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Unlocking the Ecological Complexity: Investigating Diversity and Community Patterns among Alpine and Subalpine Vascular Plants Through Phytosociological Examination

[1]Siddrameshwar, [2]Dr. Sumer Singh

[1]Research Scholar, Department of Botany, Singhania University, Pacheri Bari, Jhunjhunu, Rajasthan.

[2]Research Supervisor, Department of Botany, Singhania University, Pacheri Bari, Jhunjhunu, Rajasthan.

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ABSTRACT:
Alpine and subalpine ecosystems are among the planet's most biologically distinctive and biodiverse environments, they also confront considerable environmental difficulties. Effective conservation and management plans depend on an understanding of the variety and community dynamics of vascular plants in these high-altitude habitats. Our goal in this research work is to provide insights into the ecological complexity of alpine and subalpine vascular plant communities through a thorough phytosociological investigation. We investigate the species composition, abundance, and distribution patterns along a range of elevation gradients using comprehensive field surveys and statistical analysis. Our findings illuminate the complex ecological relationships that form these ecosystems and offer important new understandings of the variables affecting the composition of plant communities. Additionally, we talk about how our findings may affect ecosystem management, biodiversity preservation, and climate change adaptation in alpine and subalpine environments.

1. Introduction

The biological systems of the alpine and subalpine regions are typified by their extreme natural conditions, which include high winds, cold temperatures, and brief growing seasons. These environments present the greatest challenges for vegetation. In spite of these harsh conditions, these high-rise neighbourhoods are home to incredible variety and serve as important sources of inherited diversity and ecological adaptability. Vascular plants have an important role in shaping the development and functioning of alpine and subalpine habitats by acting as vital builders, settling soil, and providing vital habitat and food sources for various faunal networks.

Comprehending the heterogeneity and communal components of vascular plants in alpine and subalpine environments is crucial for the effective conservation of these systems. Regardless, the ecological complexity of these settings poses significant challenges for analysts trying to decipher the basic models and cycles governing plant networks. Conventional approaches of focusing on plant variety often fall short in capturing the complex relationships and changes that characterize alpine and subalpine vegetation.

A comprehensive framework for studying plant networks by considering the ecological relationships between species and their current state is provided by phytosociology. Through the application of phytosociological techniques, analysts can get valuable insights on the structure, dynamics, and components of plant networks, as well as the ecological cycles that propel their assembly and function. In terms of biological systems found in alpine and subalpine regions, phytosociological evaluation is a crucial tool for revealing the ecological complexity inherent in these high-altitude environments.

The findings of a comprehensive phytosociological study aimed at investigating community designs and variety among alpine and subalpine vascular plants are presented in this examination report. We examine the factors influencing species structure, overflow, and dispersion across varying height angles by meticulous fieldwork, information analysis, and factual demonstration. Our analysis aims to shed light on the ecological mechanisms that underpin the assembly and components of plant networks under these challenging circumstances, offering recommendations for environmental change transformation processes, biodiversity preservation, and environmental the board. Through revealing the ecological complexity of alpine and subalpine vascular plants, we hope to deepen our understanding of these fragile mountain biological systems and shed light on evidence-based conservation efforts made in spite of rapidly changing environmental conditions.

2. Literature Review

Dar and Parthasarathy (2022) investigated the relationships between understory vegetation and its ecological factors. The analysts examined the species composition, diversity patterns, and ecological relationships of understory plant networks by means of extensive field studies and vegetation exams. Significant relationships were found in their review between the distribution of understory plant species and environmental variables such as soil characteristics, topography, and microclimate. Additionally, the analysis highlighted how important it is for species communications and territorial heterogeneity to shape the structure and organization of understory plant networks. The findings broaden our understanding of the biological cycles underlying the characteristics of temperate mountain forests and offer recommendations for managers of woodlands and biodiversity conservation in the Kashmir Himalayas.

Nakhutsrishvili et.al (2022) An ethnobotanical and phytosociological summary of the subalpine and alpine vegetation of the Georgian Caucasus was provided thorough research. The researchers recorded the richness of plant species, the makeup of local groups, and their customary usage of plants through in-depth field surveys and ethnobotanical interviews. Their research demonstrated the Georgian Caucasus's alpine vegetation's significant biodiversity and cultural relevance, and also emphasized the value of incorporating traditional ecological knowledge into conservation efforts to preserve biodiversity. By highlighting the necessity of participatory methods to conservation and sustainable development in culturally diverse places, the research advances our knowledge of the interaction between human communities and mountain ecosystems.

