Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454

Vol. 24 | No. 4 | Article ID D1773 | 2025

Original Research Paper

https://doi.org/10.46488/NEPT.2025.v24i04.D1773

Open Access Journal

Altitude-Induced Variations in Vegetation Characteristics and Soil Properties

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Abbreviation: Nat. Env. & Poll. Technol.
Website: www.neptjournal.com

Received: 20-02-2025
Revised: 23-03-2025
Accepted: 29-03-2025

Key Words:

Altitude-induced variations
Diversity
Forest carbon
Physicochemical properties of soil

Citation for the Paper:

Masoud, M., Abdul-Hamid, H., Mohamed, J. and Alsanousi, A., 2025. Altitude-induced variations in vegetation characteristics and soil properties. *Nature Environment and Pollution Technology*, 24(4), D1773. https://doi.org/10.46488/NEPT.2025.v24i04.D1773

Note: From 2025, the journal has adopted the use of Article IDs in citations instead of traditional consecutive page numbers. Each article is now given individual page ranges starting from page 1.

ABSTRACT

Elevational gradients exhibit diverse patterns in species distribution and soil characteristics, creating distinct ecological zones. This paper aims to synthesize current knowledge on the relationships among elevation, environmental factors, plant families, and life forms to uncover the mechanisms driving these patterns. Species richness varies with elevation, with some plants declining while others thrive due to eco-physiological properties and functional traits. The review established that these elevational patterns differ among plant families and life forms. Intermediate elevation transition zones have more diverse floras, temperate species thrive at lower elevations than their primary habitats, and tropical lowland species expand to higher elevations. Climatic conditions, area size, the mid-domain effect, and biophysical processes, particularly water-energy dynamics, are crucial for understanding the intricate relationships between climate and vegetation. Changes in temperature and precipitation along altitudinal gradients significantly impact the attributes of soil. This review emphasizes the importance of microorganisms in nutrient cycling and highlights the adaptability of psychrophilic bacteria and fungi to high-altitude environments. Understanding these complex interactions is essential for predicting the impacts of climate change to ensure the sustainable management of high-altitude ecosystems. Further research into species richness patterns, soil dynamics, and microbial roles is necessary for developing effective conservation strategies and sustainable land management practices.

INTRODUCTION

Mountains are crucial in preserving biodiversity and providing habitats for various flora and fauna. Nevertheless, they are among the world's most vulnerable ecosystems. According to Fattorini et al. (2020), mountains provide various ecological services, including global temperature control, water supplies, soil preservation, and recreational possibilities. In addition, mountains are the only habitat for certain rare and endangered species (Zhou et al. 2023).

Elevational variation encompasses meteorological and physical factors that directly influence community structure (Dearborn & Danby 2017). In addition to environmental changes, these factors include anthropogenic and historical activities, species-area effects, and isolation (Choe & Thorne 2017). Understanding the impacts of altitude on vegetation and climate change scenarios can be better by examining changes in plant patterns and how these link to the environmental variables (Jiang et al. 2022, Mangral et al. 2023). Elevation gradients are widely recognized as valuable tools for studying the relationship between climate and vegetation (Salas-Morales et al. 2019). This approach is effective because temperature consistently decreases with elevation, making elevation a reliable proxy for understanding temperature variations and their impacts on vegetation. Changes in ecosystem properties, such as plant diversity, productivity, species traits, and physiology, occur along gradients (Sigdel et al. 2022). Global warming has resulted in notable alterations to the spatial distribution of many species, particularly toward higher elevations in montane regions. Consequently, this shift has led to a discernible rise in the abundance of trees in cold and humid locations (Steinbauer et al. 2018).

Altitude represents a complex environmental gradient encompassing multiple ecological factors (Wani et al. 2023). However, harsh conditions can reduce this complexity and limit the number of factors that impact species diversity (Ali et al. 2022). According to Dearborn and Danby (2017), elevation is critical in determining microclimate and vegetation distribution, along with slope aspect, slope angle, and soil type, which determine the forest dynamics at given elevations. Alexander V.H. (1799-1804) was the first to highlight that latitudinal and elevation gradients are principal factors responsible for species diversity and composition (Fischer et al. 2011). Due to the increased climatic variation over relatively short distances, striking changes in vegetation patterns and soil properties occur along the elevation gradient (Song et al. 2021). Numerous studies examining the relationship between species richness and elevation gradient (Rahbek et al. 2019, Sun et al. 2020, Wani et al. 2023), temperature and moisture as key drivers of this pattern, reflecting a climate-gradient-driven scenario (Jiang et al. 2022).

Mountainous regions are known for their high levels of biodiversity (Fattorini et al. 2020). Consequently, they offer excellent natural environments for testing environmental and biogeographical concepts and theories (Rahbek et al. 2019). The correlation between altitude and species richness has long been a topic of interest among macroecological and conservation researchers, making it a suitable framework for extensive gradient research (Bhattarai & Vetaas 2003, Sun et al. 2020). Mountainous locations provide significant environmental gradients over short distances, resulting in varied vegetation and influencing species distribution patterns, making them desirable research areas (Sun et al. 2020). Generally, the species richness along elevational gradients has diverse patterns (Wani et al. 2023). Although numerous studies have explored elevational variation, there remains a lack of consensus regarding these patterns and their underlying causes (Kluge et al. 2017, Wani et al. 2023).

Vegetation expansion improves the quality and shear strength of soil, thereby reducing soil erosion, promoting the restoration of the ecosystem (Yuan et al. 2016). Variations in microclimatic conditions affect soil types, soil stability (Song et al. 2021, Jafarian et al. 2023), soil temperature and moisture content (Charan et al. 2013, Ariyanto et al. 2021).

This paper aimed to comprehensively review the intricate relationships between the vegetation communities, soil properties, and slope aspects of mountainous regions. Data for this review were systematically extracted from relevant studies identified through a keyword-based search in Web of Science, Scopus, Google Scholar, and ScienceDirect. Inclusion criteria (peer-reviewed studies from 2000–2024 on elevational gradients, vegetation diversity, soil properties, and microbial interactions) were applied to ensure the selection of high-quality research, and key findings were synthesized into thematic categories for analysis to explore biodiversity patterns and ecosystem functioning along altitudinal gradients. This review offered a novel synthesis by integrating vegetation diversity, soil properties, and microbial interactions along elevational gradients, providing a comprehensive perspective on how these factors collectively influence mountain ecosystem dynamics.. The study sought to elucidate the patterns and causes of the distribution and richness of underlying species at altitude by synthesizing existing research. It focuses on elevational gradients and microclimatic conditions, as well as the impacts these factors have on biodiversity. The review contributes to a deeper understanding of ecosystem functioning and facilitates informed conservation strategies in these critical environments.

Patterns of Species Richness Across Different Elevations

As the primary ecological factor, topography dramatically affects the spatial variation of species on forested slopes. As one moves downslope, the physical environment undergoes significant changes, contributing to a complex environmental gradient. These changes include alterations in microclimate, water drainage and accumulation, as well as the transportation and accumulation of soil minerals. The distribution and abundance of plant species are influenced by a combination of direct and indirect effects. The former include environmental factors such as precipitation, temperature, soil properties, and light availability, which directly influence plant growth and survival.

