a broad regional perspective, failing to consider the topological perspective. Erosion in the Chure region is very severe, estimated at 20–50 t/ha/yr, leaving the top layer rich in nutrients, yet the subsoil can have different chemical compositions due to the weathering process (Lal, 2005). It is apparent that the topological view is crucial for the conservation program, failing which the plans cannot consider the leaching, weathering, and/or post-erosion nutrient losses, unique for the Siwalik slopes (Ghimire, et al., 2013).

What is unique to this study is the fact that it provides a holistic and three-dimensional assessment of soil fertility in the Chure, since this is one of the few instances in which data is available in this manner in this zone. By assessing changes in the major soil variables (TN, AP, AK, pH) in terms of both depth (0 to 30 cm) and distribution in six districts, this study provides

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perspective in terms of understanding nutrient vertical distribution in this fragile environment that is prone to erosion.

This research hypothesizes the following three things: first, that the TN, AP, AK, and pH content of the soil have discernible layers based on depth because the processes for the organic material on the surface and the geochemical processes underground differ; second, that the variations between the districts are influenced by the type of parent material, topography, and past land use; and third, that the Chure region maintains a hidden nutrient reservoir that can be leveraged for restoring the region, which is currently erosion-depleted. The objectives are to (i) determine the variation of TN, AP, AK, and pH with depth and between districts, (ii) determine if the variations between the districts are statistically significant, and (iii) explain the results in the context of the erosion, leaching, and chemical properties of Chure.

This study targets the type of soil found in the forests in order to create the reference level of nutrient patterns before degradation, against which the degradation level can be determined later on for the purposes of comparing the level of degradation of the soils and the effectiveness of the methods employed in the restoration of the nutrients in the affected areas. If agricultural lands are also considered, the level of fertilization and the effects of weathering would create ambiguity when establishing the original level of nutrients at the top of the soil profile. One constraint is the low sampling depth of 0-30 cm due to shallow regosols with stones, found in the Chure. This can result in the neglect of nutrient reserves deeper in the soil. Another constraint is the cross-sectional study design, which does not allow a conclusion on trends over time.

MATERIALS AND METHODS

Study Area

The study was conducted in the forested tracts of the Chure region within Madhesh Province, located in the southeastern part of Nepal. Geographically, the province lies between approximately 26°20′–27°10′N latitude and 84°25′–86°05′E longitude. The research focused on six districts: Bara, Parsa, Rautahat, Mahottari, Sarlahi, and Siraha (Figure 1).
These districts are representative of the core forest belt of Madhesh Province which makes up 85% of the area from 60–300 m elevation and cover all of the geomorphological diversity of these areas. The terrain is predominantly flat to gently sloping in the south, becoming more undulating and steeper towards the northern Chure hills, with elevations ranging from 60 to 300 m above sea level.

The study sites classified as Fluvisols and Regosols consist of shallow, coarse loamy soils developed from recent alluvial deposits, including sandstone, conglomerate and mudstone materials. Fluvisols, typically found in the Valley Floors and have layered sandy loam, give good representative coverage from floodplain alluvial areas (Rautahat, Sarlahi). Regosols, generally found on Hill Slopes and have very little horizon and high amounts of gravel (typical of Siwalik Formations), provide coverage from hilly areas (Bara, Parsa), giving good representative coverage for all soil fertility gradients and area based permanent monitoring areas.

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The climate is humid subtropical, characterized by three distinct seasons: a hot, dry pre-monsoon (March-May), a hot, humid monsoon (June-September) delivering 80% of the annual rainfall (1,200–1,500 mm), and a cool, dry winter (October-February). The forest ecosystems are dominated by tropical Sal (*Shorea robusta*) forests, often in mixed association with species like *Terminalia alata*, *Dalbergia sissoo*, and *Acacia catechu*. These forests are ecologically critical for biodiversity conservation, sediment trapping, and regulating hydrological cycles in this fragile landscape.