Rahman et al. (2021), following ecological parameters and ranging from subtropical-calm ecotonal woodlands to alpine pastures. By means of vegetation research and ecological investigations, the experts identified certain species of vegetation and assessed their ecological attributes and inherent tendencies. They reviewed the transient concept of vegetation along altitudinal angles as well as the effects of soil qualities, temperature, and precipitation on ecological parameters that affect species appropriation designs. The findings provide crucial information for the preservation of biodiversity, expand our understanding of how biological system components could be interpreted in ecological settings, and place executives in the Lesser Himalaya.

García-Gutiérrez et al. (2018) The beneficial variety and ecological requirements of alpine vegetation types within a biogeographical transition zone were studied Their review focused on how ecological factors affect alpine plant networks' circulation and organization. The scientists identified certain plant kinds and examined their ecological preferences and practical attributes by using multivariate quantifiable investigations and field experiments. The findings revealed enormous differences in ecological requirements and practical variety across different types of alpine vegetation, highlighting the need of taking into account both biotic and abiotic aspects when understanding plant community features in transitional zones. This study provides critical information on the biological cycles governing alpine habitats and emphasizes the need for integrated approaches to management of board and protection in biogeographically diverse areas.

Chandra et.al (2018) looked at the distribution patterns of vascular plants in connection to topography and environmental factors. The impact of aspect, slope, altitude, and soil properties on plant species distribution patterns was investigated by the researchers using field surveys and geographical analysis. Different vegetation zones were found along altitudinal gradients by their investigation, and environmental variables influencing species diversity and distribution in the alpine zone were

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discovered. The results have consequences for strategies for managing land in mountainous areas and for the protection of biodiversity. They also offer significant insights into the biological dynamics of alpine ecosystems.

3. Research Methodology

In KNP, the alpine zone is situated somewhere in the range of 4500 and 5500 meters above ocean level. The treeline and subalpine krummholz shrubs end at around 4200 m. This is trailed by a belt of alpine scour and different physiognomic classes of herbaceous improvements up to around 5200 m. Beneath that, there is scanty sub nival vegetation until the start of a durable snowline that differs somewhere in the range of 5300 and 5600 m. Around 23% of KNP's geological region (395 km2) is situated in the alpine zone.

3.1. Sampling of vegetation

In view of information from satellite remote detecting, an outline of topo guides of India, previous experience, and perception of the survey region, four physiognomic units were recognized in the vegetation of the subalpine and alpine zone of KNP: (a) Krummholz greenery, (b) alpine scour, (c) alpine knoll, and (d) riverine scour (Table 1). Flood information for 180 distinct types of vascular plants gathered during the pinnacle creating season, July-august, were remembered for the vegetation data obtained from 3000 quadrats enveloping 55 looking at stations in the audit locale. Utilizing partitioned unpredictable quadrats, the vegetation plan and species structure in different physiognomic units of the alpine zone were archived. These expansive vegetation gatherings can act as a structure for future, more top to bottom phytosociological studies. The extraordinary larger part of the plants was distinguished in the field in view of their nearest sort and species utilizing neighbourhood vegetation, explicitly Himalayan Blooms and Bhutanese Verdure, which incorporate assortments from Sikkim.

Table 1: Data on vegetation plots gathered from KNP's alpine zone in Sikkim Himalaya

Physiognomy Type	Vegetation Type
Krummholz thicket	Krummholz brush
Riverine thicket	Riverine willow brush
Alpine scrub	Juniper scour
	Rhododendron scour
	Morainic scour
	Riverine (Myricaria rosea) scour
Alpine meadow	Kobresia duthiei soggy glade
	Kobresia nepalensis soggy glade
	Kobresia pygmaea dry glade
	Deschampsia caespitosa bog glade
	Anaphalis xylorhiza blended glade
	Potentilla peduncularis herbaceous knoll
	Subnival vegetation

3.2. Phytosociological analysis

PC-ORD TURBOVEG and JUICE, two mathematical inquiry programs that rely more on multivariate analysis, were used. The group research was carried out using PCORD programming, which also yielded the Standard Correspondence Examination (CCA) and alpha diversity lists. The following five climate factors were measured at each site: height (measured in meters using GPS); perspective (measured using GPS on a scale of 1 to 5, showing hotter viewpoint); slant (degrees; measured outwardly); mean annual precipitation (measured using a precipitation dissemination guide on a scale of 1 to 5); and soil type (measured using the dirt molecule size on a scale of 1 to 8, ranging from rock to sand, residue, and earth). Following characterisation, JUICE programming was used to organize a condensed table. For suggestive species, the limit devotion incentive was set at 4, and for consistent species, the edge recurrence incentive was set at 80.

