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The dynamics of soil nutrients in cold desert environments in the north-west Himalayas under a variety of forest types using geographical information system

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Abstract
The amount of nutrients present in the soil is one of the most important factors that decide the overall productivity of an ecosystem as well as the variety of species that live there. The north-west Himalayas, which are home to a dry temperate and alpine forest of cold desert, served as the study location for the present research. The major purpose of the research was to investigate the dynamics of soil nutrients in connection to the structure and content of nine distinct kinds of forest ecosystems that may be found in the area. In each of the chosen forest types, the nutritional condition of the soil was analyzed for two distinct soil depths: the top layer (0–20 cm) and the bottom layer (> 20 cm) (21–40 cm). The different kinds of forest had pH readings that ranged anywhere from 4.81 to 6.82 in their soil. In a birch-rhododendron scrub forest, the levels of available soil nutrients such as nitrogen, phosphorus, potassium, copper, manganese, and zinc were found to be at their highest levels. Other soil properties such as organic carbon and electrical conductivity were also found to be at their highest levels in this type of forest as well. When it comes to the creation of forest plantations and artificial regeneration, there is a potential that forest managers may find the information on nutrients and biogeochemicals to be beneficial.

Keywords Forest types · Physicochemical properties · Soil depths · Bulk density · Altitude

1 Introduction

Soil nutrient availability is critical for controlling plant-soil feedbacks (Putten et al., 2013) and nutrient cycling in terrestrial ecosystems (Sistla et al., 2012). Nitrogen (N) and phosphorus (P) are the principal soil nutrients that restrict vegetation production (Craine et al., 2013; Fang et al., 2019; Kumar et al., 2022a; Norouzi et al., 2010), and their availability and dynamics change ecosystem structure and functions through influencing species diversity (Fernández-Martínez et al., 2014; Terre et al., 2019), hence controlling the terrestrial ecosystem carbon cycle. N enters the environment mostly via nitrogen fixation, while P is primarily derived through weathering of native minerals (Wieder et al., 2015; Goll, 2016; Chapin et al., 2011; Delgado-Baquerizo et al., 2013; Bhattacharyya et al.,

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2000; Geng et al., 2017). Soil accessible nitrogen (SAN) and soil available phosphorus (SAP) are nutrients that plants may directly utilize from the soil. Importantly, biotic and abiotic environmental variables regulate and govern soil nutrient cycle processes, and alterations in environmental parameters might possibly affect the patterns and dynamics of SAN and SAP. Soils provide various ecological functions, including serving as a substrate to grow plants, acting as a habitat for soil organisms, rain water filtering, and nutrients and waste recycling. Thus, the soil information is essential to understand the growth and reproduction of forests. Different tree species have varying capacities for selective nutrient absorption and return them back to the soil (Yadav and Bisht, 2014). Therefore, information regarding the soil is necessary in order to comprehend the development and reproduction of forests. There is a wide range of capacity among tree species for the selective absorption of nutrients and the subsequent return of those nutrients to the soil (Singh et al. 1986; Yadav and Bisht, 2014).

The patterns and dynamics of N and P and other soil nutrients have been shown to be influenced by a variety of factors, including temperature, topography, soil parent material, microorganisms, the dynamics of vegetation (Augusto et al., 2017; Binkley et al., 2019; Nelson and Sommers, 1996; Brady et al., 2010; Bartier and Keller, 1996; Matias et al., 2011), and human activities (Peuelas et al., 2013). Both biological and abiotic environments have been altered as a result of climate change, which has had a substantial effect on biogeochemical processes. Numerous studies have demonstrated that the deterioration of perennial permafrost caused by global warming may result in the release of soil nutrients (such as N and P) that are beneficial to the growth of plants (Keuper et al., 2017; Salmon et al., 2016). Temperature increases, in particular, promote the decomposition of organic matter in the soil, as well as the accumulation and cycling of nutrients that may be accessed from the soil (Conant et al., 2011). Hydrothermal conditions cause soil nutrient imbalance or cyclic decoupling by altering surface temperature, soil moisture content, and microbial activities (Mooshammer et al., 2017; Tian et al., 2010b; Yue et al., 2017), which can have an effect on the growth of vegetation, the composition of communities, and the functions of ecosystems (Mooshammer et al., 2017; Yue et al., 2017). However, an increase in temperature may reduce the availability of soil nutrients (Sasaki et al., 2010). In recent decades, increased anthropogenic nitrogen emissions have resulted in increased atmospheric nitrogen deposition in grassland areas of northern China (Liu et al. 2013). The increasing rates of atmospheric nitrogen deposition range from 5.2 to 18.7 kg N ha1 yr1 (Lu et al., 2007), and it has been shown that elevated nitrogen deposition significantly affects the nitrogen status of ecosystems. The availability of phosphorus in the soil is determined by the biogeochemical processes that operate over longer time scales and may be affected by the surrounding environment. Temperature, for instance, may have a direct impact on the adsorption and desorption of phosphorus in soil, while precipitation may have an effect on the leaching of phosphorus from soil. In addition, topographic processes including as erosion, dissolution, and landslides have the potential to influence the accumulation or depletion of nutrients in different areas. As a consequence of this, determining the factors that contribute to oscillations in SAN and SAP on a large regional scale is essential for comprehending the underlying mechanism of soil nutrient cycling as well as the fundamental principles of terrestrial ecosystems (He et al., 2008; Sun et al., 2021).

The features of the soil, which are crucial to the plants' initial establishment and continued growth, have a direct and positive correlation with the plant's rate of growth. The fertility of the soil, which refers to the amount of available vital nutrients in the soil, is by far the most important factor among all of these different aspects. As a result, sufficient academic and practical information regarding distinct forest soils and the deep link between the lives of various trees and other forest plants need to be amended. This is because of the necessity. As a result of tree planting, the physicochemical properties of the soil undergo significant shifts. Despite this, the effect that tree plantations have on the soil's characteristics differs depending on the type of vegetation that is there (Chapman and Reiss, 1992). The physicochemical properties of the soil are responsible for determining the nutrient status of the soil, which varies according to the nature of the locality factor of that area. This factor includes the parent material, the climate of a region, slope, aspect, and the vegetation that the soil is capable of supporting (Behari et al., 2004; Chaudhary et al., 2018). The physical characteristics of soil contribute to the prevention of soil erosion and the enhancement of soil fertility (Sharma and Bhatia, 2003).