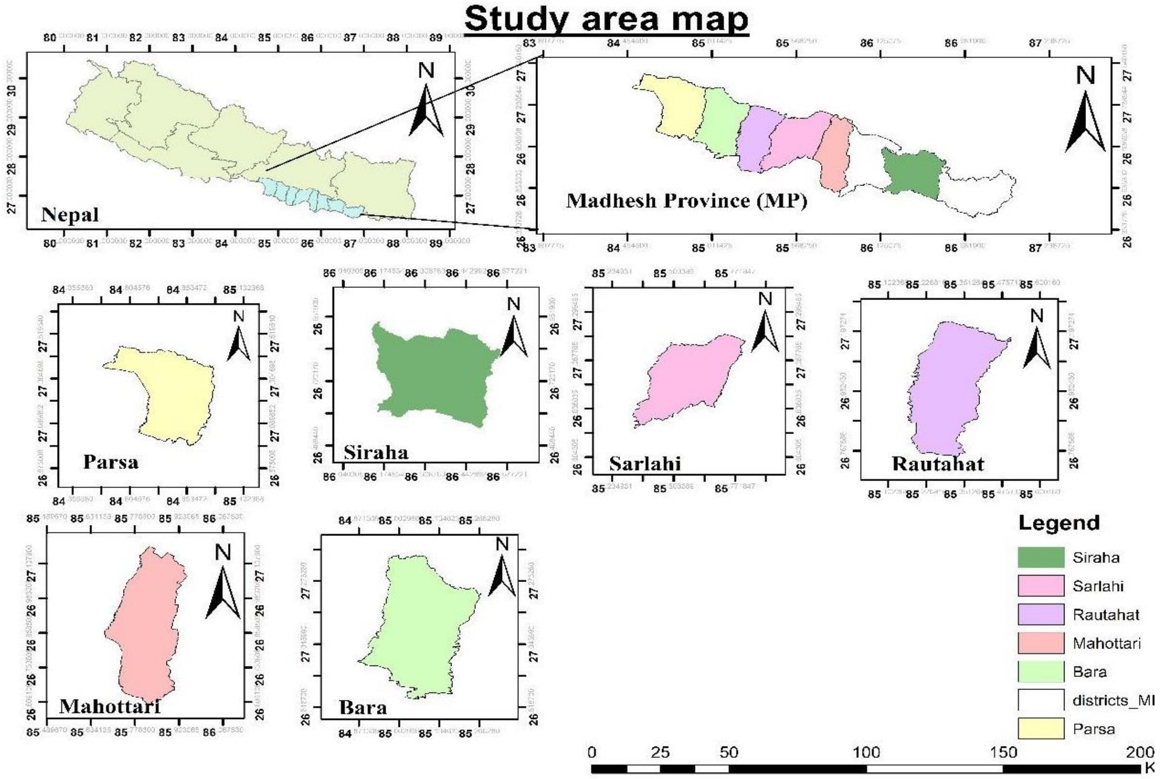

Figure 1: Map showing study sites

Soil Sampling and Data Collection

Soil sampling was conducted in the dry pre-monsoon season in the permanent sample plots established for the national Forest Resource Assessment (FRA). A stratified random sampling design, following the guidelines of the Department of Forest Research and Survey (DFRS), was employed with stratification by physiographic zone (Churia), elevation (60-300 m) and soil type (Fluvisols/ Regosols). A total of 29 plots across the six districts were selected for this study, ensuring representation of the major forest types.

At each circular plot, soil samples were collected from four soil pits dug at the cardinal directions (North, South, East, West), approximately 20 meters from the plot center. From each pit, undisturbed soil cores were extracted using a cylindrical soil corer (volume ~107.5 cm^3) at three distinct depth intervals: 0–10 cm, 10–20 cm, and 20–30 cm. Soil samples were taken up to a depth of 30 cm because this zone encompasses the biologically active root zone and the zone where most nutrient cycling occurs in forest soil profiles, although this is limited by the shallow stony Regosols found in Chure consistent with standard protocols. Depth stratified sampling is a standard approach for evaluating nutrient gradients in undisturbed landscapes (Zhou et al., 2017).

