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A multifaceted approach to expanding conservation efforts in the Pan-Himalayan landscape

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ABSTRACT

The Pan-Himalayan biogeographic domain is a significant region for biodiversity conservation and climate resilience. This region has both tropical and extratropical flora and holds ecological, cultural, and socio-economic importance. However, knowledge about the spatial distribution and threats to threatened plant species in the study area is still poorly known. In this study we evaluate the phylogenetic diversity and phylogenetic endemism of threatened flora in the region, and also examine the effect of rapid land cover transformation and landscape fragmentation between 2000 and 2020 on the preservation of distinct evolutionary lineages. Phylogenetic metrics provide a better understanding of ecological, historical, and evolutionary factors that shape plant communities in highly biodiverse regions. Our result show that current protected areas are insufficient for preserving Pan-Himalayan biodiversity, and also reveal a significant gap in conservation efforts within these areas. We highlight conservation priorities areas in the western Himalayan belt encompassing 2.43 million km^2 and covering 26.73% of the total area. However, a large conservation gap encompassed 22.67% (2.06 million km^2) hotspots of total study area, whereas non-hotspot priorities covered 67.62% (0.77 million km^2) of the total protected area, revealing a mismatch between biodiversity hotspots and protected areas. In addition, biodiversity priority areas have been threatened by rapid land cover transformation and landscape fragmentation between 2000 and 2020. There were 6.93% increase in cropland area and 172.64% increase in impervious surface, while an increase in landscape fragmentation and a decrease in landscape cohesion in different hotspots within protected areas. The biodiversity hotspot regions emphasize the need to conserve unique evolutionary lineages and high species occurrence areas with targeted conservation strategies. Mountainous, but cross-border international cooperation is highly recommended for effective preservation strategies. Our study has implications for advancing biodiversity preservation and sustainable ecosystem management not only in the Pan-Himalayan but also in similar regions, as well as for achieving the 2030 protection goal.

1. Introduction

Biodiversity plays a crucial role in addressing global ecological and conservation challenges and is essential for the sustainable development of human society (Xu and Zang, 2023). The ongoing pressures of human activities, combined with climate change impacts, have resulted in habitat loss and endangerment of many threatened species, with some plant species already extinct or on the verge of extinction (Dhyani, 2023; Huang et al., 2020). The increased rates of extinction have had adverse effects on the environment, ecological systems, and the provision of essential ecosystem services, making biodiversity loss a significant environmental concern with substantial economic implication (Rawat

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et al., 2022; Teitelbaum et al., 2021).

Conserving threatened plant species is becoming increasingly important because of their limited geographic range, small self-sustaining populations, and significant social, economic, and scientific relevance (Lawler et al., 2010; Wolff et al., 2023). Incorporating Rabinowitz's rarity concept into the IUCN Red List could enable research programs to develop a more comprehensive framework for conservation priorities. However, the limited availability of data on threatened plant species can pose a challenge to assessing the effectiveness of protected areas (Grand et al., 2007). Hence, identifying key protected areas and their primary challenges could enhance local, regional, and global conservation efforts for threatened plant species (Williams et al., 2022; He et al., 2023).

Establishing new protected areas is one of the first steps needed to reduce habitat loss and fragmentation, and protect ecosystems and to conserve species diversity (Santiago-Ramos and Feria-Toribio, 2021; Chowdhury et al., 2023). Moreover, the protected areas act as buffers and serve as sanctuaries and strongholds for species in the face of climate change (Mestanza-Ramón et al., 2023).

There has been a growing consensus that conservation research should prioritize regions with high ecological diversity and significant numbers of threatened plant species highlighting the importance of adopting a more integrated approach (Baral et al., 2021; Daigle et al., 2020; Zhang et al., 2015). However, most of the existing research has focused on individual factors like habitat loss, climate change, invasive species, and overexploitation (Wani et al., 2021). Previous studies have explored various ecological aspects of the region, including climate, vegetation indices (Zhang et al., 2012), species composition, elevational species richness patterns, and phylogenetic structure (Rana et al., 2019). However, there is still limited understanding of plant species diversity and conservation strategies in Pan-Himalayan protected areas. To address these challenges, the coupling and synthesis of threatened species diversity and phylogenetic diversity metrics in conservation frameworks becomes essential (Faith, 1992; Liang et al., 2023). By integrating both species diversity and phylogenetic diversity metrics, conservation efforts can obtain a more holistic understanding of the region's biodiversity, capturing both the breadth of species and their evolutionary distinctiveness. This involves incorporating these metrics in conservation prioritization frameworks for mountain ecosystems (Mishler et al., 2014; Carstensen et al., 2013). Phylogenetic diversity, which captures the evolutionary history of a region, complements species richness to provide a more comprehensive assessment of biodiversity (Faith, 1992).

The Western Himalayan region hosts species adapted to specialized habitats, especially at high altitudes (Rawat et al., 2022). Understanding the evolutionary relationships among these species provides insights into their ecological roles and conservation requirements (Liang et al., 2023). An integrated approach considering climate change, habitat fragmentation, and human activities can help identify key conservation areas in this significant landscape (Kattel, 2022; Rana et al., 2021). For example, a study in the Qinghai-Tibetan Plateau effectively integrated species distribution models, habitat suitability, and connectivity analyses to guide the establishment of a protected area network (Li et al., 2022).

Continued research is necessary to enhance methods for integrating multiple biodiversity metrics and ecological factors to support conservation decision-making in the western Himalayas. Given the region's intricate ecological complexity, its role as Asia's tallest water tower, and its unique characteristics, such research is important for a better understanding of the dynamic factors influencing biodiversity and for guiding targeted conservation efforts (Kattel, 2022; Rana et al., 2021).

Determining biodiversity metrics of protected areas, such as species richness, phylogenetic diversity, and phylogenetic endemism, therefore, could significantly enhance conservation efforts in these areas (Gumbs et al., 2022). These metrics can provide valuable insights, though they may respond differently to climate change (Zhou et al., 2023), which could be accounted for using tools like species distribution models (Peng et al., 2022).

Biodiversity conservation requires a multifaceted strategy that considers both species diversity encompassing the range of species in an area and phylogenetic diversity accounting for their evolutionary and genetic distinctiveness (Pio et al., 2014; Thuiller et al., 2011; Veron et al., 2017). Incorporating phylogenetic diversity, which captures evolutionary and genetic distinctiveness, can provide a comprehensive perspective to identify crucial areas and develop effective conservation plans (Winter et al., 2013; Matten et al., 2023; Cardillo, 2023; Manish, 2021). This holistic strategy, which considers both species diversity and phylogenetic diversity, can inform more efficient and thorough conservation strategies. By integrating both forms of diversity, a strong conservation framework is established, which has been proven effective in diverse environments. This approach is essential for preserving the biological richness of the planet and ensuring ecosystem resilience, demonstrating effectiveness in various complex landscapes, and assisting in the development of future conservation strategies (Azevedo et al., 2020; Bharti et al., 2021; Fenker et al., 2020; Mishler et al., 2014).

Identifying key conservation areas and their primary challenges could enhance regional and around the global conservation efforts for threatened plant species (Williams et al., 2022). The Kunming-Montreal Framework for Biodiversity, for example, proposes that 30% of Earth's land and ocean diversity should be protected by 2030 (CBD, 2022).

Conservation and sustainable management of the Pan-Himalayan should be a focus, as it is a globally significant biodiversity hotspot encompassing 35 worldwide biodiversity hotspots (Dhyani, 2023). Moreover, the plant diversity of this region remains poorly explored (Sloan et al., 2014), and the region also faces several challenges to biodiversity such as habitat loss and fragmentation, climate change, and overexploitation (Mehta et al., 2023). In addition, this region faces other challenges, including global warming, urbanization, resource extraction, and rapid land use change, which have conspired to lead to a decline in biodiversity and the designation of the area as eco-sensitive (Nautiyal et al., 2022).

