Solving the “species bias” to facilitate orchid multi-scenario conservation planning in the south of the Hengduan Mountains

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Abstract

detailed analyses of specific taxonomic groups at finer geographic scales to identify and prioritize biodiversity hotspots is a prominent method for optimizing conservation efforts, especially for the uneven species richness. The ecological suitability prediction and analysis of representative species provide vital references for conservation planning. Yet, in predicting suitability for multi-species or groups by species distribution models (SDMs) under a highly heterogeneous environment, species bias may occur cause of the unequal protection status and the spatial autocorrelation processing of occurrence data. For this, diversity, and protection hotspots were mapped in the south of the Hengduan Mountains, a significant site for global biodiversity. Specifically, creating a network of 1 km^2 grid cells spanning the region, counting the orchid species, quantifying the protection value, and classifying attributes by the Jenks. And 5 km and 10 m buffer zone for each grid containing attributes compose the diversity and protection hotspot layers and were compared with the orchid suitability map modeled by SDMs. Results showed that even though there were extensively suitable habitats for orchids, the model results cannot completely cover whole the diversity and protection hotspots at any scale. Based on the map attributes, multi-scenario conservation planning was proposed. This study identifies the critical areas of suitability, diversity, and protection of orchids in this region, providing a meaningful reference for regional biodiversity conservation planning and producing a migrated method for biogeographic analysis in global biodiversity hotspots not just orchids. Besides, the results will supply crucial regional information for global biodiversity conservation.

Introduction

Biodiversity loss is an unavoidable and pressing concern (Lefcheck et al., 2015; Oliver et al., 2015; Wallington et al., 2005). Identifying biodiversity hotspots and priorities is significant for global biodiversity conservation. Empirical studies advise that biodiversity is unevenly distributed globally, and even within biodiversity hotspots, micro-hotspots exist (Brooks et al., 2006; Cañadas et al., 2014; Jenkins et al., 2013; Marchese, 2015; Murray-Smith et al., 2009; Zhang et al., 2015a). Accordingly, finer conservation planning within global hotspots detail is necessary and fundamental to coping with global warming and regional differences.

The Hengduan Mountains are a critical area of international significance for biodiversity, a priority for global biodiversity conservation, and one of the most diverse mountain areas on earth (Brooks et al., 2006; Chen et al., 2018; Marchese, 2015; Reid, 1998; Wambulwa et al., 2021; Xing & Ree, 2017). Its south is one of China's 35 priority biodiversity conservation areas. The enormous number of endemic species and their abundance of taxa are noteworthy (Han et al., 2022; Wang et al., 2012; Yu et al., 2020; Zhang et al., 2021). Taxonomically, the orchid family (Orchidaceae Juss.) is remarkably well-represented here, occupying an essential section of the local and national flora (Zhang et al., 2015a). From the biologically evolutionary aspect, most orchids are in an actively evolving and specializing process. Their conservation means the protection of future biodiversity to a certain extent (Luo et al., 2003). Success was demonstrated in Costa Rica, Central America, where the authors used species distribution models (SDMs) to investigate the spatial distribution and potentially suitable habitat of local orchids, finally identifying crucial areas for conservation (Crain & Fernandez, 2020).

SDMs are a common and vital tool for conservation planning via establishing the relationship between environmental and occurrence data to predict suitable habitats for target species (Anibaba et al., 2022; Crain et al., 2014; Evans et al., 2020; Gogol-Prokurat, 2011; Guisan & Thuiller, 2005; Hemrova et al., 2019; McCune & Baraloto, 2016). Usually, to obtain better model performance, researchers perform spatial autocorrelation processing of occurrence data to address sampling bias (Araújo & Guisan, 2006; Eyre et al., 2022; Loiselle et al., 2007; McCune & Baraloto, 2016). This treatment is effective when simulating a single species, but when multiple species or a taxon are being targeted, we consider that "species bias" may occur. Species bias may present in two situations. One, where conservation status differs among species (such as the endangerment level or endemism), and second, under high environmental heterogeneity conditions, where any threshold setting may result in the exclusion of some valuable species from the models.