Monitoring changes in SOC is essential, and the use of field or remote sensors to monitor carbon over croplands is highly relevant to this process (Ou et al., 2020; Silvero et al., 2020). Earth Observation (EO) as well as Geographical Information System (GIS) can be a valuable data-source for area-wide mapping with a resolution that allows distinguishing between or even with field patterns (Kumar et al., 2012, 2013, 2014, 2016, 2018, 2019, 2022b; Felegari et al., 2022; Srivastava et al., 2016; Pandey et al., 2019). In this context, GIS (e.g., Gupta et al., 2014) and multispectral images (e.g., Kumar et al., 2022b) are commonly used EO datasets to derive SOC contents. The physicochemical features of forest soils can change through time and place as a result of topographical changes, climate conditions, the nature of weathering processes, plantcover, and the activities of soil microorganisms (Paudel and Sah, 2003; Dengiz et al., 2006). Plant tissue, which includes both surface waste and underground root detritus, is the primary source of soil organic matter, which is responsible for determining the physicochemical properties of soils. Taking all of the preceding into consideration, the objective of this research was to analyze the dynamics of soil nutrients in a number of different cold deserts located in the northwestern Himalayas.

2 Material and methods

2.1 Study area and soil sampling

The current investigation is being carried out in the dry temperate and alpine forests area of cold desert in the north-west Himalaya. The coordinates for this region are as follows: latitude 31°20′ 50"–31°47′ 51"; longitude 78°08′04"–78°27′29" E. The elevation of this region ranges from 2000 to 3750 m above sea level (MASL) (Fig. 1). The study region is characterized by lengthy winters (October–April) and short summers (June–August), with heavy snowfall during the winter and no summer rain, and the parent material consists of gneiss, schist, phyllites, quartzite, and granites.

According to Champion and Seth's (1968) classification, the study area is comprised of nine different types of forests. These include: Dry broad-leaved and coniferous forest (13C1), Neoza pine forest (13C2a), Dry deodar forest (13C2b), West Himalayan high level dry blue pine forest (13C3), West Himalayan sub-alpine birch forest (14C1a), West Himalayan sub-alpine fir. In the months of October and November, composite soil samples were taken from two distinct soil levels, namely the top layer

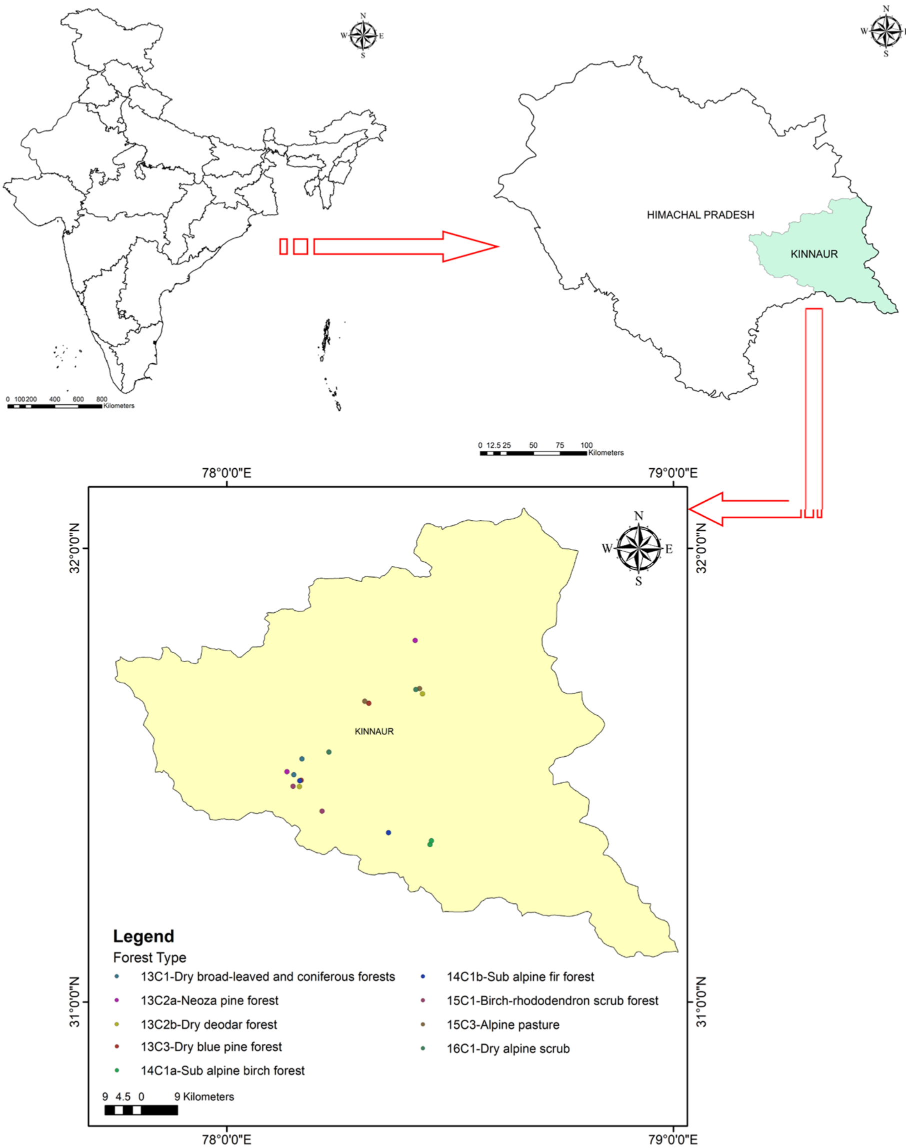

Fig. 1 Map of the location of the study area and the type of forest in the cold desert of the north-western Himalayas

(0–20 cm) and the lower layer (21–40 cm), with each depth being reproduced three times from an independent clustered plot of a different species of forest.