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The four sub-samples from the same depth within a plot were thoroughly mixed to form a single composite sample per depth per plot, resulting in 87 total samples (29 plots × 3 depths). Samples were placed in labeled plastic bags, their fresh weight recorded, and promptly transported to the Soil Laboratory of the Forest Research and Training Centre (FRTC) in Kathmandu for analysis. Resources of FRA were used in terms of data.

Laboratory Analysis

Prior to analysis, all soil samples were air-dried at room temperature, gently crushed using a wooden roller, and sieved through a 2 mm mesh to remove gravel and coarse organic debris.
Soil pH was determined potentiometrically in a 1:2.5 soil-to-deionized water suspension using a calibrated digital pH meter after 30 minutes of equilibration with occasional stirring.
Total Nitrogen (TN) was determined using the standard macro-Kjeldahl digestion and distillation method (Bremner & Mulvaney, 1982). This process involves digesting the soil sample with concentrated sulfuric acid to convert organic nitrogen to ammonium sulfate, followed by distillation and titration.

Available Phosphorus (AP) was extracted using the Olsen's method (Olsen, 1954) with 0.5 M sodium bicarbonate (pH 8.5). The phosphorus concentration in the extract was determined colorimetrically by the ascorbic acid method using a Spectrophotometer at a wavelength of 882 nm. The value in mg/kg was converted to kg/ha of P_2O_5 using the formula: AP (kg/ha) = R (ppm) × 2.24 × 2.3, where R is the reading in ppm.

Available Potassium (AK) was extracted with neutral normal ammonium acetate (1 N NH_4OAc, pH 7.0). The potassium concentration in the extract was directly measured using a flame photometer (Knudsen et al., 1982). The value was converted to kg/ha of K_2O using the formula: AK (kg/ha) = R (ppm) × 1.2 × (2 × 1.12).

Statistical Analysis

Data were compiled and analyzed using Microsoft Excel. Descriptive statistics—including mean, standard deviation, range, maximum, and minimum—were calculated for each soil parameter across depths and districts. A two-way Analysis of Variance (ANOVA) was performed, with plots as replicates, to determine the significant effects of the two independent categorical factors (soil depth, with 3 levels, and district, with 6 levels) on each dependent soil variable (TN, AP, AK, pH). The significance level was set at $\alpha = 0.05$.

RESULTS

Total Nitrogen (TN)

The TN content showed a clear and consistent decreasing trend with increasing soil depth (Table 2). The mean TN was highest in the topmost layer (0–10 cm) at 0.034%, nearly halved at 10–20 cm (0.017%), and was lowest in the deepest layer (20–30 cm) at 0.012% (Table 2). Spatially, Rautahat district had the highest mean TN across all depths (0.034%), followed by Sarlahi (0.027%), while Mahottari (0.010%) and Siraha (0.011%) had the lowest (Table 1, Figure 2). The depth-wise analysis per district confirmed this universal declining trend from surface to subsoil (Table 3). The two-way ANOVA confirmed that both soil depth ($F = 14.10$, $p = 0.0012$) and district ($F = 4.79$, $p = 0.017$) had a statistically significant effect on TN content.

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Table 1: Total Nitrogen (%) in 0-30cm soil depths under different districts

District	Mean (%)	SD	Maximum	Minimum	Range
Bara	0.019	0.012	0.056	0.001	0.055
Mahottari	0.010	0.009	0.032	0.004	0.028
Parsa	0.022	0.013	0.046	0.007	0.039
Rautahat	0.034	0.020	0.069	0.006	0.063
Sarlahi	0.027	0.010	0.044	0.014	0.030
Siraha	0.011	0.006	0.021	0.005	0.016
Mean	**0.021**				