Therefore, to address the knowledge gap regarding the distribution patterns and phylogenetic relationships of flora in the Pan Himalayan region, we focused on spatial analysis of species diversity, with an emphasis on threatened flora to elucidate the fundamental concept of large-scale plant diversity in the Pan-Himalayan. Therefore, we design our study with aims 1) to evaluate the diversity and richness of threatened plant species in the Pan-Himalayan region, and 2) to examine the geographical distribution patterns of species diversity across protected areas and understand the inherent threats posed by land use change and landscape fragmentation in different tiers in the Pan-Himalayan region.

2. Materials and methods

2.1. Overview of the study area

The Pan Himalayan domain also known as the tallest water tower of Asia, is distinguished by its immense glaciers and densely forested mountain ranges (Xu and Grumbine, 2014). The study area encompasses approximately 9.1 million km^2 and includes many countries such as India, Nepal, Bhutan, Myanmar, Afghanistan, Pakistan, and some areas within China, (particularly Xizang) as suggested in previous research (De-Yuan, 2015; Pandey and Jin, 2021)(Fig. 1). The total area of the current protected areas within the study area is 1.14 million km^2, and the land use map (Fig. S6) indicates that forests, including various forest types, cover a significant portion of the remaining landscape. This region comprises diverse habitats, such as high-altitude mountain ranges, alpine meadows, subalpine forests, and is widely recognized for its rich biodiversity and ecological and biological significance (Basnet et al., 2019; Chauhan et al., 2023; Sharma and Chettri, 2021). This region is also significant due to the convergence of China's Belt and Road Initiative (BRI) and the Kunming-Montreal Global Biodiversity

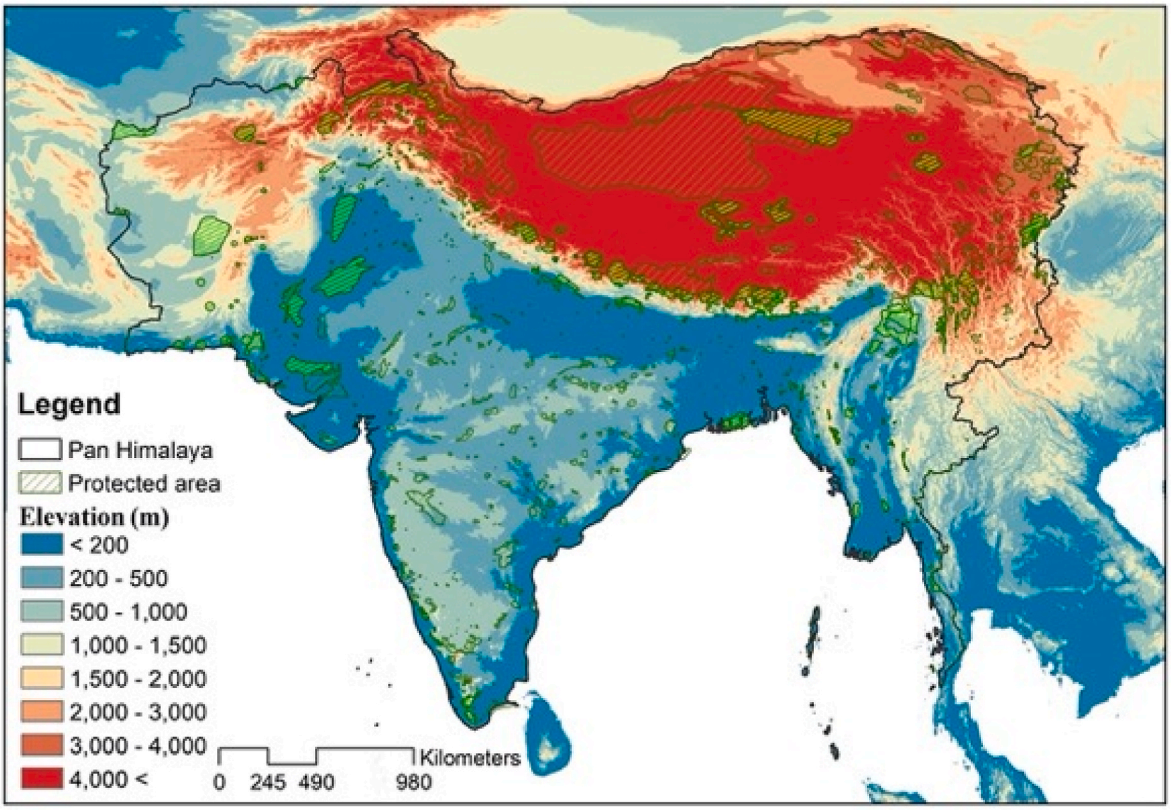

Fig. 1. Geospatial map of the study area showing the elevation and distribution protected areas in the Pan-Himalayan domain (outlined countries). Countries within the domain include Afghanistan, Bhutan, India, Myanmar, Nepal, Pakistan, and China (Xizang).

Framework, highlighting the complex relationship between conservation and development goals in this transboundary landscape (Hao et al., 2023).

In terms of biological diversity, the eastern region of the study area is reported to be more diverse in comparison to its northwestern counterparts (Chauhan et al., 2018). In addition, multiple species within the region face the imminent threat of extinction (Rawat et al., 2022). Ongoing efforts are therefore underway to conserve and enhance Pan-Himalayan plant diversity, and these efforts include the establishment of protected areas, the adoption of environmentally sustainable land use practices, and community-driven conservation initiatives (Baral et al., 2021; Basnet et al., 2019).

2.2. Framework overview

The methodology outlined in this study presents a detailed framework for evaluating biodiversity and formulating conservation strategies in the Pan-Himalayan region (Fig. 2) distributions using occurrence data sourced from various sources, such as the IUCN, GBIF, and regional Red Lists. Environmental variables are integrated into account, and correlation analysis is utilized to forecast habitat suitability. The MaxEnt model accurately predicts species distributions and elucidates the connections between environmental factors and species occurrences. The framework also assesses phylogenetic diversity and endemism by utilizing the "V. PhyloMaker" R package and Biodiverse v2.0 software to identify regions with distinct evolutionary histories.

Furthermore, biodiversity threats are evaluated by scrutinizing land use and cover data, population density changes, land fragmentation, and connectivity metrics. By amalgamating the outcomes of the MaxEnt model, phylogenetic analyses, and threat assessments, the framework identifies biodiversity hotspots and classifies them into various conservation tiers based on their conservation importance, offering guidance for targeted conservation endeavors both within and beyond protected areas. With this framework, informed decisions can be made and customized conservation policies and strategies can be developed for the Pan-Himalayan ecological landscape.

2.3. Plant species distribution location and attributes

For the current study, we extracted the distribution records of 129 threatened plant species (comprising 116 genera and 94 families) found within the study region, and which are classified as being endangered, critically endangered, and near-threatened following IUCN Red List classifications (Challender et al., 2023; Huang et al., 2020; Yao et al., 2020) (Table S1; S2). Our dataset therefore comprised of species with small distribution ranges and with high risk of becoming extinct (IUCN, 2023; Pimm et al., 2014). To analyze our data, we used 8503 georeferenced occurrence records.

We compiled information on the geographical distribution of these species point data from various reliable sources, including the IUCN Red List (IUCN, 2023), the Global Biodiversity Information Facility (GBIF) - a globally recognized repository of biodiversity information, and regional Red Lists of threatened plant (Qin et al., 2017; Yao et al., 2020), while most studied species had limited distribution ranges, we separately analyzed around 55 species with wider geographical distributions. The remaining plant species, with a narrow geographical distribution, were grouped by families sharing similar habitat and were analyzed collectively. Several species with less than five occurrence records were combined based on their habitat similarities to ensure accurate results (Tables S1 and S2).