2.2 Observations and statistical analysis

The different soil physicochemical characteristics viz., soil organic carbon (OC) (Walkley and Black method, 1954), pH (1:2.5 soil: water suspension using pH meter, Jackson, 1973), electrical conductivity (EC) (1:2.5 soil: water suspension using digital conductivity bridge, Jackson, 1973), bulk density (specific gravity method, Singh 1980), available nitrogen (N) (alkaline potassium permanganate method of Subbiah and Asija, 1956), available phosphorus (P) (Olsen et. al., 1954), available potassium (K) (flame photometer method of Merwin and Peach, 1951) and available micro-nutrient (Cu, Mn, Fe and Zn) (Diethylene triamine pentaacetic acid (DTPA) method)were analyzed in all the selected forest types at two different depths. The observed data on different soil physicochemical properties were statistically analyzed as per two-way ANOVA using the procedure described by Gomez and Gomez (1984). To test the significance of forest effect on soil physicochemical properties, the F test was performed and critical difference was calculated at 5 per cent level of probability.

2.3 GIS-based spatial modeling of soil nutrients

Regression techniques like kriging provide a least squares estimate of the data (Delbari et. al, 2016). It creates an approximated surface model from a dispersed collection of data points' spatial description using z-scores. It has its roots in mining geology and is now a crucial tool in the geostatistics arsenal. This form of interpolation has the advantage of producing both an interpolated spatial model and an assessment of the level of uncertainty at each place in the model. Kriging interpolation, in contrast to linear regression or inverse distance-weighted interpolation is largely based on empirical observations, or the observed sample data points, as opposed to a pre-assumed model. In order to lessen soil sampling bias, the interpolation weights clusters less strongly than single points and provides weight to sample points closer to a place than those further away. Each soil point's value is determined in a method that minimizes the predicted error for that specific point.

2.3.1 SOC extraction using kriging method

The Kriging method was used to interpolate the location points of the SOC. This approach generates an estimate for an unmeasured plot location and weights the nearby dignified values. Variograms and covariance functions were used to generate the statistical values for auto-correlation models. After the data have undergone autocorrelation, the model forecasts the unknown values. Equation below can be used to determine the prediction value for an unmeasured site.

$$Z(s_O) = \sum_{i=1}^{N} \lambda_i Z(S_i)$$

where:

$Z(s_O)$ = Prediction value for unmeasured location.

$Z(S_i)$ = ith location by measured value.λ_i= ith location by an unidentified weight for the estimated value

N=The number of measured value.

We employ standard kriging during spatial modeling of soil nutrients. The semivariogram produced by the geostatistical wizard has blue crosses that represent the typical variance for each pair of soil points. The size of a distance class into which pairs of locations are categorized is known as the lag size. Soil sampling data were not crowded so average nearest neighbor tool was used.

3 Results and discussion

Throughout the north-west Himalaya, our research mapped the spatial patterns of various soil parameters, such as pH, EC, OC, N, P, K, Cu, Fe, Mn, and Zn, with a geographic pattern of higher values in the east and lower values in the west. This was done in order to better understand the relationship between these soil parameters. In general, there was a considerable rise in the amount of N, whereas there was a significant decline in the amount of P. In the north-west Himalaya, the contents and dynamics of nitrogen and phosphorus were diverse and were influenced by the interaction between many environmental variables. The physicochemical qualities of the soil were the main determinants among these multiple environmental factors (Table 1).

3.1 Soil organic carbon

Organic matter in the soil makes up a sizeable amount of the soil's organic carbon pool (Koutika et al., 2019), which has an effect on the soil's characteristics, specifically its biological, physicochemical, and biological qualities (Woomer et al., 1999). In the current investigation, the value of soil organic carbon (OC) (percent) varied significantly depending on the kind of forest as well as the soil layer, and it was found to fall anywhere between 0.56 and 2.56%. (Table 2). The soil of the birch-rhododendron scrub forest has the highest carbon content (2.56%), which may be attributable to the large proportions of leaf litter and the slow rates of decomposition of organic residues due to the limited light penetration to the soil surface. Both soil layers contain the same amount of carbon (Dimri et al., 1997). However, in dry alpine scrub, the combination of low litter generation, high wind speed, and an absence of overstorey plant life might result in rapid litter decomposition, which in turn can result in a decrease in soil organic carbon (0.56%).

Additionally, regardless of the types of forests present, the topsoil layer (0–20 cm) revealed a considerably greater level of soil organic carbon (1.74%) than the bottomsoil layer (21–40 cm). Senneh (2007), Kaushal (1992), Sharma (1991), Maurya et al. (2014), and Meena et al. (2018), researchers working in a variety of habitats, all found findings that were comparable to one another. Senneh (2007) revealed their study and find SOC stock in 0–20 cm in layer to be significantly higher than that of L layer. Maximum soil organic carbon 2 stock (0–40 cm layer) was recorded in forest land use system (108.9 t/ha). In his investigation, Maurya et al. (2014) looked into and discovered. Acidic soils were present in both fallow land and forest areas. Potassium, nitrogen, phosphorus, organic carbon, and nitrogen all have high ranges of content. Total nitrogen, phosphorus, and potassium levels in forest lands averaged 2115.39 kg/ha, 111.89 kg/ha, and 2189.36 kg/ha, respectively. The similar figures for the fallow fields were also 1491.27, 80.26, and 2650.75 kg/ha, respectively. Meena et al. (2018) analyzed the carbon management index (CMI) and discovered that it was averaged throughout (Fig. 2). Spatial variability of different soil nutrients at 0–20 cm are shown in Fig. 3.