Table 2: Total Nitrogen (%) at different soil depths

Soil Depth	Mean (%)	SD	Maximum	Minimum	Range
0-10 cm	0.034	0.017	0.069	0.006	0.063
10-20 cm	0.017	0.008	0.034	0.001	0.033
20-30 cm	0.012	0.006	0.025	0.004	0.021
Mean	**0.021**				

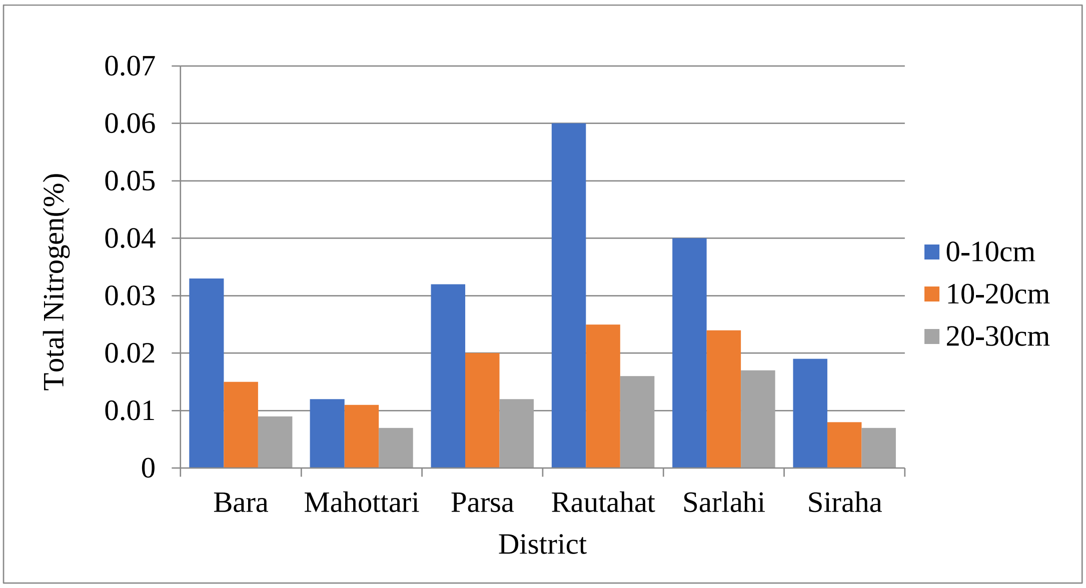

Figure 2: Total Nitrogen (%) according to soil depth under different districts

Available Phosphorus (AP)

In contrast to TN, the AP content increased with soil depth (Table 4). The mean AP was 100.92 kg/ha at 0–10 cm, increased to 104.71 kg/ha at 10–20 cm, and was highest at 106.38 kg/ha at 20–30 cm (Table 4). District-wise, Rautahat had the highest mean AP (106.46 kg/ha), and Siraha had the lowest (99.84 kg/ha) (Table 3, Figure 3). All districts exhibited this increasing pattern with depth without exception (Table 3). The ANOVA results indicated that both depth ($F = 23.58$, $p = 0.00016$) and district ($F = 6.77$, $p = 0.0053$) significantly influenced AP levels.

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Table 3: Available Phosphorus (kg/ha) in 0-30 cm soil depths under different districts

District	Mean (kg/ha)	SD	Maximum	Minimum	Range
Bara	104.380	3.804	111.480	97.490	13.990
Mahottari	104.260	5.104	110.100	94.720	15.380
Parsa	105.410	3.018	109.130	99.850	9.280
Rautahat	106.460	3.901	112.310	99.290	13.020
Sarlahi	103.200	4.869	108.710	93.480	15.230
Siraha	99.840	1.507	101.370	97.490	3.880
Mean	**104.570**				

Table 4: Available Phosphorus (kg/ha) at different soil depths

Soil Depth	Mean (kg/ha)	SD	Maximum	Minimum	Range
0-10 cm	100.920	3.293	107.600	93.480	14.120
10-20 cm	104.710	3.261	111.070	97.360	13.710
20-30 cm	106.380	3.464	112.310	97.490	14.820
Mean	**104.570**				