2.4. Selection of environmental variables

We examined the spatial distribution patterns and ecological

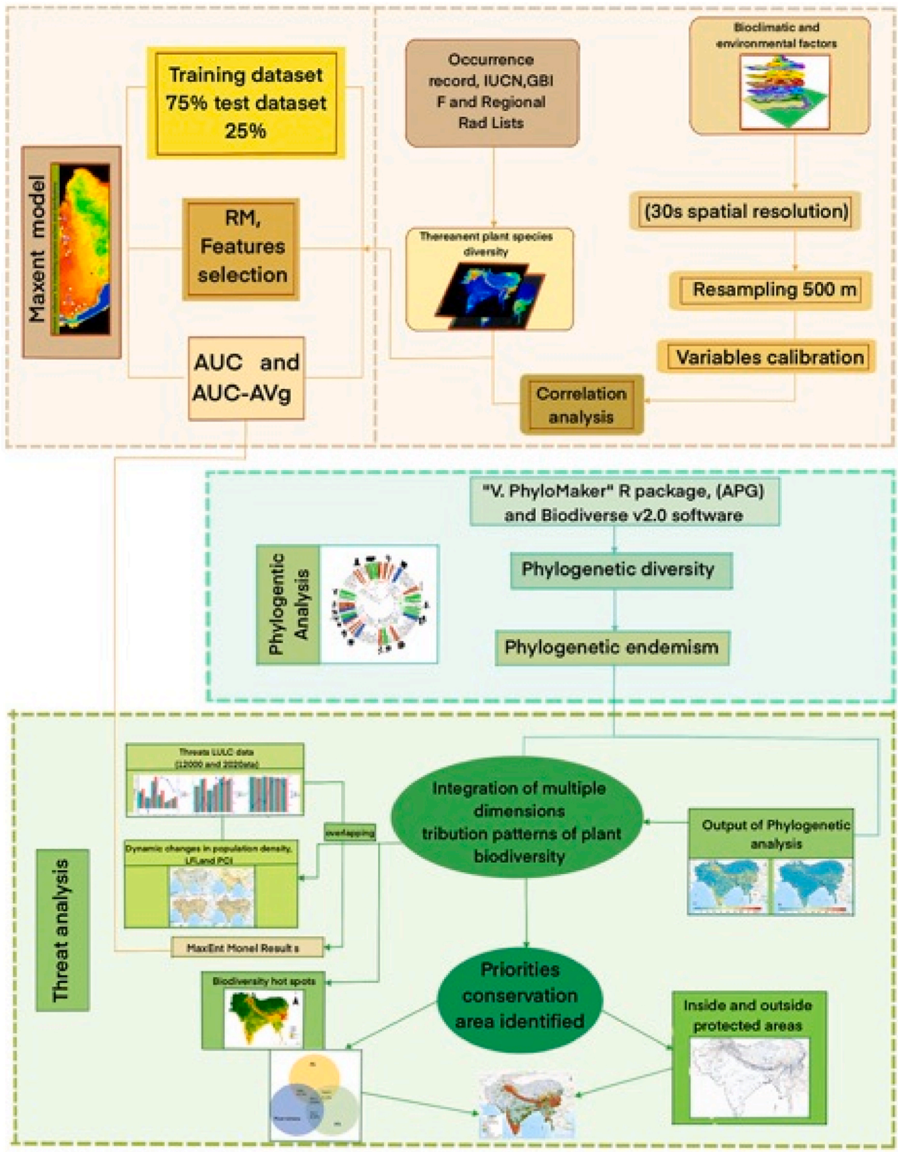

Fig. 2. The methodological workflow implemented in this study.

characteristics of threatened plant species using an extensive dataset and comprehensive selection of environmental variables. The evaluation of the suitability of a particular geographical region for a species can be accomplished through the use of species distribution models (Gaston and Garcia-Vinas, 2013). The study analyzed a dataset that included information on plant species and different environmental factors obtained from various data sources. The bioclimate factors were sourced from the WorldClim database, which provides bioclimatic variables at a spatial resolution of 30 arc-seconds (approximately 1 km). However, other variables such as land use and land cover had a higher resolution of 30 m. To standardize the resolution for all variables, we used Kriging interpolation to resample the bioclimate factors to a consistent resolution of 500 m (Table S3). This resampling process enabled the integration of bioclimate factors with higher-resolution with other variables, ensuring that all environmental variables were aligned at a standardized 500-m resolution. Subsequently, the resampled data were projected into the WGS-1984-UTM-Zones_47 coordinate system for the study area. For detailed information on the variables and their original resolutions (see Supplementary Material: Table S3). In order to minimize the interference of these variables the correlation analysis, we initially computed the correlation matrix using the pairs function in R. Subsequently, we eliminated highly collinear variables with large correlation coefficients based on previous studies (Li et al., 2021; Thakur et al., 2023). Variables with a correlation value less than 0.8 were eliminated following the methodology previously modified by (Yang et al., 2021), and finally, a total of 24 distinct climate variables were ultimately chosen for analysis (Table S3; Fig. S2). However, variables with a correlation value greater than or equal to 0.8, indicating a strong correlation, were selected from the analysis as shown in (Table S3), and a graphical representation in (Fig. S2). We also used the variance inflation factor (VIF) to identify and address collinearity. Although some variables had high VIF values, we retained them due to their importance for plant growth (Table S7).

2.4.1. *Biodiversity conservation priorities assessment*

The systematic approach to biodiversity conservation in the Pan-Himalayan region involves a combined model that considers both species diversity and phylogenetic diversity. By combining species distribution modeling with evaluations of phylogenetic diversity (PD) and phylogenetic endemism (PE), essential conservation areas can be identified by considering factors such as species richness, distinct evolutionary lineages, and ecological significance.

2.4.2. MaxEnt for species distribution modelling

We used MaxEnt to investigate plant species distribution and to investigate 129 threatened plant species distribution and the impact of various environmental factors on their distributions. MaxEnt's user-friendly interface, low sample size, quick model runtime, and ability to handle incomplete datasets make it ideal for our purposes (Srivastava et al., 2018; Tsoar et al., 2007). This modeling approach gathers target species occurrence and environmental data from the study area. Probabilistic maps were then created to characterize species suitability using Maximum training sensitivity plus specificity threshold values (Phillips et al., 2006, 2017)· Following stratification, a binary representation of the categorized probability maps was created to indicate the presence or absence of species at specific locations. This study followed (Huang et al., 2020) approach where true Skill Statistics were compared to Area Under the Curve and AUC-Avg values with the most widespread results to determine species model validity. That showed noteworthy True Skill Statistics values of 0.564–0.956 (mean = 0.779). The models' Area Under the Curve values ranged from 0.658 to 0.999 (mean = 0.986). Test AUC-Avg values varied from 0.817 to 0.999 (mean = 0.962) (Fig. 3c, Table S4). A combination of binary distribution maps revealed species' spatial vulnerability. This comprehensive study demonstrated ecological characteristics and prevalence patterns among the studied species (see Supplementary Material for complete methodology). This comprehensive modeling approach demonstrated the ecological characteristics and prevalence patterns of the plant species in the study area.

2.4.3. Phylogenetic analysis

This study integrated species distribution modeling using Maxent with evaluations of phylogenetic diversity and endemism to investigate the connections among evolutionary history, genetic diversity, and ecological functions of the plant species being studied (Faith, 2016; Qian et al., 2022).The primary objective was to enhance understanding of species vulnerability and extinction risk.

The phylogenetic tree for the study's species was constructed using the "V.PhyloMaker'' R package, which generates trees based on the Angiosperm Phylogeny Group (APG) classification system, following the approach used in previous work (Jin and Qian, 2019) (Fig. S3). We then calculated the phylogenetic diversity and phylogenetic endemism indices, using the Biodiverse v2.0 software (Crisp et al., 2001). Our analysis specifically targeted threatened species, highlighting the crucial role of conservation efforts in conserving them from extinction due to their substantial ecological importance and the abundance of valuable resources.