Table 1 Different forest types and their description in north-west Himalaya

Forest types	Altitude range (m)	Symbol (Champion & Seth 1968)	Coordinates	
			Latitude	Longitude
F1-Dry broad-leaved and coniferous forests	2000–2450 m	$13C_1$	31°30′05’’ and 31°32′11’’ N	78°08′59’’ and 78°10′05’’ E
F2-Neoza pine forest	2300–2750 m	$13C_{2a}$	31°30′29’’ and 31°47′51’’ N	78°08′04’’ and 78°25′18’’ E
F3-Dry deodar forest	2450–3000 m	$13C_{2b}$	31°28′31’’ and 31°40′48’’ N	78°09′45’’ and 78°26′17’’ E
F4-Dry blue pine forest	3000–3450 m	$13C_3$	31°29′21’’ and 31°39′32’’ N	78°09′58’’ and 78°19′05’’ E
F5-Sub alpine birch forest	3100–3550 m	$14C_{1a}$	31°20′50’’ and 31°21′20’’ N	78°27′17’’ and 78°27′29’’ E
F6-Sub alpine fir forest	3150–3550 m	$14C_{1b}$	31°22′25’’ and 31°29′17’’ N	78°21′43’’ and 78°09′47’’ E
F7-Birch-rhododendron scrub forest	3300–3600 m	$15C_1$	31°25′15’’ and 31°28′33’’ N	78°12′47’’ and 78°08′53’’ E
F8-Alpine pasture	2900–3350 m	$15C_3$	31°39′48’’ and 31°41′29’’ N	78°18′032’’ and 78°25′53’’E
F9-Dry alpine scrub	3300–3750 m	$16C_1$	31°33′05’’ and 31°41′22’’ N	78°13′42’’ and 78°25′23’’ E

Table 2 Analysis of organic carbon, bulk density, soil pH, and electrical conductivity in Himalayan dry temperate and alpine forests of the north-west Himalaya treatments organic carbon (%) Bulk density (g cm^{-3}) pH electrical conductivity (dsm^{-1})

Treatments	Organic carbon (%)	Bulk density (g cm^{-3})	pH	Electrical conductivity (dsm^{-1})
Forest types (F)				
F_1-Dry broad-leaved and coniferous forests	2.24^{b}	1.19^{g}	6.82^{a}	0.13^{b}
F_2-Neoza pine forest	0.71^{h}	1.59^{b}	6.35^{d}	0.06
F_3-Dry deodar forest	1.75^{c}	1.21^{f}	6.67^{b}	0.11^{b}
F_4-Dry blue pine forest	1.08^{f}	1.29^{d}	5.62^{f}	0.09^{d}
F_5-Sub alpine birch forest	1.48^{d}	1.22^{f}	4.81^{i}	0.11^{b}
F_6-Sub alpine fir forest	1.29^{e}	1.27^{e}	6.37^{c}	0.13^{b}
F_7-Birch-rhododendron scrub forest	2.56^{a}	1.17^{h}	5.15^{h}	0.18^{a}
F_8-Alpine pasture	0.97^{g}	1.32^{c}	6.15^{e}	0.10^{c}
F_9-Dry alpine scrub	0.56^{i}	1.68^{a}	5.35^{g}	0.07^{d}
CD at 5%	0.01	0.02	0.01	0.02
Soil layer (L)				
L_1 (0–20 cm)	1.74^{a}	1.31^{b}	5.88^{b}	0.11^{a}
L_2 (21–40 cm)	1.07^{b}	1.34^{a}	5.96^{a}	0.09^{b}
CD at 5%	0.004	0.01	0.004	0.01