Meanwhile, indirect effects involve interactions mediated through other organisms or ecological processes, such as competition, herbivory, seed dispersal, and nutrient cycling (Dearborn & Danby 2017, Jiang et al. 2022, Bátori et al. 2023). According to Sekar et al. (2023), the vegetation characteristics of richness, variety, and density were positively linked to the climatic variables of temperature,

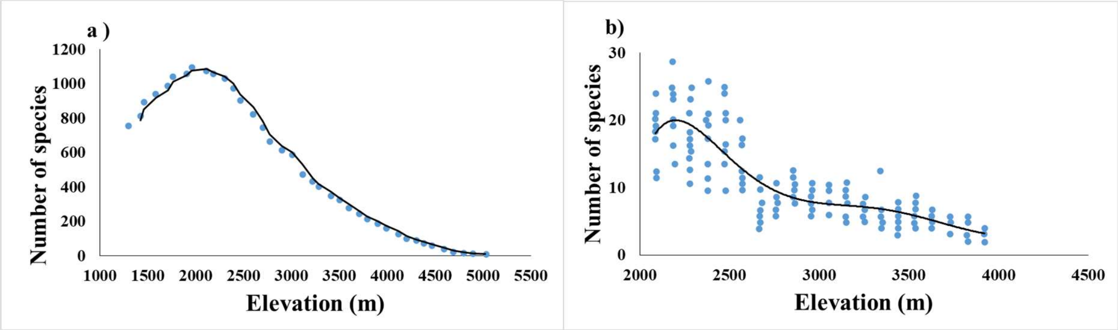

Fig. 1: Elevational patterns of the species richness of vascular plants in mountain regions showing: (a) hump-shaped pattern (Zhou et al. 2019), (b) decreasing pattern (Wani et al. 2023).

precipitation, and solar radiation. In the literature, it has been established that elevation gradients affect species diversity and spatial patterns (Cirimwami et al. 2019, Zhou et al. 2019, Sun et al. 2020, Wani et al. 2023). Two primary patterns of biodiversity along elevation gradients have been found through studies. The first is a hump-shaped pattern with a peak in variety at mid-elevations (Fig. 1), while the second is a reduction in total vascular flora with rising elevation (Wani et al. 2023, Zhou et al. 2019). Wani et al. (2023) explored the impact of environmental variables on plant species diversity and distribution in the Kashmir Himalayas, particularly elevation, aspect, and habitat type. The study identified 361 vascular plant species from 71 families and 214 genera. Zhou et al. (2019) investigated species richness patterns in tropical mountain ecosystems, focusing on Mount Kenya. The study categorized plant species into twelve groups based on their life form and geographic distribution and analyzed their species richness trends along an elevational gradient.

The principal factor influencing the richness of species in mountainous regions is that the species richness depends on productivity as the altitude increases. Furness et al. (2021) found a positive correlation between enhanced production and the progressive augmentation of species richness. Nevertheless, a drop can occur after productivity surpasses its average value. Moreover, Sinha et al. (2018) in Eastern Himalaya, India, found that species density is often higher near the foot of mountain slopes, with a higher bioclimatic amplitude than is found at the summit. Sinha et al. (2018) explained that resource scarcity and climate aridity limit the variety of plant species in the upper reaches of mountains. Ali et al. (2022) documented a negative correlation between altitude and species richness in Pakistan. According to Dorji et al. (2014), in central Tibet, China, the evenness of species increased with soil moisture at lower elevations, while it decreased at higher elevations. All environmental factors except solar radiation were strongly correlated with species composition. According to Sklenář's (2006) findings, there is a correlation between a decrease in species richness and an increase in altitudinal variance in the superparamo of Volcano Iliniza in Ecuador. In a study of Italy's Apuan Alps, Di Musciano et al. (2021) revealed that the plant species richness declined with increasing elevation, while the endemic species richness grew.

In contrast, Bhatta et al. (2021) found unimodal responses along elevation gradients across six sectors in a Himalayan study. However, rare plants may sometimes have a less continuous distribution along an elevation gradient. Therefore, to better target conservation efforts, the responses of different life forms and endemic species must be considered, particularly at high elevations, where rare species could become endangered due to competition from climate change-induced woody species (Puglisi et al. 2023).

Mountain ecosystems are considered selective barriers to species distribution (Perrigo et al. 2020, Zhou et al. 2023). As such, several studies have shown that the proportion of endemic species grows with altitude, and their elevation ranges exhibit greater median significance than other groups, indicating that endemic species are more prevalent at higher elevations (Di Biase et al. 2021, Di Musciano et al. 2021). This observed phenomenon can be attributed to the biogeographical impact of mountainous areas, which function as ecological archipelagos (fragmented landscapes of isolated habitats that resemble islands, fostering unique species interactions and evolutionary processes) that facilitate evolutionary mechanisms (Rahbek et al. 2019).

In terrestrial ecosystems, species richness, height, and latitude have all been found to be negatively correlated in earlier research. The relationship under consideration is commonly depicted as a curve in the form of a hump, where the maximum species richness is observed at intermediate altitudes. Furthermore, there is a steady decrease in species richness as one moves to higher latitudes (Di Biase et al. 2021, Khadanga et al. 2023, Wani et al. 2023). However, the associations between altitudinal gradients and connections are complex and depend on many environmental parameters, including precipitation, temperature, solar radiation, wind, the duration of the growing season, terrain, surface area, and land use (Wang et al. 2020, Daco et al. 2021). Empirical research has supported the correlation between elevation and vegetation (Wani et al. 2023). Contagious distribution is the most prevalent pattern observed in nature, which can be attributed to subtle but notable environmental variations. On the other hand, regular distribution indicates intense competition among plants within a community, while random distribution is typically observed in uniform environments (Sharma et al. 2023).

The Influence of Altitude on the Diversity of Families

The correlation between species richness and the lifeform to which a family belongs does not always conform to the overall trend (the general or expected pattern observed in most cases or across a wide range of conditions). This deviation can be attributed to the unique sensitivity of certain families due to differences caused by elevation, the ecophysiological effects on each family, and genetic traits (Cirimwami et al. 2019). For example, the study by Li et al. (2023) provides quantitative evidence supporting a hump-shaped species richness pattern along an elevational gradient in a Chinese subtropical forest. The Shannon–Wiener index ($R^2 = 0.58$, $p < 0.01$) and Simpson index ($R^2 = 0.57$, $p < 0.01$) both demonstrate a statistically significant hump-shaped trend, with species diversity increasing from 300 m to a peak at 1100 m before declining towards 1400 m. In contrast, the tropical mountains of East Africa experience a decline in tree species richness above elevations of 2027 m asl (Zhou et al. 2019). The decline in species richness within families was more pronounced for trees and shrubs across the elevation range, whereas the opposite trend was found in herbaceous lifeforms. The Rubiaceae family exhibited modest increases in species diversity and population size with increasing elevation, particularly in the shrub lifeform. Phyllanthaceae and Pandanaceae, on the other hand, decreased with increasing elevation in tropical forests (Cirimwami et al. 2019).

The association between altitude and species richness can vary between different taxonomic families (Fig. 2) (Salas-Morales & Meave 2012). The ecophysiological characteristics of plant families and their functional

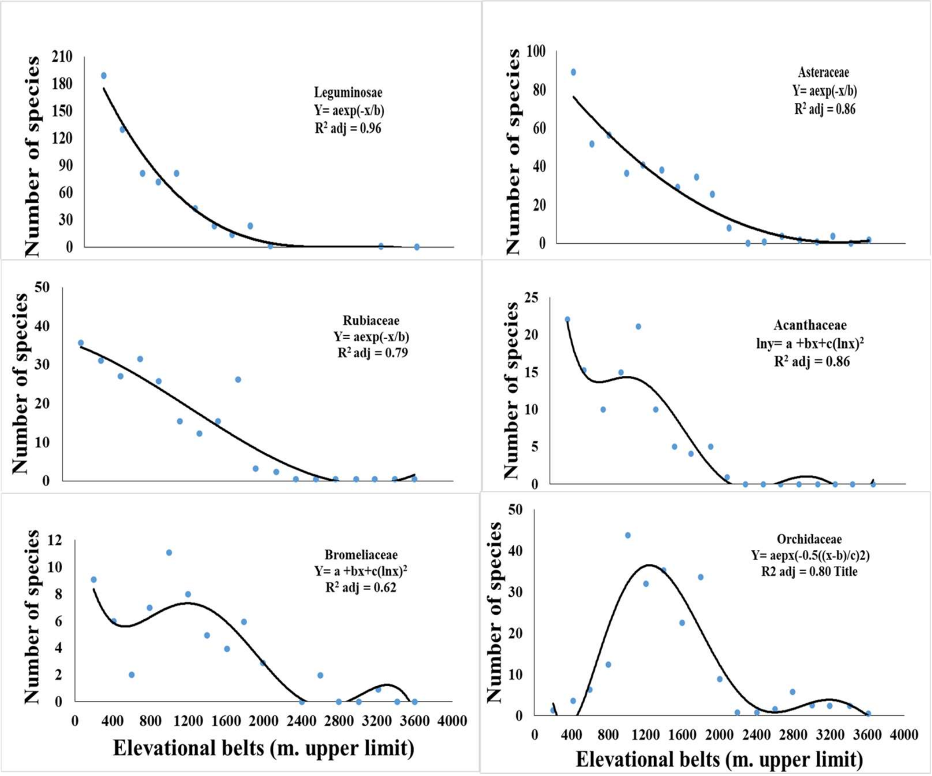

Fig. 2: The regression between elevation and species richness within certain taxonomic families (Salas-Morales & Meave 2012). Salas-Morales & Meave (2012) analyzed vascular plant richness along an extensive elevational gradient (0–3,670 m a.s.l.) in the Sierra Madre del Sur, Oaxaca, Mexico, using a database of observed and interpolated species richness across 18 elevation belts, and revealed general and family-specific patterns influenced by altitude and climatic factors.

qualities are crucial in depicting various patterns of species richness (Salas-Morales & Meave 2012, Zhou et al. 2019). Furthermore, the distribution of species richness within lifeforms across different families may exhibit variations compared to the overall plant community (Di Biase et al. 2021).