Mapping the geographical spatial distribution and evaluating the species protection value were used to address this bias. Combined with orchids' ecological suitability, the ultimate objective of this study was to identify conservation hotspots and generate multi-scenario conservation plans for the south of the Hengduan Mountains (an overview of the study showed in Fig. 1). We aimed to answer the following questions: 1) How are orchids distributed in the southern section of the Hengduan Mountains, and where do diversity and protection hotspots occur? 2) Are there deviations among these hotspots? 3) What conservation planning is adopted for the different regional attributes? The results of these analyses will support the identification of orchids habitat sites in the southern section of the Hengduan Mountains, the assessment of protected areas, and improve our understanding of the underlying biogeographic distribution patterns in local, Central Asian, and even other global biodiversity hotspots. In addition, our conservation planning efforts in the region will be supposed to provide geographic evidence to support biodiversity conservation globally.

Material And Methods

Data collection and processing

The species occurrences came from field investigation and specimen collection. The orchid plots we recorded from 2020 to 2022, meanwhile, we used the specimen records (containing possessed accurate coordinates and photos) from the National Specimen Information Infrastructure (NSII, http://nsii.org.cn/). All of these were used to build our orchids' occurrence data for the south of the Hengduan Mountains, which included 4301 distributions and 192 species. For running in the species distribution model, the spatial autocorrelation distance was limited to 1km, remaining 1922 occurrences to model.

Considering biological and abiotic variables comprehensively that may affect the orchid's geographical distribution will improve the model performance. Bioclimatic factors were our primary consideration. The

Worldclim database (Fick & Hijmans, 2017) provides the latest 19 bioclimatic variables. After the Pearson correlation analysis reduced the variable autocorrelation to eliminate factors ($|r|>0.7$), five variables were involved in our model. Thinking about the potential effects on orchids' physiology and ecology, local vegetation, terrain features (elevation, slope, and aspect), and four topsoil properties were modeled as environmental variables (Crain & Fernandez, 2020; Djordjevic et al., 2020; Figura et al., 2020; Wieder et al., 2014). Complete variable information was shown in Appendix S1.

Species distribution model

The maximum entropy model proposed by Jayne (Jaynes & Cummings, 1963) is widely used for predicting potential distribution and evaluating suitable habitats of target species. When the entropy value is maximum, the redundant information will be eliminated and the probability value of species existence will be generated, usually between 0–1. The two most important parameters of the model are the Feature combination (FC) that contains Linear (L), Quadratic (Q), Product (P), Threshold (T), and Hinge (H) and the Regularization Multiplier (RM). Users can generate hundreds of model compositions randomly. We used the R package ENMeval to carry out the prediction operation of different parameter settings and generated a series of significant models with omission rates lower than 0.05. According to the Akaike Information Criterion (AICc), the FC and RM corresponding to the minimum value will be used for the model.

The Maxent model also produces background points (pseudo-absences, PA) to establish a functional relationship with environment variables. To reduce spatial sampling deviation, our PAs were selected preferentially from the highest density in this occurrence data kernel density function. In MaxEnt 3.4.4, we set optimized FC and RM, chose the Random seed, divided 75% of the data for training while 25% for testing, used the area under the Receiver Operating Character Curve (AUC) to verify model performance, and modeled 10 times. From the results of the most performance model, we reclassified probability (0.4, 0.6], (0.6, 0.8], and (0.8, 1.0] into the low, medium, and high orchids suitable areas respectively ($S_H>S_M>S_L$).

Mapping orchid geographical diversity hotspots

All occurrences were imported into ArcGIS 10.1 (Environmental Systems Research Institute, 2011) to generate a raster representing the distribution of orchids. A network of 1-km^2 grid cells spanning the study area was created, and the number of species in each cell was quantified. Do ensure the uniqueness of species in the same pixel during the statistical process. Jenks Natural Breaks Classification (Jenks) was used to divide the richness grids into three levels, representing different degrees of geographical abundance patterns (R1 > R2 > R3). Each pixel with richness attributes was regarded as a geographical protection point, and based on these, spatial analysis was applied to generate 5 km and 10 km protection buffer zones individually. The resulting layers were used as the input feature in the final conservation planning scenarios ($R1_5$, $R1_{10}$, $R2_5$, $R2_{10}$, $R3_5$, and $R3_{10}$).

Orchids protection value evaluation

The evaluation of orchids' protection value includes two meanings in our study: protection level and endemic species. For the protection level, referring to the Red List of Endangered Species which is rated by the International Union for Conservation of Nature (IUCN) and classified into nine levels, including Extinct (E), Extinct in the Wild (EW), Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), etc. And the List of National Key Protected Wild Plants in China revised version in 2021, representing the current important and endangered wild plants in the country. The endemism characteristic was defined by endemic species distributed in China and the specific regions (the southeast end of the Qinghai-Tibet Plateau, the eastern part of the Himalayas, and the southern end of the Hengduan Mountains. From the perspective of geopolitics, location in Tibet, Sichuan, and Yunnan in China, Nepal, northern India, Bhutan, etc.)