Different letters superscripting the values in columns denotes significant

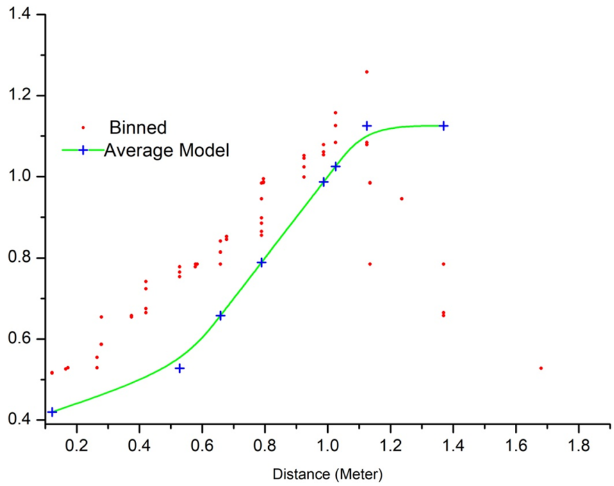

Fig. 2 Spatial modeling of soil nutrients with a semi-variogram

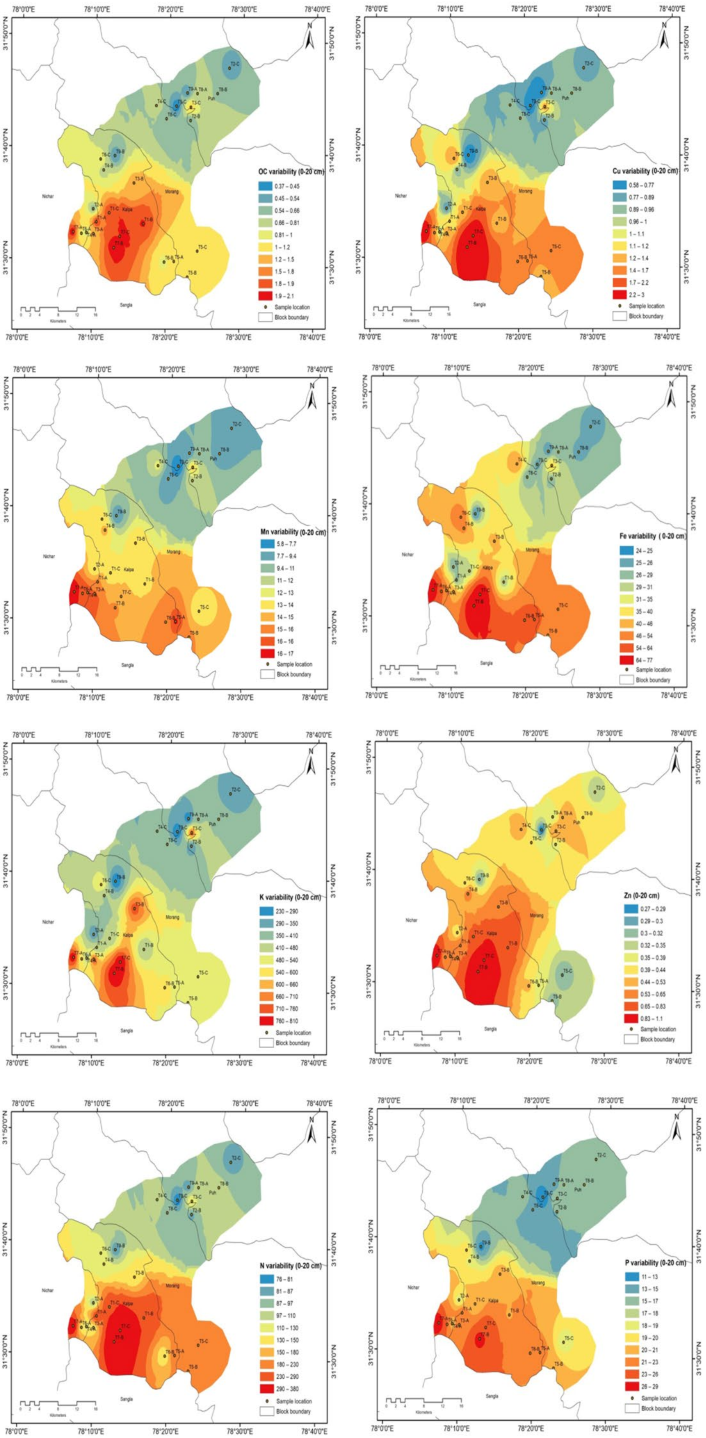

Fig. 3 Spatial variability of different soil nutrients at 0–20 cm

There may be a greater building of organic carbon in the top soil than in the subsurface, which may be the result of a greater accumulation of litter in the top soil. It is possible that increasing accumulation and mineralization, in addition to a reduction in root biomass in deeper soil layers, are to blame for the steady reduction in the availability of nutrients that occurs as one moves downward through the soil layers. There is also the possibility that nutrient cycling is to blame. This process involves a plant's deep tap roots drawing nutrients from deeper soil layers and then depositing them on top soils, most preferably at the surface. Our findings for the chir pine woods of Himachal Pradesh are in good accord with those found by Malik (1992), Sharma (1991), and Soni (1991).

3.2 Soil pH, bulk density and electrical conductivity

For plants to receive an adequate amount of all nutrients, forest soils should have a slightly acidic pH (Leskiw, 1998). The pH of rich soil often falls anywhere between 5.5 and 7.2, which makes it possible for plants to access the elements and nutrients they need to thrive. The current investigation found a considerable difference in soil pH across the various types of forests, which ranged from an acidic level of 4.81 in sub-alpine birch forests to a neutral level of 6.82 in dry broad-leaved and coniferous forests (Table 2). The acidity of the soil rises as a consequence of the buildup and decomposition of organic materials, in addition to the release of organic acids brought about by the decomposition of leaf litter.

Additionally, the bulk density was found to be at its highest in dry alpine scrub (1.68 g cm^{-3}), which was significantly different from the bulk densities recorded in the other studied forest types. Despite this, the lowest value for bulk density (1.17 g cm^{-3}) was found in an area that was covered in birch and rhododendron scrub. In a similar fashion, the electrical conductivity of the soil also varied greatly amongst the various types of forests, with the birch-rhododendron scrub forest having the highest observed soil EC (0.18 dsm^{-1}). On the other hand, it was discovered that dry broad-leaved and coniferous forests, sub-alpine fir forests, and sub-alpine birch forests are statistically equivalent to one another. The dry alpine scrub had the lowest measured soil electrical conductivity, although statistically speaking, it was on par with the neoza pine forest. Differences in the rates of leaf litter deposition and decay contribute to the wide range of bulk densities that can be found in different types of forests. Zeng et al. (2014) also found a drop in bulk density that was comparable to this one. Both Srikanth et al. (2002) and Jayabaskara et al. (2001) reported finding that were very similar in ecosystems that were very similar to one another.

The bulk density of the bottomsoil layer (21–40 cm) was much greater (1.34 g cm^{-3}) and the soil pH was significantly higher (5.96) than the top soil layer (1–3 cm). This was the case regardless of the type of forest (0–20 cm). It is possible that this is due to the fact that as depth increases, the amount of soil organic carbon rapidly decreases, whereas at shallower depths, an increase in bulk density is caused by factors including soil texture, gravel content, structure, compaction (Soltanpour and Jourgholami, 2013), and decreased porosity (Bhavya et al., 2018).

In a similar vein, the pH and the amount of available phosphorus both increase in proportion to the depth of the soil. The possibility exists that alkaline cation leaking from the upper layer to the lower layer is the cause of the elevation in soil pH that was observed by Mengistu et al. (2017). (Yuksek et al., 2013). However, the electrical conductivity of the soil considerably reduced with increasing soil depth, going from the top soil layer (0–20 cm) to the lowest soil layer (21–40 cm).

Table 3 Available N, P, and K under different forest types of dry temperate and alpine forest in north-west Himalaya

Treatments	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})
Forest types (F)			
F_1-Dry broad-leaved and coniferous forests	333.23^{b}	24.48^{c}	450.43^{e}
F_2-Neoza pine forest	112.32^{h}	17.70^{g}	317.78^{h}
F_3-Dry deodar forest	163.05^{d}	22.98^{e}	786.80^{b}
F_4-Dry blue pine forest	141.83^{f}	20.34^{f}	432.30^{f}
F_5-Sub alpine birch forest	246.71^{c}	23.81^{d}	563.70^{d}
F_6-Sub alpine fir forest	156.15^{e}	25.69^{b}	594.41^{c}
F_7-Birch-rhododendron scrub forest	407.11^{a}	30.37^{a}	873.60^{a}
F_8-Alpine pasture	134.12^{g}	16.20^{h}	400.25^{g}
F_9-Dry alpine scrub	102.09^{i}	13.80^{i}	245.05^{i}
CD at 5%	1.62	1.16	0.56
Soil Layer (L)			
L_1 (0-20 cm)	232.42^{a}	24.33^{a}	549.87^{a}
L_2 (21–40 cm)	166.82^{b}	19.08^{b}	486.65^{b}
CD at 5%	0.79	0.55	0.27