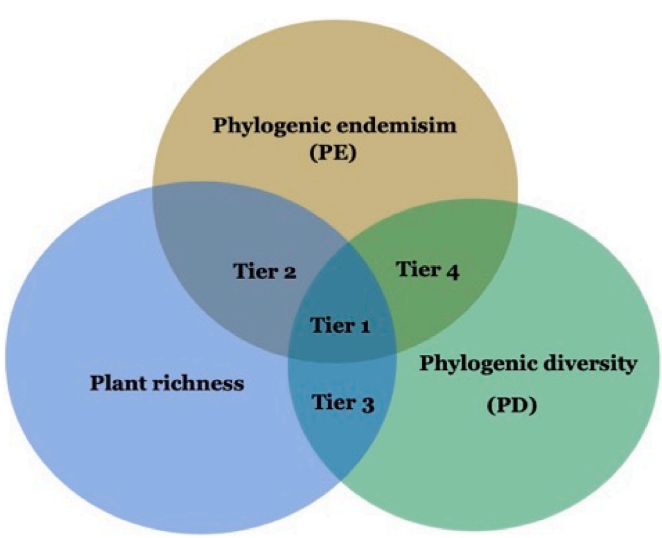

Fig. 3. Venn diagram showing relationships among threatened plant species richness, phylogenetic diversity (PD), and phylogenetic endemism (PE) across design tiers.

This targeted approach is well-justified, as threatened species often exhibit lower phylogenetic diversity than common species. Threatened plants can serve as indicator species, providing insights into ecosystem health and sensitivity (Lavergne et al., 2010; Vamosi and Vamosi, 2008). Their reduced phylogenetic diversity is likely due to restricted distributions and lack of gene exchange, resulting in the accumulation of evolutionarily distinct lineages at high risk of extinction (Davies et al., 2013; Tietje et al., 2023). Analyzing the phylogenetic diversity of these threatened taxa allowed the researchers to identify areas harboring high concentrations of unique evolutionary lineages that require urgent conservation attention.

Furthermore, the sensitivity and indicative nature of threatened plants are related to their gene expression and phylogenetic richness (Herrera, 2017; Tietje et al., 2023). Integrating the species-level sensitivity of threatened plants with an assessment of their phylogenetic diversity is a well-justified approach for prioritizing in-situ conservation of threatened plant biodiversity.

2.4.4. Conservation priority analysis

To conduct our conservation priority analysis, we combined results from phylogenetic analysis and species distribution modeling of threatened plants. This integrated methodology offered a thorough evaluation of rarity and vulnerability, guiding the development of efficient conservation strategies for the research area**.** The study used three indicators of biodiversity - species richness, phylogenetic diversity, and phylogenetic endemism - to identify priority areas for conservation. Specifically, the top 25% of the study area with the highest values for each of these indicators were selected for in-depth analysis and prioritization. This top 25% threshold is a common practice recognized in previous studies as a systematic and evidence-based method for identifying high-value areas of high ecological importance, with at least 75% of these areas deemed suitable for targeted conservation assessment and planning (Huang et al., 2020; Hughes, 2017). Based on the heterogeneity of the Himalayan landscape and align with the Kunming-Montreal Global Biodiversity Framework guidelines, we refined our spatial overlay analysis. We integrated plant biodiversity and phylogenetic evolution hotspots, both within and outside existing protected areas, while excluding extensive agricultural areas, human habitations. We set different conservation priorities. 'Tier 1′ representing the highest priority, which are the overlay areas of three types of results: plant biodiversity hotspots (based on species richness and endemism), phylogenetic evolution hotspots (based on phylogenetic diversity and phylogenetic endemism), and protected areas. The 'Tier 2′ represents areas where two of the above three results are superimposed. 'Tier 3′ represents the priority area with only plant diversity, while the 'Tier 4′ represents the priority area with only phylogenetic diversity and phylogenetic endemism. The 'Non-priorities' indicate areas with poor diversity that are unsuitable for conservation efforts. This refined approach provides a framework for gradual conservation efforts expansion, prioritizing the most critical areas while acknowledging the challenges in achieving the 30% protection goal set by the Kunming-Montreal Global Biodiversity Framework. The total protected area data was obtained from various sources, including the Protected Planet database and GADM maps database. To contextualize our conservation priorities within the global landscape, we compared our study area's conservation coverage to global figures reported by Protected Planet. Our approach aims to bridge the gap between existing protected areas and the 30% protection goal set by the Kunming-Montreal Global Biodiversity Framework (Fig. 3).

2.5. Land cover and landscape index analysis

Studying landscape metrics and land use change patterns is crucial for comprehending the impacts of changes in land cover on important or protected areas. Analyzing these landscape-level factors is crucial for understanding the challenges that changes in land cover pose to priority or protected areas. Evaluating landscape pattern indices, such as fragmentation and patch cohesion, can provide valuable insights into the spatial configuration, connectivity, and dynamics of habitats and ecosystems. This information is essential for identifying priority areas for biodiversity conservation and developing effective management strategies. To explore landscape metrics relevant to specific biodiversity priorities, categorized as "Tiers," we have identified key indicators like the landscape fragmentation index and patch cohesion index for different land cover types of conservation significance (Figs. 6 and 7). This approach allows for a more detailed evaluation of the ecological landscape and facilitates the design of targeted measures to protect biodiversity (Figs. 6 and 7). The landscape fragmentation index values indicate landscape fragmentation, while the patch cohesion index values evaluate habitat patch cohesion. Conventional methodology was used to assess land cover transformation within and outside protected areas for gap analysis (See Supplementary for details). To analyze landscape indices, we used the landscape pattern analysis software, FRAGSTATS (ver. 4.2.681), was employed. The patch cohesion index and landscape fragmentation index were used to assess the structure and evolution of landscapes (Fergus et al., 2023). They also assisted to give insights into their ecological characteristics from 2000 to 2020 (see Supplementary Table S5: Table S6). The aim was to analyze land cover and landscape indices to enhance our better understand of land cover type conversions, changes in landscape patterns, and patch connectivity within the study area.

3. Results

3.1. Investigating the multifaceted distribution patterns of species diversity

The study was conducted in the Pan-Himalayan domain using MaxEnt modeling to identify habitats, prioritize conservation efforts, and evaluate species distribution and environmental impacts (Fig. 4a). Phylogenetic analysis was used to investigate evolutionary relationships in a specific region. It focused on integrating data related to threatened flora, phylogenetic diversity, and phylogenetic endemism. These metrics focus on the evolutionary history and uniqueness of species, identifying hotspots that are not only species richness but also repositories of distinct evolutionary lineages. The region's exceptional role in biodiversity conservation highlights the urgency of enhanced conservation measures (Fig. 4b–c).

The distribution of diversity integrated hotspots for the studied plant species was prominent in the western Himalayan mountainous regions. The results revealed several areas with low diversity, "cold-spots," in Afghanistan, Pakistan, India, and some parts of China. In addition, significant hotspots distribution were identified in Myanmar, Nepal, and China (Xizang)(Fig. 4a).

A species phylogeny analysis indicated spatial variation in historical evolutionary information hotspots. The phylogenetic diversity analysis revealed a notable concentration of core hotspots with a patchy distribution pattern. These hotspots are found around the mountain ranges within the study area. The spatial analysis of phylogenetic diversity and species richness occurrences indicates spatial distribution of hotspots that are consistent, emphasizing substantial biodiversity loss and the importance of conserving distinct evolutionary lineages (Fig. 4c). While phylogenetic endemism has only demonstrated an uneven distribution of several core hotspots in western parts of the Pan Himalayan domain, particularly Myanmar, Nepal, and China (Xizang), its high variability indicates that greater conservation efforts are needed for the area (Fig. 4b).

3.2. Identification of conservation priorities and conservation gap

The results reveal that current protected areas (PAs) are insufficient to preserve Pan-Himalayan biodiversity and that there are significant gaps in conservation efforts within these areas. The proportion of the current PAs covers a total area of 1.14 million km^2. A comprehensive assessment of existing protected areas was performed by incorporating them into diverse biodiversity habitats. The integrated species hotspot results revealed that the conservation priority area covers 2.43 million km^2, accounting for 26.73% of the total area. However, a large conservation gap encompassed 22.67% (2.06 million km^2) of tiger habitats located outside protected areas. Non-hotspot priorities within PAs occupied 67.62% (0.77 million km^2) of the total PAs. We aimed to determine the extent to which these habitats serve as suitable guides for achieving the 2030 convention biodiversity goals, specifically targeting the protection of hotspots. We found that Tier 1 habitats, which are considered highly suitable and in close proximity to achieving the 30 x 30 goals for the particular importance area, covered an area of 0.91 million km^2 which accounting for 9.94% of all study areas (Table 1; Fig. 5). However, up to 82.37% (0.75 million km^2) of Tier 1 was located outside protected areas, making multifaceted hotspots for threatened species extremely vulnerable under their current conservation system (Table 1; Fig. 5).