We used the difference score of 1–7 to evaluate each species for obtaining those protection values, as shown in the following table. Based on the created network grid, we quantified the protection value for every grid cell. Of course, the uniqueness of species in one pixel was ensured. The same reclassification and buffer methods as richness mapping were adopted (P1 > P2 > P3), to generate protection demands layers for conservation planning eventually ($P1_5$, $P1_{10}$, $P2_5$, $P2_{10}$, $P3_5$, and $P3_{10}$).

Table 1
Scoring standard of species protection value. " " and " " means the first-class and the second-class national protection species in China. "√" means it's an endemic species belonging to this category.

	1'	3'	5'	7'
The Red List of Endangered Species	NT	VU	EN	CR
The List of National Key Protected Wild Plants	/	/	/	/
The national endemic species	/	/	/	√
The specific regions' endemic species	/	/	/	√

Multi-scenario conservation planning

When conservation management authorities are faced with difficult issues such as economic development and biodiversity conservation, especially in less economically developed countries and regions, a multi-scenario conservation planning program is an important tool to provide scientific reference for policy choices with different tendencies on the premise of ensuring species diversity and curbing biodiversity loss. We conceived three conservation scenarios using overlay and fusion spatial analysis. The strict conservation scenario (SS) represents the most suitable habitat and the narrowest ranges for geographical distributions and endangered species ($SS = S_H+R1_5+R2_5+R3_5+P1_5+P2_5+P3_5$). The economical conservation scenario (ES) is a compromise that considers location economic and limited protection resources. And the richest geographical distributions and the most protective species take the maximum protection ($ES = S_H+S_M+R1_{10}+R2_5+R3_5+P1_{10}+P2_5+P3_5$). The positive conservation scenario is the most ecologically friendly form, protecting all suitable habitats and all 10 km protection buffers ($PS = S_H + S_M + S_L + R1_{10} + R2_{10} + R3_{10} + P1_{10} + P2_{10} + P3_{10}$).

Results

Species distribution model results

The ENMeval results showed that the best model parameter FC was LQHPT, and RM was 5. The AUC of the adjusted MaxEnt model was 0.816. Whether for the training and test sets, the model accuracies were higher than the random prediction, indicating that the model had a high-quality performance. Combined with the jackknife test of variables, the most important environmental variables affecting the geographic distribution of orchids were vegetation, elevation, and bio10 (see Appendix S1 for details).

Mapping of different levels of suitable habitat, the results showed that the highest suitable area was 14145.64 km^2 (6.53% of the study area), the medium suitable area was 42536.02 km^2 (19.62% of the study area), and the lowest suitable area was 59824.96 km^2 (27.60% of the study area). Geopolitically, we mainly focused on the county level. The first two levels of habitat were mainly distributed from Mianning and Yangyuan counties in the eastern part of the study area across the central (Muli County, Shangri-La City, and Ninglang County) to Gongshan County in the west. In the southeast corner of the map, distribution centers were also formed. Combined with the variable response curves (see Appendix S1), Most vegetation types in the study area were suitable for orchids (more than seventy out of 96 types), but only five types belonged to the highest suitability. Elevation was negatively correlated with habitat suitability, and the model showed that areas below 4600m were more suitable. According to the mean temperature of the warmest quarter (bio10), between 0℃ and 17℃ shown as a nearly smooth horizontal line on the graph representing the high suitability for orchids, but falls precipitously above 17℃ and was unsuitable for distribution above 26℃.

The diversity hotspots and orchids protection evaluation

The hotspot analysis identified 346 grid cells as significant geographical protection points. Through grading, there were five primary grid cells, 23 secondary grid cells, and 314 tertiary grid cells, with respective ratios of 1.4%, 6.65%, and 90.8%. Geopolitically, the clusters of hotspot cells emerged in Muli, Yangyuan, and Dacheng counties (the central part of the study area). For example, a priority cluster formed in the Muli Mountain Plain (generally in the subtropical montane coniferous forest area between 2200 and 3800 elevations) belonging to the Hengduan Mountains. The other two sub-priority clusters occurred in the southern part of the Shaluli Mountain System and the western slope of the Great Snowy Mountains, distributed along the mountain vertical zone (generally between 1700 and 5000 elevations). The orchids protection evaluation screened 239 points, of which 12 (5.0%) were primary grid cells, 25 (10.5%) were secondary grid cells, and 202 (84.5%) were tertiary grid cells. Its overall spatial distribution pattern almost coincided with the hotspot layer, but the priority and sub-priority of the cell clusters were different. The original sub-priority belonging to Dacheng and Muli changed to the priority. And while the