4. Results and Discussion

4.1. Differentiation of landscape levels: Tibetan, Inner, and Outer Himalaya

The topography of KNP is represented by the Kangchenjunga massif. Regardless of being found near each other, the seven watersheds, or waterway subsystems — the Lhonak, Zemu, Lachen, Rangyong, Rangit, Prek, and Churong — show significant ecological and geological diversity. While the more outstanding Himalaya by and large runs east-west, the center edge of the Kangchenjunga range is situated in a north-south heading, with some west-east intersection focuses. The tempest's southeasterly turns give weighty precipitation; however, they are obstructed by advancements along the west-east line, which lessens how much precipitation that moves north. The typical yearly precipitation is 2.15 m; be that as it may, it diminishes to 0.65 m in the north and 1.55 m in the southeast. While Zemu, Lachen, and Rangyong in the central locale of the KNP address the impermanent Internal Himalaya, the high valley of Lhonak tends to the Tibetan Himalaya, and the southern part of the KNP (Rangit, Prek, and Churong) addresses the wet area, or possibly the Outside Himalaya.

4.2. The composition and organization of vegetation

Ten kinds of vegetation were distinguished from the alpine zone in view of mathematical characterization: The accompanying kinds of glades are tracked down in various pieces of the country: Deschampsia caespitosa swamp knoll, Anaphalis xylorhiza blended knoll, riverine willow (Salix sikkimensis) shrubbery, riverine clean (Myricaria rosea), and juniper scour. Future phytosociological research should be more deliberate and exhaustive.

The following is a fast rundown of the cosmetics and association of these 10 vegetation networks.

Two populaces have been accounted for to live in juniper clean, which favors hotter slants in the 3500-4500-m height territory:

1. Juniperus squamata scour: Ordinarily, this type is tracked down on more sweltering slants with a yearly precipitation of around 2200 mm, somewhere in the range of 300 and 4200 m. This community contains something like 30% bush cover, with Juniperus squamata being the transcendent species. Grass and sedge cover can reach 20%. The significant grasses and sedges are Carex alpina, Poa alpina, Calamogrostis filiformis, and Kobresia nepalensis. Rhodiola bupleuroides, Bistorta vivipara, and a few types of Arisaema, Potentilla, Primula, and Pleurospermum are the significant parts of the zest layer.
2. Juniperus indica scour: This vegetation stretches to 4700 m in the interior evaporate valleys, and is thought to be between 4200 and 4500 m in range. Rhododendron lepidotum also likes to invade the openings in this association, where J. indica typically grows as an upright shrub. At least 11% are made up of grasses and spices, with the herbaceous species including Pleurospermum and Potentilla kinds, Rheum acuminatum, and Rhodiola bupleuroides. This flora is quite widespread and covers vast areas across KNP's alpine zone.
3. Clean Rhododendron: The Bantam Rhododendron is found in the upper elevations above the Krummholz zone. Under 1.5 m tall, this flora targets alpine clammy scour and prefers the colder views between 4000 and 4200 m. Nevertheless, it can reach elevations of up to 5000 meters in the interior arid valleys. It can withstand an elevation of 1350–2600 mm in precipitation. In winter, a thick layer of snow shields it from the cold and wind. With extremely few gaps or openings, the Ericaceous cover makes up over 55% of the very dense vegetation. Rhododendron anthopogon, Rhododendron setosum, and R. lepidotum codominate in the shrub layer.
4. Morainic clean: This class is for the most part tracked down somewhere in the range of 4000 and 4500 meters above ocean level in the glaciated valleys along the equal and terminal moraines. This bush overwhelmed vegetation is expanded in the lower heights and confined and meager in the higher rises. The most evident suggestive sort of this verdure, Potentilla fruticosa, is tracked down in the center ascents.
5. The shrubbery of riverine willow (S. sikkimensis): This is restricted to slant streams and riverbanks somewhere in the range of 3600 and 4300 meters in rise. The prevalent types of this verdure, with a high cover level of 35%, is S. sikkimensis. The fundamental buddies in wet valleys are Rosa sericea, Abies densa, Rhododendron lanatum, Sorbus microphylla, and Rhododendron thomsonii and hodgsonii. Acer campbellii, R. hodgsonii, Betula utilis, and Hippophae salicifolia are codominants in the upper shade in the inward valleys.
6. M. rosea (riverine) clean: In the subalpine and alpine zone up to 4500 m, this class is much of the time found in the upland valleys and stream courses