Different letters superscripting the values in columns denotes significant difference

3.3 Soil nutrients (N, P, K, Cu, Fe, Mn and Zn)

Extreme climatic and topographical circumstances may have an impact on soil qualities in north-west Himalaya's high altitudes (Bhattacharyya et al., 2008; Velmuurugan et al., 2014). Climatic parameters, including air temperature, yearly precipitation, and water balance, impact the direction and intensity of physical, chemical, and biological activities in soil and on its surface, including weathering (Jenny et al., 1994; Alexandrovskiy, 2007). As a result, the soil in the current research region revealed substantial fluctuation along the elevational gradient, as previously reported in the literature (Rubinic et al., 2015; Dahlgren et al., 1997; Mani et al., 1990; Huang et al., 2011; Bowman et al., 2002). The results are provided in Table 3, and it was found that the forest type and soil layer had a substantial influence on the amount of accessible nitrogen, phosphorus, and mineral potassium (exchangeable potassium) in the soil. In birch-rhododendron scrub forest, the appreciable maximum available nitrogen was recorded at 407.11 kg ha^{-1}, whereas the maximum available phosphorus was reported at 30.37 kg ha^{-1}, and the highest available potassium was recorded at 873.60 kg ha^{-1}. On the other hand, dry alpine scrub forest reported the lowest available levels of nitrogen (102.09 kg ha^{-1}), phosphorus (13.80 kg ha^{-1}), and potassium (245.05 kg ha^{-1}). Comparing the top layer of soil (0–20 cm) to the bottom layer (21–40 cm), it was found that the top layer had a greater amount of accessible nitrogen (232.42 kg ha^{-1}), phosphorus (24.33 kg ha^{-1}) and potassium (549.87 kg ha^{-1}) than the bottom layer (Table 4).

A close examination of the data depicted in Fig. 4 demonstrates that the amount of copper (Cu), iron (Fe), manganese (Mn), and zinc (zn) that is readily available varies greatly under the various forest types and soil layers. When compared to the other types of forests that were studied, the Birch-Rhododendron Scrub Forest had significantly greater

Table 4 Correlation (Pearson's) matrix different parameters of soil (0–40 cm) under forest types in dry temperate and alpine forest of north-west Himalaya

Soil parameters	pH	EC	OC	N	P	K	Cu	Fe	Mn	Zn
pH	1									
EC	−0.11	1								
OC	0.04	0.85*	1							
N	−0.20	0.80*	0.93*	1						
P	−0.05	0.84*	0.86*	0.79*	1					
K	−0.07	0.79*	0.79*	0.62*	0.82*	1				
Cu	−0.29	0.85*	0.81*	0.82*	0.82*	0.85*	1			
Fe	−0.46	0.76*	0.61*	0.61*	0.82*	0.81*	0.86*	1		
Mn	−0.05	0.65*	0.69*	0.57	0.88*	0.74*	0.60*	0.77*	1	
Zn	0.04	0.80*	0.87*	0.79*	0.74*	0.75*	0.84*	0.62*	0.54	1

*Level of significance 0.05 = 0.58 [*N* Nitrogen, *P* Phosphorus, *K* Potassium, *Cu* Copper, *Fe* Ferrous, *Mn* Manganese, *Zn* Zinc, *OC* soil organic carbon and *EC* Electrical conductivity

levels of accessible Cu (3.09 mg kg^{-1}), Fe (72.71 mg kg^{-1}), Mn (17.64 mg kg^{-1}) and Zn (0.99 mg kg^{-1}) than the other types of forests. In dry alpine scrub, the lowest available concentrations of copper (0.63 mg kg^{-1}), iron (22.41 mg kg^{-1}), manganese (9.05 mg kg^{-1}), and zinc (0.25 mg kg^{-1}) were found. In addition, when considering the effect of soil depth, the available Cu (1.42 mg kg^{-1}), Fe (41.86 mg kg^{-1}), Mn (16.56 mg kg^{-1}) and Zn content (0.53 mg kg^{-1}) were all found to be significantly greater in the topsoil layer (0–20 cm) than in the bottomlayer (21–40 cm).

The differential rates of deposition and decomposition of leaf litter, the availability of water, the modulation behavior, and the site nutrient status could all be factors in the increased availability of soil nutrients in the birch-rhododendron scrub forest. Previous studies in the same environmental genus by Russel (1975), Mishra et al. (1994), and Souza et al. (2019) have all revealed findings that are comparable to these new ones. In addition, it has been shown that the status of the soil nutrients (nitrogen, phosphorus, potassium, manganese, zinc, copper, and iron) decreases with increasing soil depth across all types of forests. In the upper levels of the forest that is being researched, there may be a significant amount of litter and humus present, which may account for the greater capacity of these layers to store water. The quantity and characteristics of organic matter (OM) have a much greater influence on the availability of soil nutrients than does any other factor (De Hann 1977). Therefore, the significant amount of OM present in various forest categories in the transcend soil layer may also be the factor that determines the abundance of plant nutrients in the surpass layers in comparison with lower layers (Figs. 3, 4 and 5).

3.4 Correlation (pearson's) matrix of soil parameters

The positive association between nitrogen and organic carbon in the soil ($r = 0.93$) is proof of the fact that the availability of soil nitrogen is highly dependent on the quantity and properties of organic matter (De Hann, 1977). Similarly, it was found that P had a positive correlation with OC. This was due to the fact that P concentration is intimately associated with the humus in the soil (Gupta and Sharma 2008). The inorganic form of phosphorus found in many soils has been transformed into an insoluble form by the organic matter