Species belonging to the Marantaceae and Zingiberaceae families exhibit notable declines in abundance as the elevation increases. These declines can be attributed to their preference for lower elevations, where they are found primarily in the understory, in clearings, and along river banks (Cirimwami et al. 2019). The correlation between the rise in species richness across various taxonomic families and their micro-thermal characteristics and light requirements may be attributed to the elevated light availability in higher-elevation forests (Thakur et al. 2022). Asteraceae and other fern species belonging to families that include Aspleniaceae, Dennstaedtiaceae, and Lycopodiaceae exhibit limited distribution at lower elevations. However, the diversity of these organisms is more significant in tropical highland regions and temperate habitats. This could be attributed to their structural similarity to daisies, which aids their spread by mountain breezes (Poulsen et al. 2005).

In confined geographical areas, inflexible limits and the resulting limited dispersion ability may also form hump-shaped patterns in species diversity in relation to elevation (Njogu et al. 2019). Sharma et al. (2022) reported a discernible hump-shaped pattern in the richness and density of woody plants across the altitudinal range at the species, genus, and family taxonomic levels. In a study by Cirimwami et al. (2019), a negative correlation was observed between altitude and woody family richness in tropical forests.

Species Richness along an Elevation Gradient Depends on the Life Form

Recently, there has been growing scholarly interest in the correlation between elevation and species richness in many living forms. Several studies have evaluated this relationship (Zhang et al. 2016, Xu et al. 2017, Wani et al. 2023), and several researchers have observed a consistent correlation between altitude and the number of species in various life forms (Nanda et al. 2018, Furness et al. 2021). However, this correlation more often varies between different life forms, as shown in Fig. 3 (Grytnes et al. 2006).

According to previous research (Irl et al. 2020, Di Biase et al. 2021), hemicryptophytes and chamaephytes predominate in high mountain environments. On the other hand, phanerophytes have been found to live at a greater range of elevations but are restricted by a low seasonal mean ground temperature (Irl et al. 2020, Di Biase et al. 2021). In many forest habitats, herbaceous species are more prevalent at higher altitudes (Cirimwami et al. 2019, Zhou et al. 2019). Due to their ability to resist challenging climate conditions, they are also a crucial element of highland ecosystems (Fattorini et al. 2020). Furthermore, the species richness of herbaceous life forms tends to increase with elevation in tropical environments (Nanda et al. 2018). This pattern can be attributed to light availability, as most herbaceous species are intolerant to shade (Jiang et al. 2016).

Unlike woody life forms, herbaceous plant species exhibit a positive association between species diversity and elevation, as shown by the consistent upward trend in Fig. 4. According to this association, there are considerable differences in the link between elevation and species richness among various living forms as a result of physical and

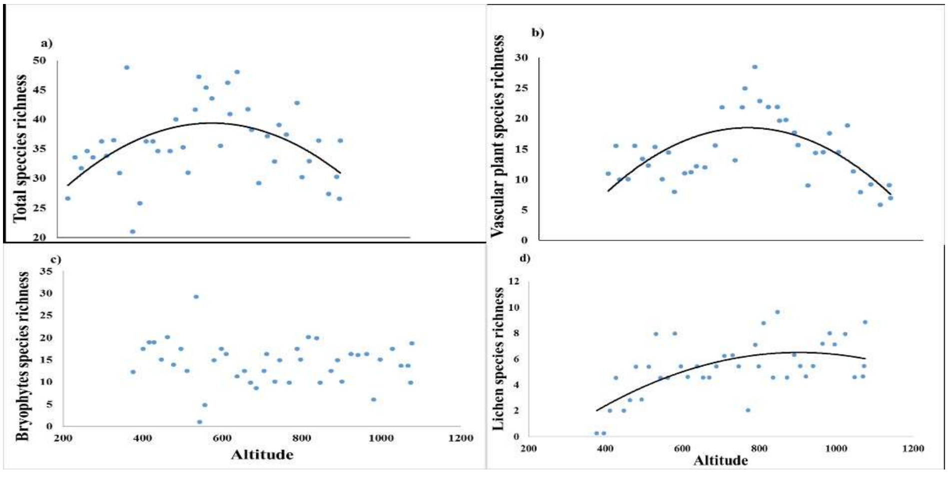

Fig. 3: Scatter plots of the relationship between species richness and altitude showing (a) the unimodal total species richness, (b) the hump in vascular plant species, (c) constant bryophyte species richness, and (d) a steep increase in lichen species (Grytnes et al. 2006).

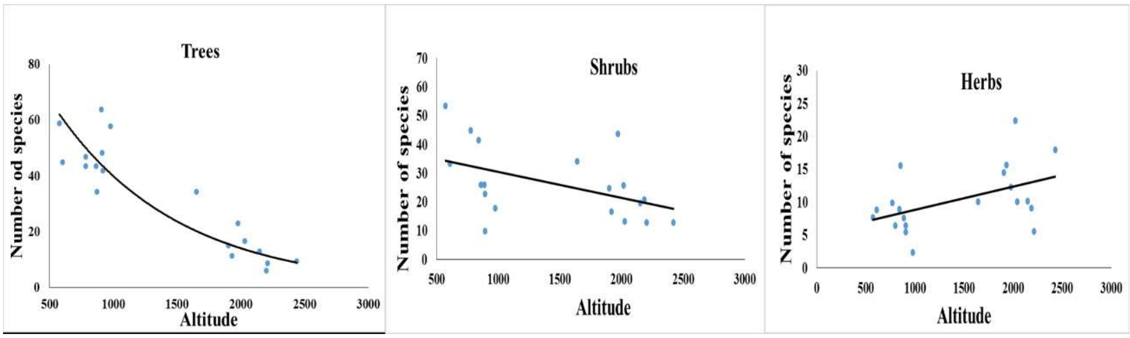

Fig. 4: The relationships between the number of species and the altitude depend on the life forms: (a) trees, (b) shrubs, and (c) herbs (Cirimwami et al. 2019). The study explored the relationship between elevation and species richness in East Africa's Kahuzi-Biega National Park, analyzing patterns across tree, shrub, and herbaceous lifeforms in 20 plots spanning 810 to 2760 m asl.

biological environmental conditions. According to Salazar et al. (2015), the scientific community generally agrees that the richness and variety of plant species are negatively correlated with distance from the equator and with greater elevations and latitudes. However, compared to studies that concentrated on latitudinal gradients, research on the distribution of species richness along elevational gradients has been more thorough (Zhou et al. 2019). A hump-shaped diversity trend can be seen in many plant taxa along elevational ranges within the Andes region. This pattern has been observed in vascular epiphytes in Bolivia (Krömer et al. 2005), non-vascular bryophytes in Colombia (Henriques et al. 2016), and ferns in Ecuador and Bolivia (Salazar et al. 2015). Nanda et al. (2018) in Kashmir conducted a study wherein they discerned four discrete patterns of species richness concerning elevation changes. The observed patterns consisted of a plateau at low elevations characterized by moderate peaks in bryophytes and lichens, a moderate peak pattern in pteridophytes, and an inverted hump-shaped trend in monocots. Zhou et al. (2019) observed that various life forms and phytogeographic affinities exhibited comparable patterns of hump-shaped distribution, mirroring those observed in the overall composition of the species. The study found that the size of the average elevation ranges of herbaceous species and the total species exhibited upward trends along the elevation gradient.