described by skeletal and sandy soils. Under 0.3 meters in height, the vegetation is addressed by mat-shaping prostate hedges blended in with grasses, sedges, and flavors. The trademark species is M. rosea, whose cover differs enormously (from 6-65%) contingent upon edaphic and microtopographic factors.

The alpine knoll vegetation was determined to be substantially segregated into three groups: sedge glade, bog glade, and herbaceous knoll, based on the mathematical classification. Sedge glade was further divided into three groups: K. pygmaea, K. duthiei, and K. nepalensis

7. K. nepalensis sodden knolls: With a typical yearly precipitation of 2200 mm, this vegetation is the most far reaching and predominant in heights going from 4200 to 5200 m. It happens in the higher scopes of sloppy, uncovered, glaciated valleys, on smooth slants and edge tops. The typical level of this thick, delicate, mat-like development is 0.2 meters. K. nepalensis' front fluctuates enormously with microtopography; it codominates with Arenaria, Juncus, Carex, Bistorta milletii, Potentilla peduncularis, R. lepidotum, and Primula capitata.
8. Sodden Knolls, K. duthiei: This can be tracked down in the 4200-4700 m rising zone in secret clammy valleys and rough inclinations. With a typical degree of 0.33 m, K. duthiei (cover more noteworthy than half) overpowers the tussock-outlining vegetation. Regularly, openings are where one might view as K. nepalensis, Kobresia capillifolia, R. acuminatum, R. anthopogon, Geranium donianum, and a few types of Heracleum, Swertia, Pleurospermum, and Juncus.
9. K. pygmaea dry glades: Tracked down in the higher ranges of the glaciated and rather dry Zemu and Lhonak valleys (mean yearly precipitation of 1600 mm), these dells are situated somewhere in the range of 4200 and 5000 m in rise. As the name proposes, the vegetation is hampered upon landing in this area, with a mean degree of 0.06 m. Kobresia schoenoides and Bistorta vivipara are tracked down in the lower districts, particularly close to streams, while Kobresia spp., B. milletii, R. fruiticosa, and Aster falconeri are tracked down in the higher locales.

In addition to these three Kobresia people groups, we also discovered bog glade networks made up of the following:

10. D. caespitosa swamp glades: These knolls are located between 4200 and 4500 meters above sea level, on the wet pads that surround alpine lakes and in the upper courses of meandering streams. The highest level of this tussock-shaped vegetation is less than one meter. In terms of flowers, D. caespitosa clusters are common (covering more than half of the area), especially around the ends of long conduits. Carex setigera, Lagotis kunawarensis, Potentilla coriandrifolia, Festuca valesiaca, Calamogrostis filiformis, Epilobium wallichianum, and several Pedicularis, Juncus, greenery, and lichen species are among the frequently occurring species in the openings.

4.3. Environmental Factors

All five climatic parameters (altitude, precipitation, edaphic, angle, and slope) were considered to be strongly correlated with the appointment space. The main CCA hub showed a negative correlation with both precipitation and height. Precipitation and soil type were negatively correlated with the next pivot, while soil type was strongly associated with the third hub. It was believed that precipitation and height were negatively correlated, or that precipitation decreases with increasing elevation. Table 2's biplot of the first two tomahawks demonstrates how locations with more precipitation are more varied and support more vegetation networks, and vice versa.