Yunnan Xiaoliang Mountains in Ninglang County and the Daliang Mountains in Yajiang formed new sub-priorities. Collectively these areas comprising 347 km2 represented the most significant orchid diversity and protected hotspots in the regions.

Notably, although the SDM results in the western and southeastern portions of the study area indicated highly suitable habitats, the diversity and protection evaluation did not result in significant cell clusters. Conversely, the sub-priority of protection value formed in the northeastern corner was not identified as priority cells by the model.

Spatial analysis between different maps

Spatial analysis of all layers was performed using Arc Map to calculate the centroids and their mutual offset distance (see Fig. 3). All centroids were distributed in Muli, Yulong, and Shangri-La city. Mapping the different attribute characteristics (S, R, and P) showed a similar spatial distribution pattern. For example, the centroid of all layers classified as priority emerged east part, and the corresponding attributes gradually decreased as they headed westward, forming the distribution cores of secondary layers. For the layers with the same attributes and different classifications, the habitat suitability gradually decreased from southeast to northwest, while other centroids (R1, R2, P1, and P2) were located near the Muli Mountains Plain and close to each other. Besides, they were far away from the center of the R3 and P3. Indicating the orchid's diversity and protection value gradually decrease from the eastern and northeastern to the southwest in our study area. For the layers with different attributes at the same level, in the primary and secondary layers, the centroid of mass of the suitability layer distribution was skewed to the northwest and more than 90 km away from the diversity and protection hotspot centroid at the same level, while in the tertiary layers, them close to each other and similar to the overall layer center of mass distribution (each point was within 40 km). Resulting that although the species distribution model makes High-accuracy performance for species suitability habitat, it may be influenced by a large number of "low-quality" (here, we mean species with wide distribution and low conservation value) occurrence data to form suitability cell clusters, generating the spatial bias between species diversity and protection hotspot.

In addition, we intersected the diversity and conservation hotspot layers at each level sequenced, based on the suitability map, to calculate how many areas were not included in the suitability model results. The habitat layers could not fully cover the hotspot areas, at any scale, even based on the smallest 5 km of the most strictly protected buffer zone. The maximum spatial deviation is as high as 38822.98 km^2, and the minimum deviation area is 7.64 km^2 (see detail in Appendix S2).

Conservation planning scenarios

According to the three conservation planning scenarios envisaged, the strict conservation planning scenario covered an area of 28,780.32 km^2 (13.28% of the total study area), the economic conservation planning scenario covered an area of 65,797.16 km^2 (30.35%), and the positive conservation planning scenario covered an area of 130,201.76 km^2 (60.07%). Analyzing the maps, four large clusters were shown (Fig. 4). Cluster I and Cluster III were located in the southwestern corner and western part of the study area, respectively, and belong to the southern and northern sections of the Gaoligong Mountains, which are influenced by the southwestern monsoon and have abundant precipitation. The lowest elevation of the southern section is only a few hundred meters, providing suitable habitat for a large number of orchids with tropical floristic composition. Cluster II belonged to the Jinsha River basin (Yalong River DC), and species differentiation is intense in the region, which was the core of diversity and protection hotspots. We considered the relatively fragmented cells distributed along the river valley in the northwestern part of the study area as a conservation cluster (Cluster IV), which provides suitable habitats for orchids at high altitudes and maybe become important corridors for the dispersal and migration of orchids.