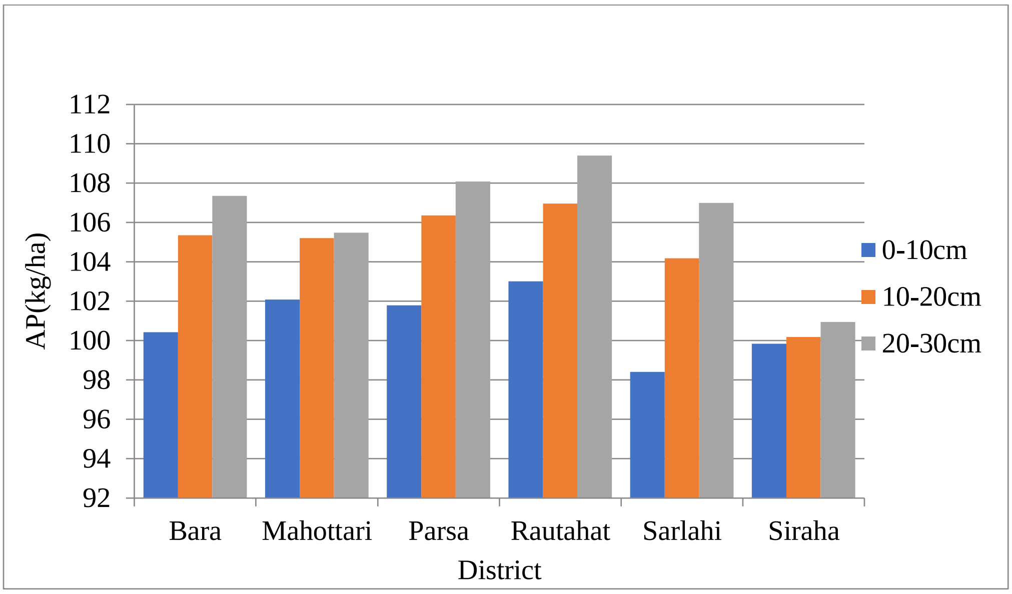

Figure 3: Available phosphorus according to soil depth under different districts

Available Potassium (AK)

Similar to AP, AK content exhibited a significant increasing trend with depth (Figure 4). The mean AK was 19.63 kg/ha at 0–10 cm, 20.45 kg/ha at 10–20 cm, and 20.81 kg/ha at 20–30 cm. Rautahat again recorded the highest mean AK (20.67 kg/ha), while Siraha had the lowest (19.38 kg/ha) (Table 5). This increasing pattern was consistent across all districts (Figure 4). The ANOVA confirmed highly significant effects of both depth ($F = 37.96$, $p = 0.000021$) and district ($F = 11.59$, $p = 0.00067$) on AK content.

Table 5: Available Potassium (kg/ha) in 0-30cm soil depth under different districts

District	Mean (kg/ha)	SD	Maximum	Minimum	Range
Bara	20.259	0.738	21.640	18.920	2.720
Mahottari	20.239	0.989	21.370	18.390	2.980
Parsa	20.458	0.585	21.180	19.380	1.800

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District	Mean (kg/ha)	SD	Maximum	Minimum	Range
Rautahat	20.665	0.758	21.800	19.270	2.530
Sarlahi	20.030	0.947	21.100	18.140	2.960
Siraha	19.380	0.294	19.680	18.920	0.760
Mean	**20.297**				