The priority areas are categorized into different tiers based on decreasing levels of conservation priority:

Tier 1: High priority areas characterized by heightened levels of phylogenetic diversity, phylogenetic endemism, and threatened plant species.

Tier 2: Areas where two of the three main components - phylogenetic diversity, phylogenetic endemism, and the richness of threatened species - intersect.

Tier 3: Priority areas determined based on plant species richness.

Tier 4: Priority areas identified solely based on phylogenetic diversity, regardless of other biodiversity measures.

Non-priority Areas: Areas with low overall biodiversity, considered less suitable for targeted conservation efforts.

3.3. Threats in Pan-Himalayan

Land cover composition changed dramatically within the study area due to rapid land cover transformation and landscape fragmentation between 2000 and 2020, making developing conservation strategies development challenging. Threats to biodiversity within protected areas were identified, including, grassland reduction, increased impervious surfaces, and water body movements (Figs. 6 and 7). In all study areas, forest area by 29,000 km^2 (1.20% change), while grassland decreased by 4.36%, causing a loss of 110,000 km^2 of habitat for dependent species. Cropland decreased (0.87%), resulting in transformation into forest, grassland, and impervious surfaces (Fig. 7a). This finding suggests a connection between landscape changes and environmental trends, highlighting the relationship between biodiversity conservation and climate change mitigation and adaptation.

We observed significant land cover changes. Impervious surfaces increased notably, from 0.046 million km^2 (0.51% of total land) in 2000 to 0.104 million km^2 (1.14% of current land cover) in 2020, representing a substantial 1.24% rise. Furthermore, permanent ice and snow cover has grown notably by 13.58%, growing from 0.178 million km^2 (1.96% of total land) in 2000 to 0.202 million km^2 (0.02% of current land cover) in 2020, suggesting potential implications for climate change.

Over the past decade, there have been significant and rapid changes in land cover and landscape fragmentation within the PAs. There have been substantial conversions between different categories of land as a result of these transformations. Forest cover has declined by 2.56%, mainly due to the transformation of grassland and barren land and cropland into forest, accounting for 23.84% of the total land cover (Fig. 7a). Conversely, the area of grasslands has significantly transitioned into forest and cropland (Fig. 7a). This change has led to a substantial increase in cropland by 6.93%, representing 14.31% of the total land cover in PAs. Impervious surfaces increased by 172.64%, constituting 0.14% of the current land cover. Moreover, barren land has

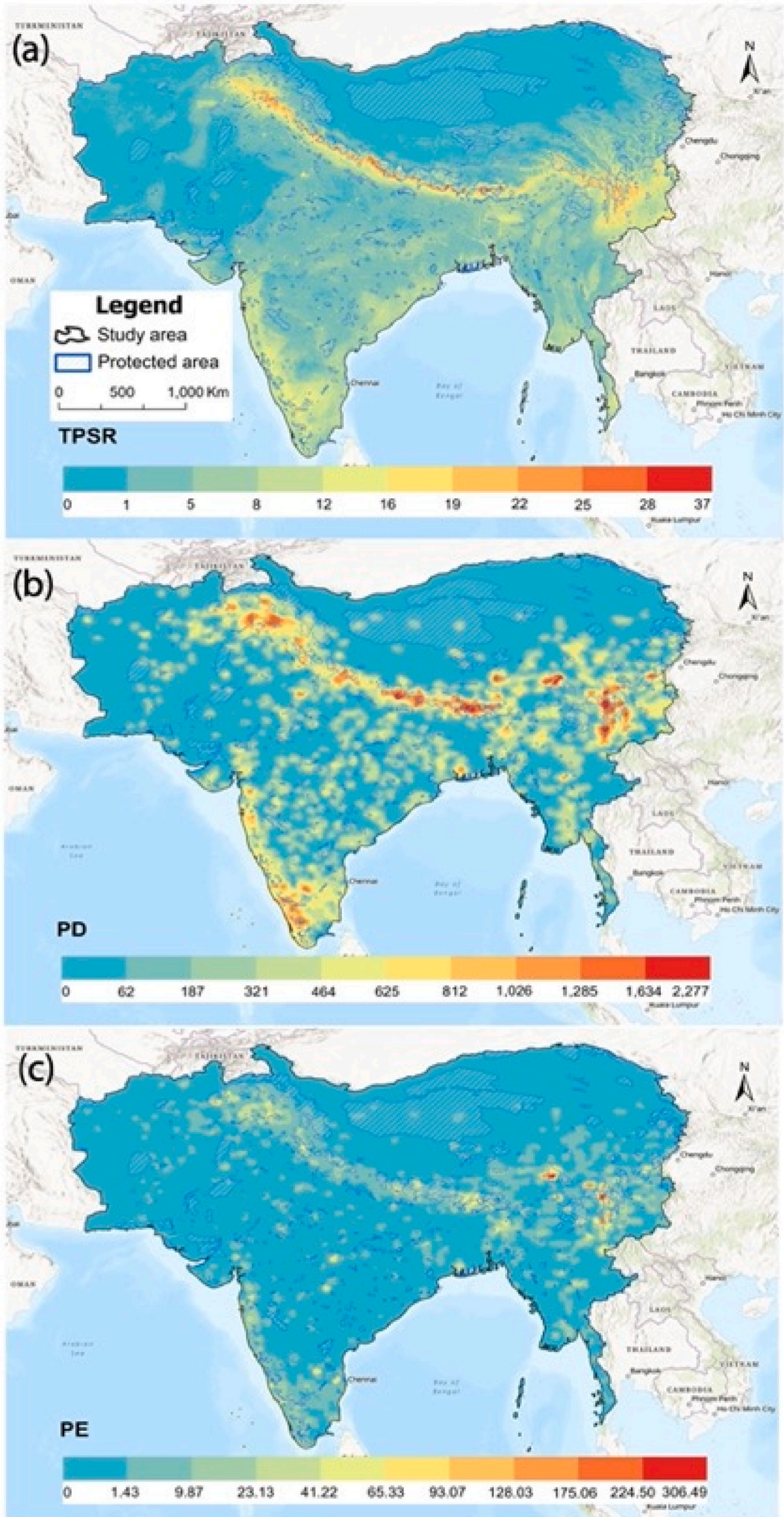

Fig. 4. Maps of (a) spatial distributions of threatened plant species richness (TPSR) (b) PD (phylogenetic diversity), (c) PE (phylogenetic endemism), in the Pan-Himalayan region.

Table 1
Conservation priorities for five biodiversity tiers, in the Pan-Himalayan, encompassing protected (PA) and non-protected areas.