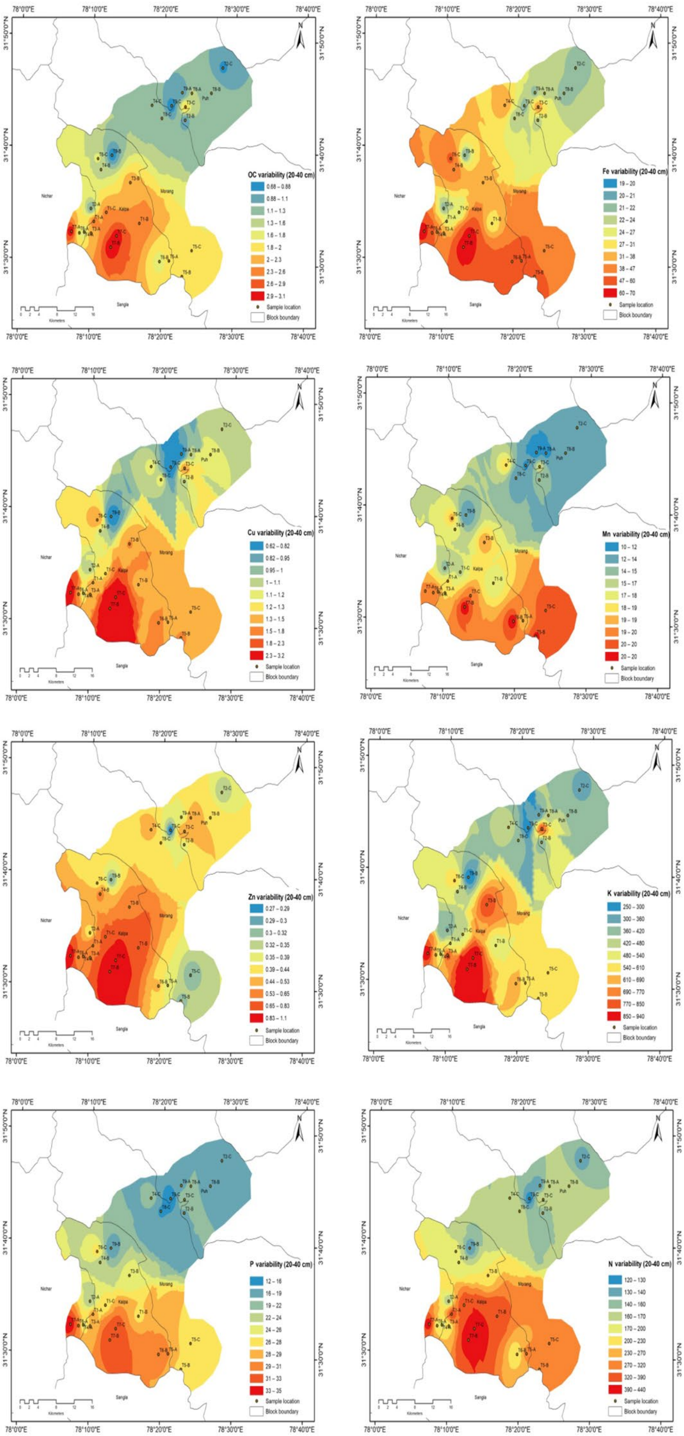

Fig. 4 Spatial variability of different soil nutrients at 20–40 cm

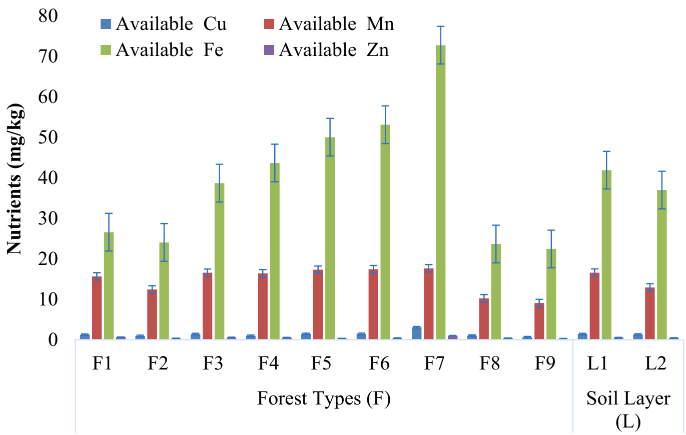

Fig. 5 Available copper, manganese, iron and zinc under different forest types of dry temperate and alpine forest of north-west Himalaya (bars line are standard errors) [F_1-dry broad-leaved and coniferous forests, F_2-neoza pine forest, F_3-dry deodar forest, F_4-dry blue pine forest, F_5-sub alpine birch forest, F_6-sub alpine fir forest, F_7-birch-rhododendron scrub forest, F_8-alpine pasture and F_9-dry alpine scrub; L_1- top soil layer (0-20 cm)and L_2-bottom soil layer (21–40 cm)]

found in the soil. The C–P and N–P ratios are not the same since they are dependent on the parent material, which is influenced by a variety of variables including weathering (Paul and Clark 1996). A significant and positive correlation was found between K and organic carbon ($r=0.79$). In a similar manner, Basumatary and Bordoloi (1992) and Boruah and Nath (1992) suggested that a layer of OM significantly improves the amount of potassium that is retained in soil. However, contrary to the findings of the present study, Gupta and Sharma (2008) argued that the organic matter in soil has a minimal effect on the amount of potassium that is available because OM is not a direct source of potassium. In addition to this, the N and k have a significant positive correlation ($r=0.62$) in the process of plant development. As a result of this, plant responsiveness to applied nitrogen fertilizers decreases when the available potassium concentration of a soil falls below an acceptable level. It would be difficult to read the genetic code in plant cells in order to build proteins and enzymes if there wasn't enough potassium present. Even if there is an abundance of nitrogen, plants that are deficient in potassium will not be able to produce proteins even if there is an abundance of nitrogen. On the other hand, incomplete proteins like amino acids, amides, and nitrates tend to build up inside the cell. This is due to the fact that K is responsible for the activation of the enzyme nitrate reductase, which is the catalyst for protein synthesis.

In addition, K has direct synergistic interactions with two micronutrients, Fe ($r=81$) and Mn ($r=74$), as shown by the positive correlation between these nutrients, which can be shown in the graph (Malvi, 2011). Dehydrogenase, decarboxylase, and oxidase enzyme production are all helped along by manganese, which is an essential component of photosynthesis, nitrogen metabolism, and nitrogen absorption. At the same time, iron is absolutely necessary for the production of chlorophyll. This is a component of ferrodoxin, which is responsible for oxidation and reduction reactions in plant systems such as nitrogen fixation and the reduction of nitrates and sulfates. It also plays a role in the enzymes that plants use for defence, called peroxidase and catalase.