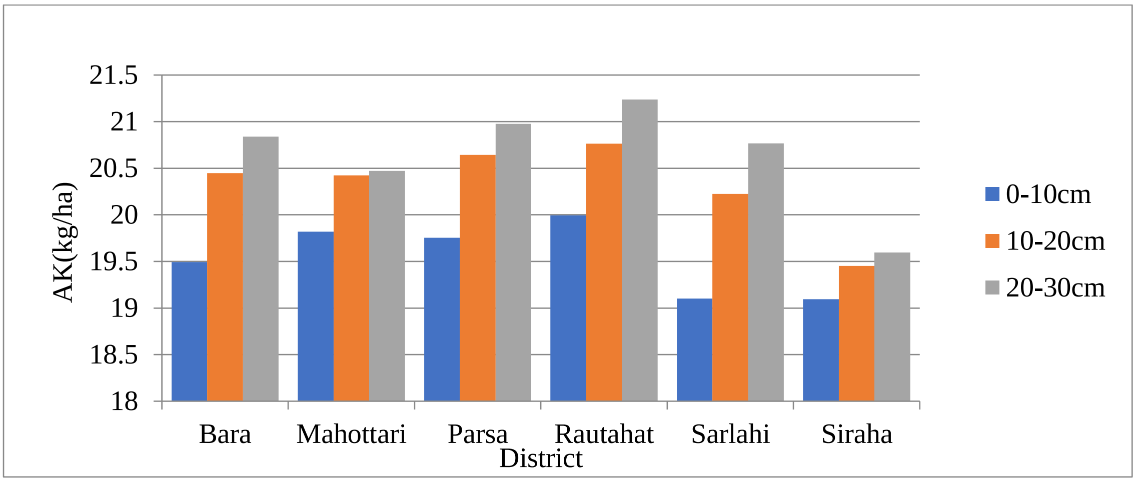

Figure 4: Available Potassium according to soil depth under different districts

Soil pH

Soil pH also increased significantly with depth, indicating a shift towards alkalinity in the subsoil. The mean pH was 7.30 (neutral) in the surface layer (0–10 cm), became moderately alkaline at 10–20 cm (pH 7.61), and was most alkaline at 20–30 cm (pH 7.74). Spatially, Rautahat had the highest mean pH (7.69), and Siraha the lowest (7.21) (Table 6). The depth-wise increase was a persistent feature observed in all districts. The two-way ANOVA showed that both depth ($F = 38.02$, $p = 0.000021$) and district ($F = 11.60$, $p = 0.00066$) had a highly significant effect on soil pH.

Table 6. Available soil pH in 0-30cm soil depths under different districts

District	Mean	SD	Maximum	Minimum	Range
Bara	7.537	0.274	8.050	7.040	1.010
Mahottari	7.529	0.368	7.950	6.840	1.110
Parsa	7.611	0.217	7.880	7.210	0.670
Rautahat	7.687	0.281	8.110	7.170	0.940
Sarlahi	7.452	0.351	7.850	6.750	1.100
Siraha	7.210	0.108	7.320	7.040	0.280
Mean	**7.551**				

DISCUSSION

This study provides a comprehensive, depth-resolved analysis of the spatial distribution of key soil fertility parameters in the forest ecosystems of the Chure region, revealing distinct and statistically significant patterns that have critical implications for management. The consistent and sharp decrease in Total Nitrogen (TN) with soil depth (Table 2, Figure 2) is a classic pedogenic pattern observed across terrestrial ecosystems (Jobbágy & Jackson, 2001). This pronounced stratification is primarily driven by the concentration of organic matter derived from leaf litter and root turnover in the surface horizons. The subsequent mineralization of this organic matter releases plant-available nitrogen, which is largely retained and recycled within the topsoil due to biological demand (Brady & Weil, 2016). The significant variation among districts (Table 1) can be attributed to differences in forest composition, litter quality, and past land-use history, all of which influence organic matter accumulation. Our findings align with studies from other parts of Nepal, such as the Chitwan-Mustang transect, where surface soils were significantly richer in nitrogen than subsoils. This underscores that the nitrogen capital of Chure forests is a surface phenomenon, making it exceptionally vulnerable to loss through erosion, a severe problem in the region (Lal, 2005). Loss of topsoil often disproportionally depletes nutrients essential for plant growth (Lal, 2005; Pimentel et al., 1995).