In contrast, lycophytes, ferns, and woody species exhibited clear downward trends after reaching a peak in high-elevation regions. Di Biase et al. (2021) discovered that in Italy, phanerophytes and geophytes, mostly connected to forests, clustered in the middle of the elevation, where these ecosystems generally predominate. Elevation increased the number of hemicryptophytes, which is consistent with their ability to withstand harsh climates at high altitudes. Since they are adversely affected by falling temperatures, the population of Mediterranean species dropped with elevation. The U-shaped pattern of chamaephytes suggests that they may survive in parched and chilly conditions at gradient extremes. Due to their link with mountains, which served as important sites for the evolution of endemism, endemic plants grew more abundantly at higher elevations.

The decline in species diversity at higher altitudes is commonly attributed to ecophysiological limitations, including reduced levels of temperature and carbon dioxide (CO_2), which can affect the ability of organisms to photosynthesize, perform primary productivity, and maintain their physical structures (Gong et al. 2019). The impact of environmental conditions on tree life forms is more significant than it is on shrub life forms throughout the ascending process, resulting in a more pronounced decline in tree species richness compared to that of shrubs and herbs (Cirimwami et al. 2019).

Influence of Altitude on Attributes and Distribution of Plant Species

The effects of altitude on the attributes and distribution of plant species have been widely investigated in recent years. According to Halbritter et al. (2018), research on how altitude and other factors affect the attributes and distribution of different plant species may highlight the adaptive potential of certain features during climate change. Plants have evolved various traits to adapt and thrive in such challenging habitats. The abundance of growth forms generally rises with increasing altitude (Pellissier et al. 2010). In addition, reproductive methods exhibit differentiation in response to altitudinal and climatic gradients (Daco et al. 2021).

Recent studies have revealed that alpine flora exhibit limited seed distribution, which may threaten their survival during rapid climate change (Johnson et al. 2017). Moreover, small-scale topographic and geomorphological processes create microhabitats with considerably different species compositions across short spatial scales (Qianwen et al. 2022). For example, the thermal conditions that impact plant growth vary across many features, leading to a notable species diversity in the southern exposition of the north-temperate orobiome (Winkler et al. 2016). According to Gentili et al. (2015), several microhabitats within valley slopes can serve as refuges for species acclimated to cold environments.

Elevation gradients provide an excellent opportunity to investigate the response of tree distribution to global climate change (Sundqvist et al. 2013). The spatial arrangement of tree species at varying elevations is influenced by abiotic factors, including the climate, the soil conditions, and the leaf characteristics of the trees (Soudzilovskaia et al. 2013). Previous research has indicated a pattern in the vertical distribution of woody plant species along the ecological continuum of the leaf economic spectrum (Read et al. 2014).

The leaf characteristics of various species substantially influence their geographical range (Soudzilovskaia et al. 2013, Vesk et al. 2020). This range is defined by the capacity of the species to disperse, colonize, and ensure seeds survive (May et al. 2013). Leaf qualities are a significant determinant of the ability of a species to colonize and survive in different environments (Reich 2014). Consequently, these traits directly impact species distribution patterns (Vesk et al. 2020). Therefore, species that can adjust their traits in response to specific environmental conditions can colonize and survive, leading to the observed distribution patterns of these species. Consequently, understanding the functional traits of leaves is crucial to understanding the adaptation-to-elevation strategies of woody plant species (Reich 2014).

Sigdel et al. (2022) conducted a recent study in which they detected a decrease in numerous plant characteristics with increasing elevation, including leaf area, specific leaf area, plant height, the length of blooming branches, leaf carbon (C), and leaf nitrogen (N) concentrations. The study found that alterations in water–energy dynamics significantly drove intraspecific variability in leaf functional traits. This variability reflects changes in ecosystem productivity at different elevations.

Understanding the resilient adaptations of leaf characteristics in response to environmental changes, particularly along elevation gradients, is of the utmost importance. Akinlabi et al. (2014) investigated the morphological and anatomical adaptations of *Chromolaena odorata* to altitudinal gradients by analyzing leaf traits across three elevation levels (280 m, 312 m, and 360 m). Data include measurements of morphological features like leaf area and petiole length, and anatomical traits such as stomata index, leaf thickness, and mesophyll thickness. These revealed significant changes in response to varying altitudes, as shown in Fig. 5.

Numerous studies have analyzed leaf traits to investigate how leaves acclimate to environmental changes at species and community levels. According to the study by Khan et al. (2022), the individual leaf surface area shows a reduction in drought conditions. However, the leaf thickness and the

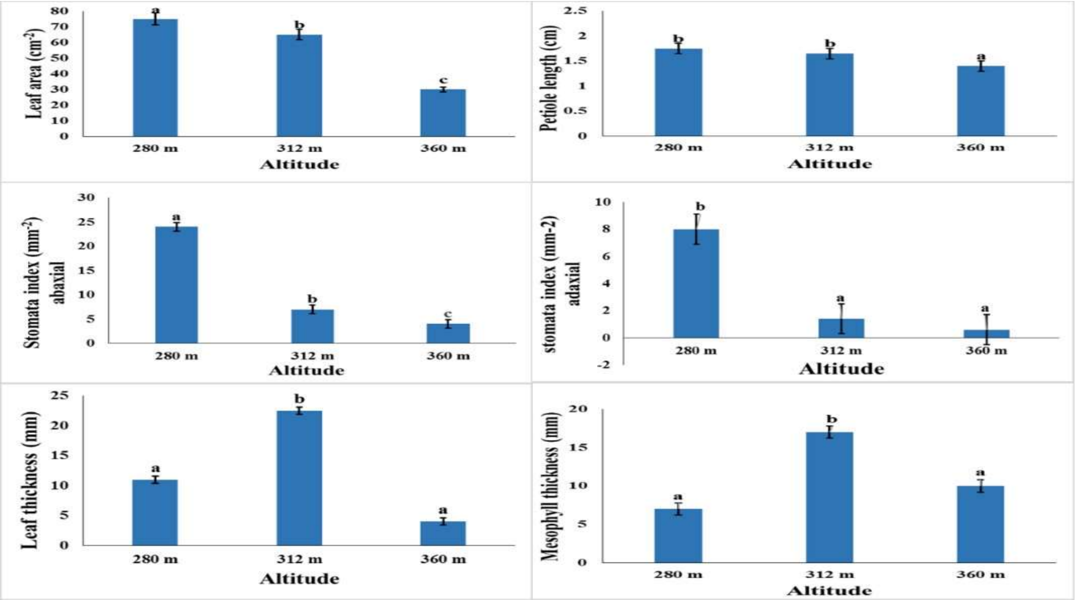

Fig. 5: Impact of altitudinal gradients on morphological anatomy characteristics of *Chromolaena odorata* (L.) The presence of similar letters at the tops of comparable bars denotes the absence of statistically significant differences (determined by a p-value of less than 0.05) at each site (Akinlabi et al. 2014).

specific dry weight demonstrate increases. On the other hand, there is a correlation between leaf area and minimum temperature at a local level, specifically in relation to the altitude gradient (Guerin et al. 2012). Typically, the physical dimensions of plants decrease when they ascend to higher altitudes due to alterations in the altitudinal gradient (Akinlabi et al. 2014). According to Li et al. (2014), bamboo development is constrained by high light intensity and low elevations. In their study, De la Riva et al. (2016) observed that species exhibiting greater leaf mass per area and leaf density tend to be primarily distributed in ecosystems characterized by limited water availability.

Several studies have documented how environmental factors such as temperature affect the characteristics of leaf communities, leading to a transition from acquisitive to conservative tactics (Moles et al. 2014, Bruelheide et al. 2018). Understanding the relationship between plant characteristics and the environment in various temperature ranges is essential to fully understanding plant adaptations, assembly principles, and the composition of plant communities (Pellissier et al. 2010). This knowledge can help in identifying potential threats to plant species and developing appropriate conservation measures.

Understanding how plants react to environmental gradients is of the utmost importance in accurately predicting how drivers of global change influence plant communities (Pellissier et al. 2010). Variations in plant functional traits between sites and species provide insights into community structures, population dynamics, and ecosystem functioning (Garnie et al. 2016, Wang et al. 2018). These can reflect the deterministic processes of community organization. Altitude gradients can explain the variation of functional traits at different biological levels (Pescador et al. 2015, Sigdel et al. 2022). For example, studies have documented specific leaf area reductions in species at higher elevations (Akinlabi et al. 2014), variations in growth and resource utilization traits in populations of vicariant species (Ramírez-Valiente et al. 2014), and functional differences between lowland and highland plant species (Wang et al. 2019). However, the challenge lies in scaling up the variation of functional traits from individual plants to the community level (Auger & Shipley 2012).