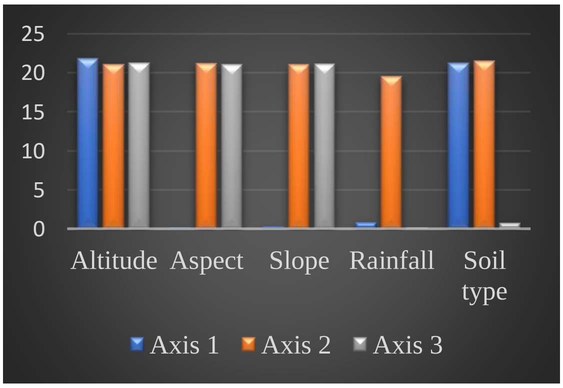

Figure 1: Connection Scores with The Five Natural Factors

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Table 2: For the first three Tomahawks, the PC-ORD CCA give connection scores with the five natural factors

Variable	Axis 1	Axis 2	Axis 3
Altitude	21.800	21.10	21.299
Aspect	0.135	21.243	21.105
Slope	0.245	21.080	21.160
Rainfall	0.798	19.535	0.045
Soil type	21.275	21.515	0.735

4.4. Discussion

At the scene level, the central Kangchenjunga range broadens toward the west and structures a get over that obstructs southeasterly tempest winds and makes an unmistakable nearby partition of the Tibetan, Inward, and Outer Himalayas inside KNP. This outcomes in a scope of conditions, from marine in the south to mainland in the middle and dry in the far north, and it likewise influences the examples of vegetation. In this way, the treeline vegetation that traverses the entire Himalayan reach and incorporates deciduous Betula, evergreen Rhododendron, and types of Acers and Juniperus is restricted to a 50-kilometer range along the KNP's north-south pivot.

Not at all like in the WH, sedges overwhelm the alpine meadows of KNP: K. pygmaea and K. schoenoides in the dry meadows, and K. nepalensis on smooth inclinations and K. duthiei on broken inclines in the clammy meadows. These Cyperaceae mats play a urgent ecological part in forestalling the separation of tremendous alpine scenes. The dry dells of A. xylorhiza and K. pygmaea in the Lhonak and Zemu valleys in the farthest north look like the Tibetan level and the encompassing vegetation of Mount Everest. Incidentally, the moist dells of K. nepalensis and K. duthiei in the southern locale were contrasted with those portrayed in the Rolwaling Himal, which is situated in focal Nepal. Tall forb networks in profound soil and green meadows of Danthonia cachemyriana are different attributes of the WH and were basically missing in KNP. The D. caespitosa swamp dale, which is found right on the boundaries of crisp lakes and streams, is the most prominent illustration of grass-congested vegetation in the KNP. In the Sikkim Himalaya, subalpine bushes and alpine unadulterated vegetation are undeniably more predominant.

In the alpine zone of KNP, three organic limits — precipitation, level, and edaphic factors — assume a significant part in deciding the vegetation plans. In contrast with the alpine dells of the White Mountains, the alpine locale of KNP has a lower animal groups diversity.

Table 3: Results of the Monte Carlo test: connections between species and environments

Axis	Species–environment correlation	Mean	Minimum	Maximum	p-value (pa)
1	0.960	0.889	0.799	0.935	0.0020
2	0.950	0.869	0.773	0.939	n.a.
3	0.945	0.848	0.750	0.932	n.a.

Explanation:

- "Axis" represents the different axes.
- "Species–environment correlation" indicates the correlation value between species and environment for each axis.
- "Mean", "Minimum", and "Maximum" are descriptive statistics related to the correlation values.
- "p-value (pa)" represents the p-value calculated for each axis. For Axis 2 and Axis 3, p-values are not reported (n.a.) because doing a straightforward randomization test for this axis might introduce bias.

5. Conclusion

This exploration utilized in concentrating on the alpine zone of Kangchenjunga Public Park (KNP) in the Sikkim Himalaya yielded significant bits of knowledge into vegetation design, structure, and natural impacts. Utilizing satellite data, topo maps, and on-ground observations, the study effectively categorized the alpine and subalpine zones, revealing distinct plant communities. Phytosociological analyses identified key vegetation types and their environmental associations, highlighting landscape-level variations within KNP. Influenced by the Kangchenjunga massif, regional differences were observed, impacting precipitation patterns and vegetation distribution. Ten major vegetation types were delineated, reflecting adaptation to specific environmental conditions. Altitude, rainfall, and soil characteristics emerged as primary drivers of vegetation patterns, supported by Canonical Correspondence Analysis (CCA). The study's findings underscore the significance of environmental factors in shaping alpine ecosystems, laying a foundation for future research and emphasizing conservation efforts to preserve these unique habitats in the Sikkim Himalaya.

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