The increasing trend of Available Phosphorus (AP) with depth (Table 4, Figure 3) presents a more complex dynamic. While surface layers receive organic phosphorus inputs from litterfall, the observed subsoil enrichment suggests that other processes dominate. In the well-drained, coarse-textured soils typical of the Chure's sedimentary geology, soluble phosphorus can be leached from the surface by heavy monsoon rains. Furthermore, phosphorus is susceptible to fixation in neutral to alkaline conditions, which are present in the subsoil, potentially rendering it less available in surface layers and allowing mobile fractions to move downward. The weathering of phosphorus-bearing minerals in the parent material at deeper horizons could also be a slow but steady source. Phosphorus mobility is generally low, but under certain pH and moisture regimes, it can move via colloidal transport (Hinsinger, 2001). The district-level variation, with Rautahat having the highest and Siraha the lowest AP as shown in Table 3, likely reflects fundamental differences in parent material geology and soil texture, which control phosphorus retention and availability.

The increase in Available Potassium (AK) with depth (Figure 4) can be explained by its high mobility in sandy and sandy-loam soils. Potassium ions can be readily leached from the surface horizons during intense monsoon rainfall and re-adsorbed on the cation exchange sites in the subsoil. Additionally, the weathering of potassium-rich primary minerals occurs continuously in the deeper soil layers and the parent material, steadily releasing potassium into the available pool (Brady & Weil, 2016). The consistently higher AK in Rautahat and lower in Siraha, as shown in Table 5, points to the influence of local geologic substrates and potentially different degrees of nutrient removal.

The clear and consistent increase in soil pH with depth is a common phenomenon. Surface soils tend to be more acidic or neutral due to the decomposition of organic matter, which releases organic acids, and the leaching of basic cations (Ca^{2+}, Mg^{2+}, K^{+}) from the topsoil. These leached basic cations accumulate in the subsoil (illuviation), increasing its alkalinity and buffering capacity (Brady & Weil, 2016). This pattern has been documented in other Nepalese landscapes, such as the Kathmandu Valley. The significant spatial variation in pH among districts is strongly influenced by the chemical composition of the parent material and localized land-use practices.

CONCLUSION

This study presents the first comprehensive, depth-resolved soil fertility assessment of the Chure region, revealing systematic vertical stratification and significant spatial heterogeneity that fundamentally redefines nutrient dynamics in this fragile sedimentary landscape. The marked surface accumulation of nitrogen, coupled with increasing phosphorus, potassium, and pH with depth, demonstrates a distinct divergence between biological nutrient cycling in topsoil and geochemical processes in subsurface layers. Spatially, Rautahat exhibited consistently higher fertility status, while Siraha and Mahottari recorded the lowest nutrient levels, reflecting the influence of localized parent material and land-use history.

These findings advance scientific understanding by: (1) documenting a counter-intuitive nutrient stratification pattern where phosphorus and potassium are enriched with depth—contrary to conventional surface-focused models; (2) establishing a direct linkage between soil architecture and erosion vulnerability, illustrating how surface nitrogen loss exposes alkaline, nutrient-rich subsoil; and (3) providing a three-dimensional baseline that integrates vertical and spatial variability for targeted ecosystem management.

Based on the evidence, we recommend: (1) prioritizing erosion control in nitrogen-sensitive areas through vegetative barriers and litter retention; (2) selecting deep-rooted native species to access subsurface phosphorus and potassium reserves in degraded sites; (3) developing district-specific reforestation protocols calibrated to local fertility gradients; and (4) implementing long-term soil monitoring across depth intervals. This research provides a scientifically robust framework for soil conservation, sustainable forest management, and climate-resilient land restoration in the Chure and analogous fragile ecosystems worldwide.

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Authors' contribution

N. Neupane designed the research, conducted the field work, and analyzed the data. N. Neupane and G. Kafle prepared the manuscript. G. Kafle supervised the overall research, report, and article preparation. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Ethics Approval Statement

This study involved soil sampling only and did not include human or animals. Sampling was conducted with permission from relevant local authorities and in accordance with environmental and institutional research guidelines.

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