Conservation priorities	Total		Area within protected area		Outside of protected area	
	Area (million km^2)	% of study all area	(million km^2)	% of PAs	Area (million km^2)	% of study-area
tier1	0.91	9.94%	0.16	14.01%	0.75	8.19%
tier2	0.63	6.96%	0.11	9.48%	0.53	5.77%
tier3	0.59	6.59%	0.06	4.87%	0.54	5.98%
tier4	0.29	3.24%	0.05	4.03%	0.25	2.74%
no priorities	3.86	–	0.77	67.62%	3.11	33.94%
total	9.11	–	1.13	–	2.43	–

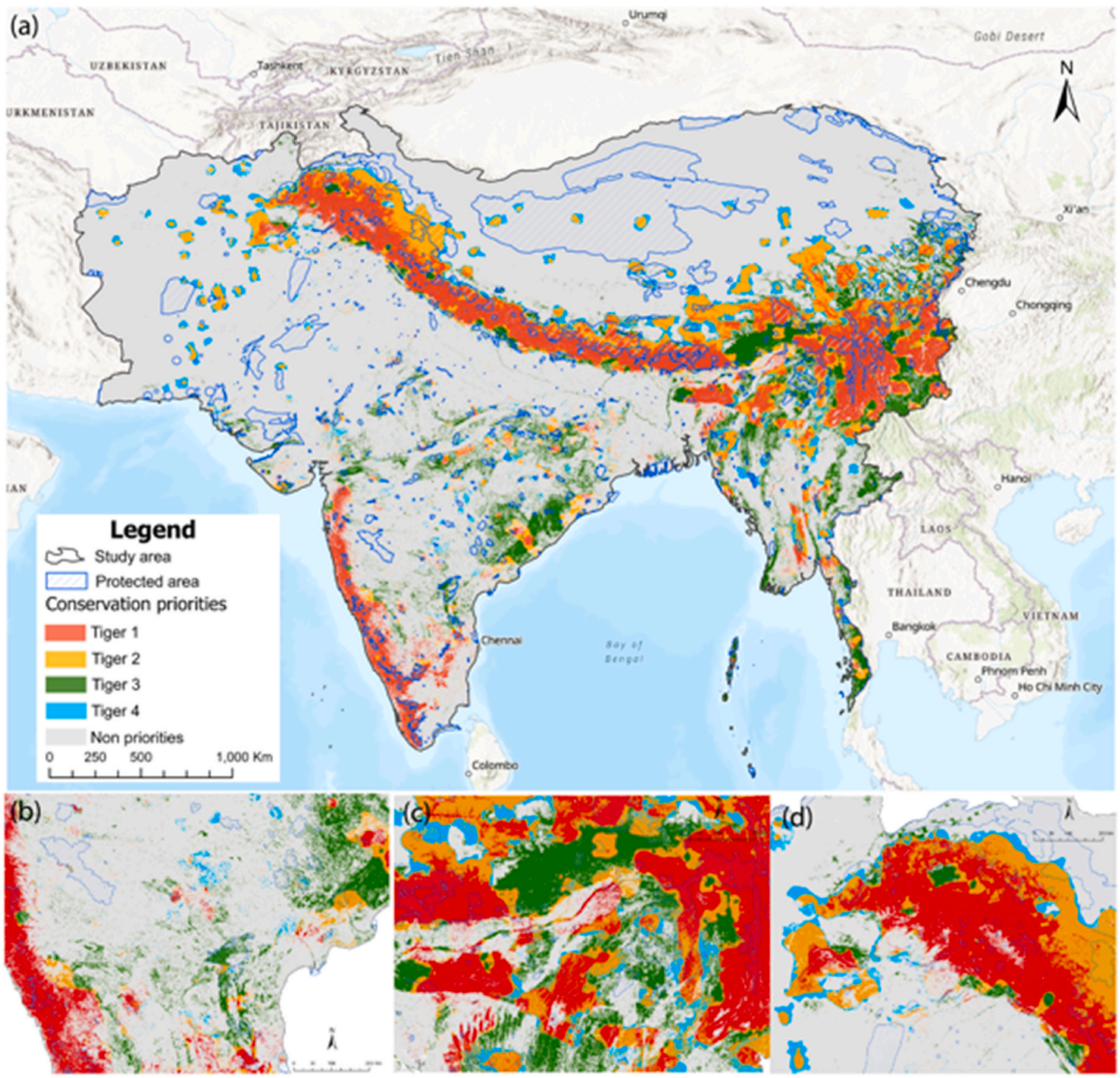

Fig. 5. Spatial distribution patterns of conservation priority areas based on phylogenetic diversity, phylogenetic endemism, and spatial distributions of threatened plant species richness within and outside protected areas; (a) Composite overlay of integrated tiers, (b) magnified view of the Southern Himalayan margin, highlighting the hotspot in the Indian region, (c) magnified view of the Northeast region hotspot, and (d) magnified view of the Western Himalayan biodiversity hotspot, emphasizing Pakistan and Afghanistan.

decreased representing 16.48% of the total arable area within PAs, primarily replaced by forests. Furthermore, there has been a 10.24% increase in permanent ice and snow cover. This accounts for 4.97% of the current land cover within the PAs, with potential implications for biodiversity.

4. Discussion

4.1. Model differences for conservation priorities

We used a multifaceted approach, combining species distribution modeling and phylogenetic analysis to investigate the distribution patterns of 129 threatened plant species across the Pan-Himalayan domain.

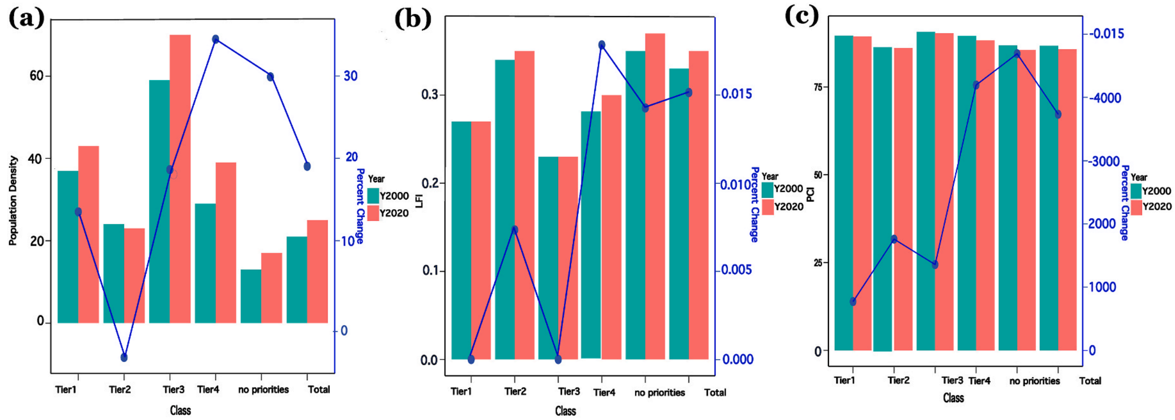

Fig. 6. Changes observed within Protected Areas (PAs) for conservation for five biodiversity priorities; (a) Human population density, (b) Landscape Fragmentation Index (LFI), and (c) Cohesion Index (PCI). 'Tier1' highest conservation priority, 'Tier2' higher level, 'Tier3' medium level, 'Tier4' low level, and 'NP' Non-priority.