3.5 Environmental factors controlling soil nutrients

The first ever estimate of organic carbon (OC) stock in Indian soils was 24.3 Pg based on 48 soil series taking into account of a few major soils by Bhattacharyya et al. (2008). Variations in soil nutrients show substantial variances throughout the north-west Himalayas. The most significant determinants are soil parameters, which account for about 80% of the spatial variance in N, P, K, Cu, Fe, Mn, and Zn. Soil pH, EC, and OC are important components of the soil nutrient cycle. Soil OC, in particular, may impact plant productivity and soil pH (Liu et al., 2020; Castaldi et al., 2019; Tian et al., 2017), whereas soil texture can influence community structure and soil moisture-holding capacity (Abdu et al., 2008), and hence soil accessible nutrient contents. Previous research indicates that parent material may be a major component in the world scale soil phosphorus pool (He et al., 2021; Allison et al., 2008). Climate change has an impact on the dynamics of soil nutrients, either directly or indirectly. Temperature and precipitation increases mineralization, nitrification, and denitrification rates (Tian et al., 2010a; Chen et al., 2016) and has been proven to promote microbial activity. Furthermore, climatic change affects the weathering rates of parent materials (Goll et al., 2016a, 2016b; Tian et al., 2010a) as well as plant production, altering soil nutrient availability. Furthermore, increased atmospheric nitrogen deposition may boost the N (Fu et al., 2017). Increased precipitation may slow phosphorus weathering (Goll et al., 2016), whereas heavy precipitation may accelerate phosphorus leaching, resulting in P loss. Furthermore, this crucial biogeochemical process may result in a drop in N and P, particularly in alpine meadows. Soil nutrient availability is highly tied to vegetation condition. The productivity of vegetation directly influences the N and P contents (Bing et al., 2016). In particular, litter intake might alter soil organic matter content and microbial breakdown processes, hence influencing N and P levels. Furthermore, plant root exudates improved soil nutrient mobility and availability (Dakora et al., 2002). Previous research found that soil nitrogen increased with higher vegetation NDVI and net primary production (NPP), whereas soil phosphorus was unrelated to vegetation status (Maeda et al., 2018; Tian et al., 2018). The shifting tendency of soil accessible nutrients corresponds to changes in soil total nitrogen and phosphorus. Furthermore, alpine meadows contain more carbohydrates to fulfil the high energy needs of available nitrogen and phosphorus, resulting in a greater N meadow than N steppe.

3.6 Uncertainties and limitations

When mapping the spatiotemporal patterns of soil nutrients in cold desert environments in the north-west Himalayas at the regional scale and investigating the underlying processes in this work, uncertainties and limits remain. To begin, although comprehensive and adequate environmental components were included in modeling, certain biases may exist when using global-scaled information, such as climate and soil data, to regional-scaled analyses (Fick et al., 2017; Poggio et al., 2021). Second, the samplings in the depopulated zone were scarce, which added uncertainty to our findings. Fourth, data on atmospheric nitrogen deposition (Liu et al., 2013), microbiological activity (Caldwell, 2005; Miransari, 2013), and litter stoichiometry (Zhou et al., 2019) were difficult to gather across regional regions, which might result in either overestimation or underestimation of the true value. Finally, ecological conservation initiatives such as fencing, grazing bans, and artificial grasslands have the potential to significantly alter the dynamics of soil accessible nutrients (Li et al., 2022). In summary, enough useful indicators should be examined to mine the soil nutrients driving mechanisms at the regional scale, and long-term observation is required for future study. Meanwhile, since global changes alter the dynamics of soil nutrients, future research should incorporate controls to deal with variations in N, P, K, Cu, Fe, Mn, and Zn, pH, EC, and OC restriction.

4 Conclusion

The types of forests that are found in the Himalayan region have a significant impact on the nutrient content of the soil in that region. When compared to the soil of other woods, the soil in birch-rhododendron scrub forests was shown to have a greater soil organic carbon and nutritional quality. The patterns of leaf litter deposition, the rates of leaf litter decomposition, and the behavior of nodulation varies depending on the kind of forest, which in turn impacts the water availability and nutrient quality of the site. The germination of seeds, the unit area production, the cycling of nutrients and water, the recruitment of saplings, and the phenology are all improved when nutrients are present. It is the nutrients, mainly nitrogen and phosphorus, which are responsible for the processes of growth and vital growth, particularly in colder climates. The amounts of soil nutrients decreased with increasing soil depth across the board, pointing to higher litter and humus levels in the upper layers of the different types of forests that were investigated. Therefore, foresters may make use of this niche-based information on soil qualities that are distinctive to forest types in the process of regenerating these forests on degraded and abandoned sites.

The density of seedlings, saplings, trees, and biomass production followed the soil fertility gradient, with optimum growth occurring at mid-elevation ranges. As a result, the ecotone zone is now going through the process of seedling regeneration. In the Himalayan area, major characteristics that explain seedlings, saplings, tree species distribution, and biomass production include, in addition to terrain, the amount of accessible nitrogen, phosphorus, potassium, organic carbon (percent), clay, and sand. In a nutshell, it does not seem that seed-based regeneration inside or outside the ecotones of tree lines that occur in the Himalayan area has any effect on the sensitivity of tree lines to the effects of climate change or global warming. Overall, the current research makes a contribution to a better understanding of the relationships between population distribution, biomass production, and environmental factors in the forest ecosystems of the north-western Himalayan region. It also has the potential to enable foresters, silviculturists, and environmentalists to apply their findings to forest management and vegetation restoration programmes. In addition, a redundancy analysis showed that the patterns of nitrogen and phosphorus were regulated by the interactions between a number of different environmental conditions, and the features of the soil's physicochemical makeup were the most important factors. Overall, the results of our study provided new insights into the patterns and dynamics of a variety of soil nutrients at the regional scale. Additionally, the findings offered important scientific support to researchers working across the north-west Himalayas in their efforts to adapt to upcoming changes in the environment and to maximize sustainable management.

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Declarations

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