Influence of Topography and Biodiversity on Forest Carbon

Biotic and abiotic factors, including edaphic and topographical factors (e.g., altitude, aspect, and slope), influence the growth and distribution of vegetation. Moreover, forest type, as well as plant physiology and anatomy, also play distinct roles (Khan et al. 2022, Wani et al. 2023). These factors also impact C cycling and regional and global C budgets. Nevertheless, the correlation between elevation and carbon stocks remains poorly understood (Spracklen & Righelato 2014), warranting investigations into how elevation influences aboveground and soil carbon stocks across different vegetation types and life forms in mountainous ecosystems. Ideally, such studies would identify the environmental and biological drivers of carbon storage variability.

Previous studies of tropical montane biomass stocks have demonstrated that soil organic carbon (SOC) stocks decrease with elevation (Fig. 6) (Bangroo et al. 2017). However, C stocks at given elevations vary considerably between and within continents, likely driven by differences in climate and soil nutrient availability (Spracklen & Righelato 2014). The importance of shrub or herb biomass relative to trees is not yet known because most studies have only considered tree biomass (Girardin et al. 2010), highlighting the need to prioritize prominent shrub species such as *Rhododendron*, *Artemisia*, *Salix*, *Vaccinium*, and *Erica* for investigation due to their significant roles in carbon storage and ecosystem functioning across diverse habitats.

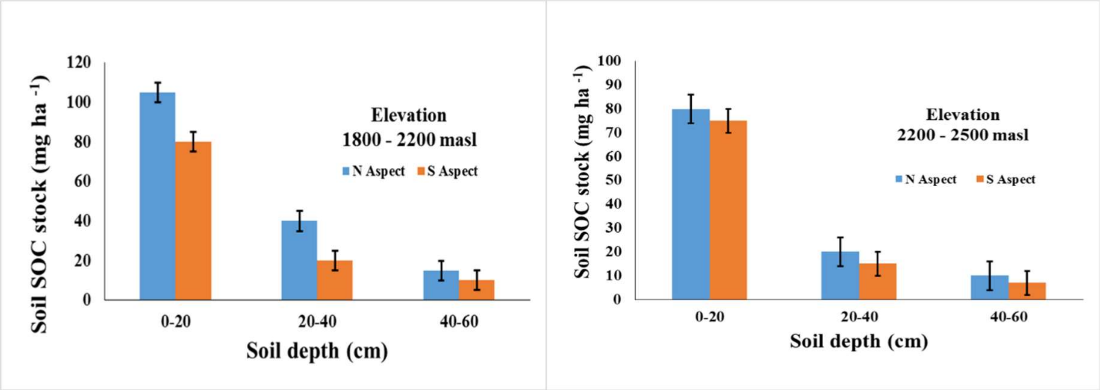

Fig. 6: Distribution of soil organic carbon (SOC) stocks (Mg ha^{-1}) at different elevations (1800-2200 msl and 2200-2500 msl) for three soil depths (0-20 cm, 20-40 cm, and 40-60 cm) under the north and south aspects in the Himalayan Mawer Forest Range (Bangroo et al. 2017).

Girardin et al. (2010) suggested that forest productivity decreases with elevation, leading to a reduction in carbon sequestration. The study by Rajput et al. (2017) provided evidence to support the notion of a positive correlation between elevation and total biomass production. More specifically, the researchers observed increased total biomass production as the elevation range shifted from 1100-1400 m to 2000-2300 m. Kobler et al. (2019) studied southwest- and northeast-facing slopes to determine aboveground biomass, net ecosystem production, and soil CO_2 emissions. The study showed that the southwest-facing slope had higher aboveground biomass, net ecosystem production, and soil CO_2 emissions than the northeast-facing slope. The authors concluded that changes in elevation and aspect over short distances in mountainous areas can significantly affect the C dynamics of forests. Therefore, it may not be reliable to extrapolate the results of C dynamics in complex topographies to larger scales.

Aboveground biomass varies by numerous variables, such as density and stand age, precipitation, temperature, and latitude, physiographic features like elevation, slope, aspect, and relief, and soil properties. A study in the Himalayas by Sharma et al. (2018) examined how tree species' growth behavior varied depending on elevation in diversity, biomass, regeneration dynamics, and carbon storage. The findings indicated that, depending on elevation, the highest total biomass density was found between 160 and 1900 m and 3100 and 3400 m. As a result, the overall C density changed with elevation.

Måren et al. (2015) highlighted that topographic factors influence mountain forests, which in turn affect radiation and moisture availability, ultimately shaping the biodiversity, composition, and structure of forest ecosystems (Thammanu et al. 2021, Cheng et al. 2023). According to Brockerhoff et al. (2017), the biodiversity of forested ecosystems is crucial for long-term carbon storage. Whether biomass (carbon) and biodiversity can be simultaneously conserved in the same forest ecosystems is still debatable (Maraseni et al. 2016).

Elevational Patterns of Species Richness: Drivers and Mechanisms

The biogeographical traits of a species play a crucial role in understanding the relationship between altitude and species variety. These traits offer valuable insights into the responses of species to various historical, biological, and environmental circumstances (Sun et al. 2020, Fine 2015), ultimately influencing their distribution patterns. For example, temperate taxa such as *Pedicularis*, *Saussurea*, *Primula* and *Rhododendron* are typically adapted to cooler conditions. They are known to originate from high latitudes or elevations, allowing them to colonize higher elevations (Kluge et al. 2017). Unlike temperate taxa that can thrive in cooler and drier conditions, tropical taxa such as *Altingia*, *Terminalia,* and *Lagerstroemia* have specific ecological requirements, typically warm and moist conditions, and they are generally confined to lower elevations (Brown 2014).

The exchange of community composition resulting in high species richness occurs at mid-elevations in floristic transition zones. According to Kluge et al. (2017), the varied altitudes of the richness peaks of tropical and temperate species highlight the idea of a transition zone between the two worlds, fusing various evolutionary histories. Although variations exist in the distribution patterns of temperate and tropical taxa throughout the elevational gradient, it is essential to note the presence of an intermediate elevation transition zone where distinct flora coexist (Sun et al. 2020). Temperate species are found at lower elevations relative to their primary high-elevation habitats. On the other hand, tropical lowland species inhabit higher elevations, establishing biogeographical transition areas, which are characterized by the highest levels of species diversity occurring at intermediate elevations. In addition, the floristic contact zone is situated at an approximate elevation of 2000 m asl, implying the presence of relatively less challenging climatic circumstances, as Sun et al. (2020) posited.

Multiple factors influence the geographical distribution of species richness, and the relationship between area and richness has been recognized as a fundamental aspect of understanding this pattern (Wang et al. 2022). Generally, regions with larger areas have higher species richness because more resources are available, which leads to increased speciation rates and decreased extinction rates. However, the relationship between area and elevational richness may only sometimes be consistent (Gillman & Wright 2014).

Most studies examining the variance in species richness along elevational gradients have reported either consistent decreases as the elevation increases or patterns characterized by peaks at intermediate elevations (Subedi et al. 2020, Di Musciano et al. 2021). The conical structure of mountains, decreased productivity, the hierarchical distribution of species, and deteriorating environmental conditions are frequently cited as reasons for the slow decline in species richness. More precisely, species discovered at higher elevations are typically subsets of species already found at lower elevations and are more adapted (Di Biase et al. 2021). Conversely, the hump-shaped pattern is commonly ascribed to overlapping species distributions in the centers of domains, which arise from dispersal limitations (referred to as the mid-domain effect) (Li & Feng 2015, Fattorini et al. 2019).

The hump-shaped pattern appears to be the most prevalent, as indicated by Liang et al. (2020) and Di Musciano et al. (2021). In contrast, the monotonic decline in species distribution is likely because of the reduced area available at higher elevations, as Fattorini et al. (2020) suggested.