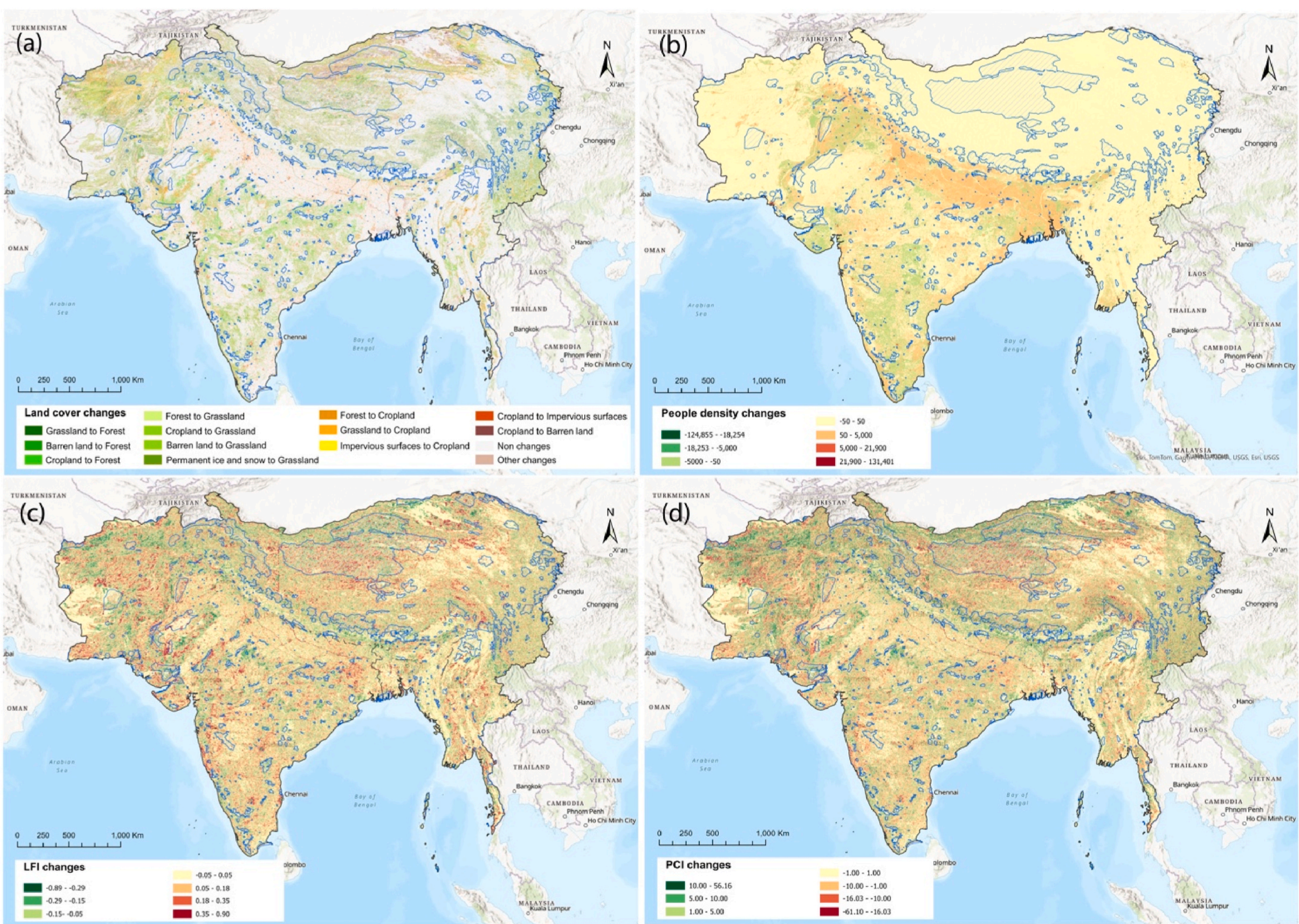

Fig. 7. Spatial patterns of various factors that threaten the biodiversity in the Pan-Himalayan domain: a) Different land cover types in the region, which can indicate the level of habitat fragmentation and degradation, b) Spatial distribution of human population across the Pan-Himalayan area. Higher population densities can lead to increased anthropogenic pressures on the natural environment, c) Landscape Fragmentation Index (LFI) which measures the degree of fragmentation in the landscape. Higher LFI values indicate more fragmented and disconnected habitats, d) Cohesion Index (PCI): This index represents the physical connectedness of the landscape. Lower PCI values suggest more isolated and disconnected habitat patches.

This integrated methodology enhanced our understanding of biodiversity patterns and conservation priorities in the study region (Cadotte and Jonathan Davies, 2010; Huang et al., 2016; Lin et al., 2021; Srivastava et al., 2018; Tsoar et al., 2007). The use of MaxEnt modeling and phylogenetic analysis in tandem proved beneficial for elucidating species distribution patterns and the correlation between phylogenetic diversity and species richness. Nevertheless, further research is necessary to assess the efficacy of these approaches in studying species evolutionary histories and guiding conservation strategies (Crisp et al., 2009; Srivastava et al., 2018). Our study identified hotspots of plant diversity, phylogenetic diversity, and endemism that are critical for conservation planning. Our analysis revealed a correlation between phylogenetic diversity and species richness, indicating that both ecological and evolutionary processes contribute to shaping biodiversity patterns. This finding is consistent with previous studies that have explored broader spatial analyses and observed that ecological and evolutionary contribute to the development of more balanced phylogenies with longer tip branches (Allen et al., 2019; Zhou et al., 2023; Carstensen et al., 2013; Tucker et al., 2019).

Major hotspots of phylogenetic endemism were identified in the core of the Himalayan biogeographic belt and Hengduan Mountains in southern India, particularly in the Hengduan Mountains, that are also transboundary areas. These regions exhibit high levels of species richness and endemism, indicating the coexistence, speciation, and long-term survival of evolutionary lineages (Fig. 4b). One advantage of using a multi-model combined strategy is its ability to overcome the limitations present in individual methods. While MaxEnt modeling is effective in predicting species distributions, it does not account for evolutionary relationships among species. Similarly, phylogenetic analysis alone may not consider ecological factors that influence species distributions. By integrating these methods, we overcame these limitations and gained a more comprehensive understanding of biodiversity patterns and conservation priorities(Crisp et al., 2009; Srivastava et al., 2018). Moreover, our study highlights the adaptability of the multi-model approach in addressing ecological challenges, especially in the context of biodiversity loss driven by climate change. Despite potential limitations in phylogenetic data quality, it can still provide valuable insights into spatial diversity patterns, which can inform conservation strategies in the face of environmental threats (Myers et al., 2021).

It is important to recognize that the advantages and unique characteristics of each model component go beyond their direct impact on biodiversity loss. For instance, MaxEnt modeling helps identify the ecological needs of species, supporting habitat restoration and management, while phylogenetic analysis reveals evolutionary relationships, aiding in the preservation of distinct evolutionary lineages. Through the integration of these methodologies, conservation decisions can be enriched by both ecological and evolutionary perspectives, leading to more effective biodiversity conservation approaches (Hamid et al., 2020; Satish et al., 2023).

Therefore, the multi-model combined strategy used in this study presents a robust framework for understanding and conserving biodiversity in mountainous regions. By integrating MaxEnt modeling and phylogenetic analysis, we identified conservation priorities but also shed light on the underlying ecological and evolutionary mechanisms shaping biodiversity patterns. Moving forward, further research is needed to enhance and validate these methodologies, ensuring their effectiveness in guiding conservation efforts amidst ongoing environmental changes (Daigle et al., 2020).

4.2. Understanding conservation patterns and priorities

The Himalayan region has been the subject of numerous biodiversity conservation research, research, particularly focused on the relationship between climate variables and vegetation indices (Zhang et al., 2012). However, there is limited knowledge regarding the influence of regional landscape factors, climate changes, and evolutionary histories that affect threatened plants in this region (Wani et al., 2021). Previous studies have consistently demonstrated an increasing pattern of species richness and diversity towards higher elevation mountain regions (Rana et al., 2019; Sharma et al., 2019; Sun et al., 2020), highlighting the importance of developing effective strategies to protect threatened plant species in these mountainous areas, which account for approximately one-third of terrestrial biodiversity (Tse-Ring et al., 2010).

Nevertheless, the fragmentation of natural landscapes has been exacerbated by different land uses, presenting a significant risk to biodiversity (Wani et al., 2021). Previous research have presented a significant risk to biodiversity (Dunn et al., 2016). However, biodiversity in the Western Himalayan remains threatened by climate change, habitat fragmentation, and other human impacts (Lin et al., 2021).

We observed scattered hotspots and modest habitat degradation within the western Himalayan domain, particularly in the mountainous region. Biodiversity is abundant in these regions, with many species with restricted distributions. To understand biodiversity hotspots in current protected area, we integrated these two dimensions of biodiversity hotspots and identified 5.15 million km^2 conservation gap outside the protected area (22.67% of the total area), indicating that the current protected areas are insufficient to preserve Pan-Himalayan endangered plant biodiversity and phylogenetic information. The results demonstrated that the landscape fragmentation index values, which measure connectivity and fragmentation, have changed over time across different biodiversity priority tiers in the Himalayan region. Tier 1 areas, characterized by high connectivity and low fragmentation, experienced a minor increase in the fragmentation index, indicating positive changes in landscape conditions that are conducive to biodiversity conservation. In contrast, the other tiers (Tiers 2–4)experienced declines in the landscape fragmentation index, signaling deteriorating landscape quality for these priorities. Additionally, the "No Priorities" tier showed a substantial decrease in the landscape fragmentation index, indicating a pronounced adverse transformation in the overall landscape condition. These results highlight the need to reevaluate conservation strategies in the Himalayan region. Extending protection of Tier 1 habitats which have been characterized by high connectivity and low fragmentation, outside protected areas for the conservation of threatened species. Integrating biodiversity, ecosystem sensitivity, and landscape fragmentation data can help efficiently prioritize positive conservation gains in this region (Figs. 6 and 7).