Numerous reasons have been advanced for species richness patterns along elevational gradients, primarily climatic conditions, area size, the mid-domain effect (MDE), and biotic processes. Of these, climate has been extensively tested and identified as one of the main drivers of elevational species richness patterns (Masoud 2012, Sun et al. 2020). The impact of climate factors on species richness is mainly attributed to their influence on ecosystem productivity, the colonization of new ecozones, and the evolution rate (Masoud 2012, Brown 2014). Jiang et al. (2016) conducted a study that supported the physiological tolerance hypothesis about the richness-elevation relationship. Their findings indicated that high temperatures restrict species richness at lower elevations, whereas low temperatures limit species richness at higher elevations. Consequently, mid-elevations provide optimal environmental conditions, resulting in more species that can survive.

Furthermore, energy-related factors and water availability are interconnected, and water dynamics significantly influence land temperature, as demonstrated by Sun et al. (2020). Thakur et al. (2022) discovered that energy, water, and water-energy balance metrics outperformed other climatic and non-climatic variables in accounting for species richness variations across space. More specifically, water variables were strongly correlated with species richness in tropical, subtropical, and warm temperate zones. However, in high-latitude regions, the energy variables (for animals) or the water-energy variables (for plants) were the dominant predictors. In a recent investigation, Jiang et al. (2022) found that energy-related variables exhibited greater explanatory capacity than other variables when examining the patterns of elevational species richness for trees and shrubs. In contrast, factors related to climatic variability were more effective in elucidating these patterns for herbs and ferns. Energy-related factors are the predominant drivers of the diversity of woody species in colder mountain regions.

In contrast, precipitation and temperature emerged as the primary determinants of species richness in hotter and wetter ecosystems along elevational gradients. According to research by Bhattarai & Vetaas (2003), there was a consistent increase in the abundance of all woody plant groups as the mean annual rainfall increased (Table 1). On the other hand, some studies have identified adverse associations between precipitation on the one hand and temperature and altitude on the other (Subedi et al. 2020). In addition to climate conditions, habitat size has been closely linked to species richness in a given region, which was explained by the species-area relationship (Jiang et al. 2022). Larger areas provide more ecological resources, allowing more species to co-exist within a specific elevation range (Sun et al. 2020).

Species with large distribution ranges tend to cluster toward the middle of the domain when the distribution range is randomly rearranged within a restricted area. A notable association between the observed species richness pattern and the null distribution supports this assertion. In contrast,

Table 1: The elevation gradient in eastern Nepal was examined in terms of woody plant species richness, mean annual temperatures (MAT), potential evapotranspiration (PET), mean annual rainfall (MAR), and moisture index (MI) (Bhat-tarai & Vetaas 2003).

Elevation (m asl)	Total number of species	MAT (°C)	PET (mm)	MAR (mm)	MI
100	212	24.7	1455.6	2001.3	1.4
200	241	24.5	1440.8	2148.1	1.5
300	225	24.2	1428.5	2216.8	1.6
400	262	24.0	1416.1	2254	1.6
500	234	23.6	1390.2	2261.9	1.6
600	267	22.8	1343.6	2201.8	16
700	255	22.2	1308.3	2072.7	1.6
800	256	21.5	1269.4	1902.2	1.5
900	208	20.9	1233.9	1718.4	1.4
1000	229	20.2	1190.9	1549.4	1.3
1100	222	19.7	1160.9	1423.3	1.2
1200	241	19.1	1124.9	1368.3	1.2
1300	237	18.5	1089.0	1408.1	1.3
1400	207	17.9	1052.5	1476.6	1.4
1500	207	17.2	1015.9	1495.1	1.5

empirical evidence shows that species characterized by limited geographic ranges and those with intermediate ranges display significant deviations from the null hypothesis. This suggests that factors other than the null model, such as species interactions, abiotic resources, and evolutionary history, might regulate the distribution pattern (Sun et al. 2020, Wang et al. 2018).

The MDE phenomenon arises due to geometric boundary limitations, leading to increased overlapping of species ranges toward the central region of a common geographic area. The MDE is a model that is commonly used to explain the relationship between species richness and geographical gradients, mainly showing unimodal diversity patterns (Xu et al. 2017). This model is considered more relevant to species of a broader range distribution than to narrow-range species (Xu et al. 2017). In their research, Sun et al. (2020) demonstrated that the MDE significantly shapes species richness patterns in the Namjagbarwa Mountains region. In addition, this effect was noted to be stronger for broad-range species than for those with a narrow range.

Furthermore, the effects of water- and energy-related variables on genus diversity depended on biogeographical affinities. The study also found that elevational patterns were mainly related to climatic factors, but the MDE could slightly alter these patterns. Although the MDE has been widely investigated, it remains controversial from both the empirical and theoretical perspectives (Xu et al. 2017, Xu et al. 2021).

A singular component cannot comprehensively elucidate the phenomenon of elevational gradients in species richness since it is, instead, influenced by various processes encompassing ecological and evolutionary mechanisms (Cai et al. 2023). Numerous studies have demonstrated that climate variables significantly determine the distribution ranges of non-woody species in large-scale investigations. However, a body of research indicates that local factors, specifically edaphic attributes, may exert more pronounced influences on herbaceous species (Singh et al. 2017, Zhao et al. 2021). The inconsistent findings on the richness-climate relationship may be attributed to the scale effect, whereby different conclusions can be drawn due to differences in the spatial scales used in the studies (Li & Feng 2015). For instance, investigations examining various elevational ranges within specific locations or their neighboring areas may reveal divergent patterns of species richness and climatic trends across altitudinal gradients. Consequently, these variations can lead to disparate interpretations regarding the relationship between species richness and climate (Lee et al. 2013, Cai et al. 2023). Several studies have demonstrated the influence of climatic variables on the distribution of non-woody species in different regions, including studies involving latitudinal or altitudinal dimensions (Lee et al. 2013, Kluge et al. 2017).

Examining elevation gradients has been pivotal in understanding broad-scale biodiversity patterns, as evidenced by the seminal research conducted by Alexander von Humboldt (Fattorini et al. 2019). Jiang et al. (2022) emphasized that various hypotheses explaining diversity gradients do not necessarily conflict but are likely to act in conjunction, with water-energy dynamics playing a crucial role. Despite numerous studies on the elevation patterns of species richness, numerous questions still need to be resolved (Wang et al. 2017). An additional explanation is required to understand the factors that impact the link between elevation and species richness, as well as the variations observed across different spatial scales, taxonomic groups, and ecological communities. The correlation between elevational gradients and species richness is a topic of academic interest and practical significance, particularly in terms of climate change, as it establishes a link between biodiversity patterns and conservation initiatives (Di Musciano et al. 2021).

Several ideas have been proposed to explain the correlation between species richness and altitude. However, further investigation is required to understand these patterns more fully (Rahbek et al. 2019, Liang et al. 2020, Di Musciano et al. 2021). By examining variations in community composition across altitudinal gradients, conservationists and policymakers can gain valuable insights that will inform sustainable biodiversity management.

Effects of Elevation on Soil Properties

The characteristics of soil systems are significantly influenced by altitude since the interaction between mineral particles and soil organisms contributes to the development and complexity of the soil body (Badía et al. 2016, Jeyakumar et al. 2020). Altitude significantly influences the physicochemical characteristics and microbial diversity of soil, as indicated by Kumar et al. (2019). He et al. (2023) found that carbon sequestration and soil conservation increase with an increasing topographic gradient, highlighting the critical role of altitude in shaping soil properties and organic matter dynamics. Elevation increases are typically associated with significant decreases in fine silt-sized particles, bulk density, exchangeable sodium percentage, and pH base saturation. However, soil aggregate, stability, hydrophobicity, organic matter, and coarse sand-sized particles have all increased (Badía et al. 2016). Furthermore, the key nutrients such as potassium (K), C, N, and P found in soils at higher elevations differ significantly from those found in soils at lower elevations (Badía et al. 2016).

According to Wilson (2019), soil characteristics are strongly influenced by the climate and parent material. Altitude changes cause climate variation, affecting soil properties and pedogenic processes by altering the sorts and amounts of the chemical, biological processes and physical and environmental phenomena of soil (Dinter et al. 2020, Di Musciano et al. 2021).

Altitude variations markedly influence the textural characteristics of soils, leading to a distinct disparity in sand composition. Yüksek et al. (2013) argued that soils at higher altitudes are categorized as sandy loam due to the significant increase in the relative proportion of sand with altitude. Soils found at high altitudes are considered immature as they are derived from gradual rock weathering. Consequently, these soils have a notable sand, gravel, and stone composition. The presence of soil particles with a larger grain size suggests a prolonged soil development process. Conversely, a decrease in altitude results in an increase in the proportion of silt and a decrease in the amount of sand (Dahal et al. 2018). Due to the lengthy process of soil formation at higher elevations, there is a higher concentration of clay particles, which can result in a low amount of nutrients that are readily available in the soil (Saeed et al. 2014).

Soil bulk density decreases as the altitude increases. Studies by Saeed et al. (2019) and Masoud et al. (2024) found that the bulk density of soil was higher at lower elevations than at higher elevations, with a significant correlation and variation with elevation. This occurrence can be ascribed to elevated organic matter levels at greater altitudes. The bulk density of soil is subject to the effect of multiple variables, including soil texture, structure, organic matter content, and freeze-thaw cycles (Lu et al. 2021). Meanwhile, Kumar et al. (2010) reported that the water holding capacity and moisture content increased with altitude, whereas bulk density decreased with altitude. The soil texture consisted mainly of sand, followed by clay and silt, at all altitudes.

Studies have established the distinct impact on soil properties of climate variations along an elevational gradient (Charan et al. 2013). Generally, a negative association exists between height and temperature and a positive correlation between altitude and precipitation. Climate alterations significantly impact vegetation composition and biomass, subsequently influencing soil characteristics and soil taxa modification. Badía et al. (2016) identified several common trends, including alterations in the soil organic matter (SOM), C:N ratio, greater soil acidity and cation-exchange capacity, and decreased base saturation.

Hailemariam et al. (2023) documented notable disparities in many soil fertility attributes, encompassing the organic matter concentration, pH levels, cation exchange capacity (CEC), phosphate sorption, and phosphorus (P) availability across altitudinal gradients. The pH of soil was sometimes acidic, which was shown to decline proportionally with increased elevation. The reduction in pH results from the accumulation and subsequent breakdown of organic matter, which releases acidic substances into the soil. A further factor for this decline is the increased precipitation at elevated altitudes. Increased rainfall leaches base-forming cations such as calcium (Ca), magnesium (Mg), and K, leading to increases in ions such as aluminum (Al) and hydrogen (H) (Ng et al. 2022). However, Charan et al. (2013) observed no significant difference between low and high altitudes in terms of soil electrical conductivity (EC). Research has indicated a negative correlation between soil pH, precipitation, and soil moisture levels. This pattern has been observed at elevational gradients in various regions, including the Galápagos Islands (Dinter et al. 2020), Hawaii (Vitousek & Chadwick 2013), and New Zealand (Dixon et al. 2016). According to Fuentes et al. (2022), the temperature and relative humidity of soil exhibit temporal (daily) and spatial (altitude-related) variations. Their study also found that the SOM and organic P content showed upward trends with increasing altitude. However, the pH, EC, and total P showed downward trends with increasing altitude.

The critical environmental factor that reduces the mineralization processes of N and affects the bioavailability of soil N is the observed increase in soil temperature. Despite the general increase in total N concentration in soil as the altitude increases, the availability of N to living organisms is restricted. It has been observed that low temperatures have a dual effect on natural processes. Firstly, they impede the breakdown of plant residues, thus affecting the decomposition process. Secondly, they have a decelerating impact on chemical weathering rates (Rodrigues et al. 2023). This phenomenon can be attributed to the fact that significant portions of N and P remain tightly bonded to the SOM, which exhibits limited degradation capabilities at low temperatures. N mineralization, SOM decomposition, and soil P concentration rates were negatively correlated with temperature. Consequently, the diminished nutrient content observed in soils at elevated altitudes can be attributed to the influence of low temperatures, reducing mineralization, and decomposition processes. Furthermore, concentrations of various micronutrients, such as Ca, cobalt (Co), nickel (Ni), boron (B), Mg, molybdenum (Mo), sodium (Na), K, iron (Fe), and copper (Cu), decrease with increasing altitude (Charan et al. 2013).

Subedi et al. (2020) found a link between increasing soil K, annual precipitation, and mean annual temperature. Wang et al. (2018) discovered that the available N concentrations in soil increased with elevation, but there was no clear elevational pattern for the total N concentrations in plant tissues. However, as the elevation increased, there were consistent declines in the levels of the available P in the soil and the total P concentrations found in all plant tissues. This observation implies that the availability of P can impose constraints on plant growth in elevated regions. In an independent investigation, Amanullah et al. (2021) observed drops in bulk density, lime content, EC, and pH in topography and soil elevation. In contrast, within the soil profile, these parameters increased from the soil surface to the subsurface. The concentrations of N, P, K, and micronutrients rose with increasing elevation. However, these parameters decreased from the surface to the deeper layers of the soil. Furthermore, elevation-dependent increases were observed in both the water-holding capacity and saturation %. However, a decreasing pattern was observed moving from the surface to the deeper soil layers (Amanullah et al. 2021).

The N and available P content significantly promote productivity, species diversity, community succession, and soil sustainability. According to a recent investigation by Mishra & Francaviglia (2021) into the impacts of altitude on soil quality in the Mon and Zunheboto districts of Nagaland, it was observed that in neither area did altitude exert a statistically significant influence on soil organic C stocks, while it impacted the available levels of N and P. The researchers observed that the maximum concentrations of both nutrients were found at lower elevations, and these levels were statistically comparable to each other, as indicated in Table 2.

The lack of substantial variations in the levels of N and P at various elevations is consistent with the results reported in research conducted in the equatorial Andes (Unger et al. 2012) and on Gongga Mountain in China (Tan & Wang 2016). Typically, young volcanic soils exhibit limited development and decreased nutrient concentrations and CEC compared to more mature soils (Tan & Wang 2016).

Studies have documented that the carbon to phosphorus ratio (C:P) of soil reaches its maximum value at intermediate elevations, specifically within the Canary pine forest belt. According to Zhang et al. (2016), a higher soil C:P ratio may suggest greater efficacy in P use by plants and microorganisms, possibly attributable to increased moisture levels. However, the slow rate at which pine needles decompose could impede the P transfer process from deceased plant matter to the soil. In areas with higher elevations, lower temperatures can have an additional inhibitory impact on breakdown rates, leading to a higher soil C:P ratio. This phenomenon was documented in a research investigation carried out in the northern region of China, which revealed that the C:P ratio of the soil exhibited a notable increase in conjunction with higher elevation (Xu et al. 2018).

According to Saeed et al. (2014), the organic C content of soil increased as the altitude increased. Meanwhile, calcium carbonate ($CaCO_3$) exhibited a negative correlation, decreasing as the altitude increased. However, the soil pH did not show significant changes with the elevation gradient. These observed events could be related to the direct influence of temperature on the equilibrium of $CaCO_3$. Geographical directions, elevation, and altitude significantly affect soil fertility, drainage, and erosion rates (Amanullah et al. 2021). Climate factors such as temperature variations, precipitation, and snowfall also impact the accumulation of organic nutrients in soil by affecting the organic decomposition over elevational gradients (Li et al. 2022, Zhou et al. 2023).

Kumar et al. (2019) revealed a significant positive association between altitude and SOM concentration. The observed phenomenon could be related to a decrease in temperature with increasing elevation, resulting in the inhibition of microbial and enzymatic processes that facilitate the breakdown of organic matter in soils found at high altitudes. Therefore, the relationship between low temperature and elevated altitude would have significantly contributed to the observed SOM increase.

According to Li et al. (2022), there is a negative correlation between elevation above mean sea level and SOM concentration. The observed decline in vegetation growth at higher elevations could be attributed to alterations in climatic conditions and reductions in organic matter accumulation along elevation gradients (Tashi et al. 2016). The findings may be related to the inverse correlation between temperature and altitude, whereby higher altitudes are associated with lower temperatures. Consequently, the ability of plants to

Table 2: Effects of altitude on soil C stock, available N, available P, and available K in the two districts of Nagaland (Mishra & Francaviglia 2021).

Altitude (m asl)	Soil C Stock (Mg C ha^{-1})		Available N (mg kg^{-1})		Available P (mg kg^{-1})		Available K (mg kg^{-1})	
	Mon	Zunheboto	Mon	Zunheboto	Mon	Zunheboto	Mon	Zunheboto
<500	27.3	24.5	427.9b	312.7	9.3b	8.8b	32.5	53.7c
500–1000	29.2	27.2	278.5a	317.9	7.1a	7.4a	30.5	27.9a
>1000	33.1	29.6	324.6a	347.3	7.1a	8.6ab	40.4	43.6b

Different letters in the same column indicate significant differences ($p < 0.05$)

thrive at elevated altitudes is hampered, resulting in the presence of less organic matter (Bangroo et al. 2017).