According to the current protected area in the Pan Himalayan domain, this study constructed priorities for flora diversity and phylogenetic diversity, which can guide future expansion patterns to achieve the 30% conservation target set by the Convention on Biological Diversity by 2030. The Tier 1 habitat was identified as the most effective landscape for achieving this goal.

The study investigated the impact of 24 key environmental variables including bioclimatic factors, geographical factors, vegetation characteristics, and soil properties, on various aspects of biodiversity in the Himalayan domain. Variables such as isothermally (bio-03), precipitation seasonality (coefficient of variation) (bio-15), organic carbon content (oc), and soil pH (PH) exhibited a significantly higher contribution to the percentage contribution. These variables, tied to climate and soil characteristics, hold crucial roles in shaping the landscape and its suitability for diverse plant species. On the other hand, annual mean temperature (Bio-1), elevation (eve), primary production products (NPP), nutrient availability (Nurt), soil water regime (swr), total phosphorous (tp), and rotting were found to significantly contribute to the permutation importance (Fig. S.4), This comprehensive analysis highlights the relationship between biodiversity conservation and climate change mitigation and adaptation, as the integration of environmental variables, landscape indices, and land use changes allowed the identification of critical challenges to biodiversity conservation, such as landscape fragmentation and shifts in habitat suitability. These analyses confirm prior findings that temperature-related climatic variables dominate flora distribution in the northwestern Himalayan (Schickhoff et al., 2014). The understanding of conservation patterns and priorities in the Himalayan region is driven by a combination of environmental variables, landscape metrics, and historical evolutionary information. The current conservation gaps and the influence of landscape fragmentation on priority area construction and diversity patterns underscore the urgent need for comprehensive conservation optimization strategies, including the expansion and management of protected areas.

4.3. Policy and conservation recommendations

The Pan Himalayan domain exhibits an abundance of ecological and biological diversity, influenced by factors such as altitude, climate, and geographical variations (Shrestha et al., 2023). However, there has been debate over the most effective method for identifying conservation hotspots (Xie et al., 2022).

Our results indicate that the mountains provide the majority of suitable habitats for the studied species, with the central and northern mountainous regions exhibiting the highest diversity. However several hotspots remain unprotected due to small PAs in priority areas. In our assessment, protection levels for every biodiversity priority tier - including Species Richness, Phylogenetic Diversity, and Phylogenetic Endemism - should increase to achieve 30% global biodiversity protection by 2030, as priorities at the national level play a key role in formulating effective biodiversity conservation strategies (Bai et al., 2021).

Firstly, we propose to optimize the protected area system by effectively expanding and optimizing the scope of current PAs to address identified conservation gaps. Our study suggests that 26.73% of the total area is protected, mainly in the western Himalayas. However, there is a significant gap of 32.38% (2.06 million km^2) between hotspot and non-hotspot priorities.

Secondly, we suggested establishing cross-border collaborative mechanisms for biodiversity conservation in the Pan Himalayan region is essential due to the mountain range covering multiple countries, and many important biodiversity hotspots and priority conservation areas across international borders. Effective conservation requires coordinated, transboundary efforts. Moreover, this area is a key focus for China's Belt and Road Initiative and the goals of the 15th Conference of the Parties on biodiversity conservation, underscoring the interconnectedness between conservation and development objectives in this transboundary landscape (Bai et al., 2021; Dong et al., 2022). Long-term intergovernmental cooperation and communication are imperative for the establishment of transboundary biodiversity corridors to effectively conserve and uphold regional priorities and targets.

Thirdly, we suggested that immediate species surveys and monitoring are needed to establish baseline data on biodiversity conservation strategies. The Pan Himalayan region is a key biodiversity hotspot with high percentages of threatened species, and providing a basic dataset will assist in implementing comprehensive conservation measures, such as in-situ conservation, ex-situ conservation, and population reinforcement or reintroduction (Ishtiaque et al., 2017).

4.4. Overcoming limitations and future conservation innovations

The assessment of simulations for the Pan-Himalayan threatened species hotspot involves use of multiple data sources. Our study was therefore constrained by certain limitations. Due to limited data availability, vulnerable species as defined by the IUCN were excluded, and our detailed analysis focused on a select subset of 129 species representative of the Pan Himalayan domain (IUCN, 2023). Conservation efforts are impeded by a lack of comprehensive data on species distribution range, population status, and ecological requirements (Bradie and Leung, 2017). The data presented here are not exhaustive but attempts to partially emphasize conservation needs. In our methodological approach, we employed the variance inflation factor (VIF) tests to assess multicollinearity among predictors. Despite some variables exhibiting high VIF values, we retained them based on their established ecological significance for plant growth. This decision was grounded in the principle that excluding ecologically relevant variables could potentially lead to model misspecification. However, we acknowledge that this approach may introduce complexities in model interpretation and could be refined in future studies. Our innovative phylogenetic analysis demonstrates substantial divergence among species, emphasizing the necessity of conducting thorough resource surveys, monitoring, and establishing protected area species lists. This approach will enhance our understanding and and facilitate more targeted conservation efforts. Some species are not on the IUCN Red List, requiring species-specific evaluations for resource allocation and conservation priorities. Government organizations, researchers, and local populations need to plan and collaborate on uncoordinated initiatives.

5. Conclusion

In our study, we provide a compelling argument for immediate and resolute conservation efforts in the Pan-Himalayan domain as most species' potential habitats remain unprotected. Conservation priorities cover only 26.73% of the total area, mainly in the western Himalayan region. However, existing 21.26% (2.06 million km^2) and non-hotspot priorities cover 67.62% (0.77 million km2) of unprotected areas, revealed that current protected areas (PAs) are insufficient to preserve Pan-Himalayan endangered plant biodiversity and phylogenetic information.

This mismatch between biodiversity hotspots and protected areas results in a significant portion of these species being at risk. The spatial consistency of endangered plant diversity with phylogenetic diversity and endemism in the Pan-Himalayan was identified, with major hotspots in the core of the Himalayan biogeographic belt, Hengduan Mountains, where prominent phylogenetic endemism hotspots exist. Our study provides a comprehensive understanding of multiple factors and highlights the urgent need for protected areas throughout constructed priorities for endangered plant diversity and phylogenetic diversity to guide future expansion patterns in the Pan Himalayan region. Additionally, our phylogenetic analyses provide an effective framework for determining biodiversity conservation priorities that considers both biodiversity and evolutionary values. The priority conservation areas we have identified, and the dynamic land use changes highlight the establishment of a solid foundation for adaptive conservation measures. Biodiversity is threatened by a 6.93% increase in cropland and a 172.64% increase in impervious surfaces. In addition, there is increased landscape fragmentation and reduced cohesion in protected areas from 2000 to 2020. Mountainous but also cross-border landscapes in particular, need urgent targeted conservation interventions, which could be accomplished through the establishment of ecological corridors and the expansion of protected areas. These conservation initiatives can be expanded to cover broader transboundary regions as a model for global biodiversity conservation.

CRediT authorship contribution statement

Maroof Ali: Writing – original draft, Investigation, Formal analysis, Conceptualization. **Zhongde Huang:** Software, Methodology. **Yang Bai:** Writing – review & editing, Validation, Supervision, Funding acquisition. **David Y.P. Tng:** Writing – review & editing, Resources, Methodology. **Fei Qin:** Software, Resources. **Zhou Fang:** Resources, Methodology.

Declaration of competing interest

No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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