Several studies have reported decreased vegetation in the altitudinal strata and between different sites. This decline could be attributed to ecophysiological constraints, low temperature, and productivity (Tashi et al. 2016). Consequently, there is a low accumulation of litter and organic C input in soils at higher elevations, resulting in a lower C density. However, some research has suggested a positive correlation between altitude and organic C reserves in forest soil. This phenomenon could be ascribed to the decelerated decomposition of SOM in regions characterized by lower temperatures and higher elevations (Tashi et al. 2016).

Altitudinal gradients are critical in shaping ecosystem properties and processes, but their impacts on nutrient status vary significantly. Temperature changes with altitude are widely believed to be the main drivers of changes in nutrient status in different regions (Sundqvist et al. 2013). There are exceptions to this pattern due to variations in other factors, such as vegetation type, parent rock, and precipitation (Sundqvist et al. 2014). Despite significant research efforts, our ability to predict how and why nutrient status changes with altitude still needs to be improved (Sundqvist et al. 2013, Sundqvist et al. 2014). Additional research is required to elucidate how the nutritional condition of vital constituents within ecosystems reacts to altitude variations. Examining climate variations can provide valuable information about the potential impacts on N cycling and the subsequent implications for plant growth.

Effect of Elevation On Soil Biological Characteristics

Soil is the largest reservoir of C on land and plays a vital role in the SOM cycle, which can act as a C sink or a source of CO_2 (Scharlemann et al. 2014). SOM consists of a diverse range of compounds in different decomposition phases. These compounds originate from litter, root turnover, and microbes. Several factors influence the dynamics of SOM, including the substrate quality, microbial activity, and ambient conditions (Cotrufo & Lavallee 2022).

High-altitude soils are home to complex and diverse bacterial communities, which may be partly due to the decreasing C. The N increases as the elevation increases, a characteristic attributed to differences in litter composition (Yüksek et al. 2013). SOM is a crucial factor in determining the structure of microbial communities, and low temperatures at high altitudes can reduce microbial and enzymatic activity, thereby slowing the decomposition of SOM. Psychrophiles and psychrotrophic organisms, which are well adapted to survive in high altitude stress, make up most microorganisms in these environments. Populations of psychophilic bacteria have been found to grow with altitude (Kumari et al. 2021). These microorganisms are highly desirable for their ability to produce cold-adapted biofertilizers, cold-active enzymes, and metabolites that function best at low temperatures.

The high-altitude soils of the Himalayas harbor diverse microbial communities. Proteobacteria, particularly Pseudomonas, are the most abundant group of bacteria, accounting for 73% of the bacterial diversity in these soils (Margesin & Miteva 2011). Psychrophilic fungi have undergone evolutionary adaptations to acclimate effectively to challenging environmental conditions at high altitudes. High-altitude soils harbor a wide range of photosynthetic microorganisms, thus exhibiting significant biodiversity. The abundance of bacterial and diazotrophic counts in high-altitude soils is significantly influenced by altitudinal differences (Kumar et al. 2019). Diazotrophic counts were improved in soils with low available N. High soil nitrate concentrations under decreased mineralization conditions of N could be the functional attribute of diazotrophs in high-altitude soils (Rui et al. 2022).

Several nitrogen-fixing bacteria adapted to cold environments, which are known as psychrophilic bacteria, have been discovered in Gangotri soil. These include *Pseudomonas helmanticensis*, *Arthrobacter humicola*, *Brevibacillus invocatus*, and *Pseudomonas mandelii* (Kumar et al. 2019). These isolates have been reported to be cold-adapted with nitrogen-fixing attributes. Despite the negative effect of temperatures on nitrogen fixation, these bacteria are least affected by very low temperatures when grown in nitrogen-deficient environments (Li et al. 2021).

Altitude has been found to strongly affect the properties of the soil of the rhizosphere, with the total N, total organic C, water, and urease content, as well as the C: N ratio, decreasing with increasing altitude (Tang et al. 2020). According to Bhople et al. (2019), soil microbial and fungal biomass stocks are changed by inherent soil qualities, which can also affect the structure of microbial communities. Environmental factors were shown to be less disruptive to these biomass stocks. Additionally, the composition of soil organic matter (SOM) differs among vegetation types, influencing the spatial distribution of gene richness across altitudinal gradients (Kumar et al. 2019). The abundance of C and N cycling genes varied significantly between different types of plants, suggesting that vegetation types play a role in shaping the composition of SOM on altitudinal gradients.

Soil-vegetation interactions are crucial in regulating nutrient cycling and ecosystem responses to climate change, with elevation-driven variations in temperature, precipitation, and soil composition significantly shaping these dynamics

(Badía et al. 2016, Jeyakumar et al. 2020). Higher elevations typically experience increased precipitation, leading to nutrient leaching and reduced soil fertility, while lower temperatures slow organic matter decomposition and microbial activity, thereby affecting nutrient availability (Ng et al. 2022, Vitousek & Chadwick 2013, Dixon et al. 2016). These soil-climate interactions directly influence vegetation composition and biomass production, as dominant plant families, such as Lauraceae and Fagaceae, play a key role in nutrient cycling and organic matter accumulation along elevational gradients (Li et al. 2023). The observed hump-shaped species diversity pattern underscores the intricate relationship between soil properties, nutrient dynamics, and climatic factors in determining vegetation distribution and ecosystem stability.

CONCLUSIONS

- The biogeographical attributes of species are vital in establishing the correlation between elevation and species richness. This relationship exhibits significant diversity between different life forms, with certain families demonstrating less species richness as elevation increases. In contrast, others exhibit an increase or a relationship that peaks and then declines.
- As elevation increases, forest productivity decreases, resulting in a decrease in C storage in forests. Most research investigating variations in species richness along elevational gradients has identified either a steady decline as elevation increases or a pattern marked by a maximum at intermediate elevations. The decline in species richness is often attributed to a combination of factors, such as deteriorating environmental conditions, decreased productivity, restricted habitat availability due to the conical shape of mountains, and the hierarchical distribution of species. The hump-shaped pattern has been attributed to climatic circumstances, area size, the MDE, biotic processes, energy-related factors, and water availability. Different mechanisms that explain a variety of gradients may not necessarily contradict each other but are likely to work together.
- With increasing altitude, soil experiences a rising sand percentage and decreases in both silt and clay. As the altitude increases, the soil density decreases due to the higher concentration of organic matter. As the altitude increases, the soil pH reduces due to the accumulation and subsequent decomposition of organic matter. An elevated soil temperature is the critical environmental element that causes a decrease in N mineralization processes, affecting the availability of N in the soil.
- Microorganisms are crucial for conserving soil fertility and ecosystem functioning in high-altitude areas by facilitating nutrient cycling and decomposing SOM.

To ensure sustainable management of mountain ecosystems in the face of climate change, conservation strategies should prioritize mid-elevation areas where species richness peaks, with a focus on preserving endemic and climate-sensitive species. Sustainable land-use practices, such as agroforestry and low-impact agriculture, are essential for maintaining soil health and preventing nutrient depletion. Reforestation and carbon sequestration initiatives should target mid-elevation regions to enhance carbon storage, while soil conservation measures, including erosion control techniques like terracing and mulching, are necessary to prevent soil degradation in high-altitude areas. Additionally, long-term biodiversity monitoring programs should be established to assess the impacts of climate change and land-use modifications on vegetation and soil dynamics. Future research should address key gaps, including the need for extended monitoring of species richness, soil properties, and ecosystem resilience across elevation gradients. Investigating microbial interactions is critical to understanding their role in nutrient cycling and soil fertility, while further studies on carbon sequestration at high altitudes can provide valuable insights into climate change mitigation. The potential for biotechnological applications in high-altitude soils should also be explored to enhance sustainable agriculture and ecosystem restoration. Furthermore, integrating remote sensing with field data can improve our understanding of elevation-driven biodiversity and soil dynamics. Addressing these research gaps while implementing targeted conservation and land-use strategies will contribute to the long-term sustainability and resilience of mountain ecosystems.

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