Discussion

Orchids distribution models

Like most terrestrial biodiversity hotspots worldwide, orchids hold a prominent place in the flora of the Hengduan Mountains (Crain & Fernandez, 2020; Crain & White, 2013; Parsons & Hopper, 2003; Perez-Escobar et al., 2017; Souza Rocha & Luiz Waechter, 2010; Vollering et al., 2016; Zhang et al., 2015b). Since orchid centers of diversity frequently correspond to hotspots of other species groups, prediction and analysis of their suitability provide an available approach to knowledge of plants' fundamental geographic distribution patterns in biodiversity hotspots, and it also would provide ancillary benefits for biodiversity conservation beyond orchids (Anderson et al., 2008; Seaton et al., 2010; Souza Rocha & Luiz Waechter, 2010; Xing & Ree, 2017). Considering the broad ecological fitness of orchids (widely distributed in terrestrial ecosystems other than polar and extremely arid deserts) (Souza Rocha & Luiz Waechter, 2010) and their critical conservation status (all wild orchids are CITES-listed) (Luo et al., 2003), the protection value among different orchids should be fully expressed when using the SDMs for habitat analysis. In addition, due to the specificity of orchids to their environment and their adaptation to microhabitats (Kaur et al., 2021), the omission of model-predicted results caused by the species bias after performing spatial autocorrelation to occurrences in hotspots with high environmental heterogeneity should be allowed to be considered. Consequently, our methodology provides a valuable and comprehensive framework for spatial planning of conservation patterns in orchid hotspots based on ecological suitability. Of course, this approach is also applicable to the protection value assessment and hotspot analysis of orchids in other hotspot areas and supports relevant studies on biodiversity conservation for species groups with similar attributes.

Orchids geographical patterns and their influencing factors

The southern section of the Hengduan Mountains is geographically diverse, experiencing long periods of complex and rapid geological movement, resulting in rugged topography and significant environmental heterogeneity (Marchese, 2015; Wang et al., 2012; Yu et al., 2020). These features favor higher levels of plant diversity and rich pollinator pools for species dispersal and diversification (Acharya et al., 2011; Crain et al., 2014; Rewicz et al., 2017; Zhang et al., 2015b). The broad geographic specialization and species formation opportunities provided for orchids can contribute to explaining their wide distribution in the study area. It would also be consistent with the assertion that habitat heterogeneity is often considered an important driver of diversity (Crain & White, 2013; Perez-Escobar et al., 2017). Examples of orchid diversity studies in Central and South America indicate that the rapid growth of mountain ranges, volcanic activity, and glaciation at high altitudes proved to be the main drivers of orchid evolution and speciation (Crain & Fernandez, 2020; Dodson, 2003; Kirby, 2011).

The significance of vegetation and elevation as prominent elements affecting orchid suitability has been confirmed in research worldwide (Acharya et al., 2011; Bernardos et al., 2007; Borrero et al., 2022; Djordjevic et al., 2020; Faruk et al., 2021; Hemrova et al., 2019; Jacquemyn et al., 2008; Perez-Escobar et al., 2017; Souza Rocha & Luiz Waechter, 2010; Timsina et al., 2016; Vollering et al., 2016). The existence of differentiated vegetation types composed of different population-building species, given the ecological pattern of regional habitats, implies that for a particular orchid, the same vegetation type may contain more potentially suitable, specialized microenvironments (such as soil with the mycorrhizal environment, stable pollinators, appropriate hydrothermal conditions) (Djordjevic et al., 2020; Kelly et al., 2013) for population development and dispersal. The difficulty of crossing natural geographical barriers created by different vegetation types also explains that only five vegetation types are the most suitable habitats in our model. Elevation change affects the distribution of orchids by influencing temperature conditions, which, as we know, affects seed germination, phenology, and population density of the orchid family (Zhang et al., 2018), and to some extent, determines the physiological upper and lower limits of geographical distribution. The possible explanation for the modeled unsuitability of orchids to higher mean temperatures of the hottest season is that the typical non-zonal dry and hot river valley climate in the study area is characterized by hot and dry summers with burning wind effects is at odds with the indication that the cool-moist environment is a possible explanation for the abundance of orchids (Crain & Fernandez, 2020). Meanwhile, studies suggest that the optimal water-energy dynamics obtained under cool-moist conditions can promote high biodiversity levels (O'Brien, 2006). By analyzing the geographic attributes intimately associated with orchid suitability, we would identify the most important environmental features that support the distribution of orchids in the Hengduan Mountains and ultimately benefit orchid conservation efforts in various respects.

Despite the existence within the study area of a wide range of suitable habitats for orchids, the unevenness of diversity was also reflected, enabling the identification of diverse hotspots. Mountainous areas with enormous vertical elevation variations, such as the Muli mountain plain, the Shaluri mountain system, and the Dasetsu mountain, were the diversity hotspots in the study area, showing peak levels of mountain diversity similar to the results of many mountain research projects (Acharya et al., 2011; Zizka & Antonelli, 2018). The distribution pattern of protection hotspots resembled the diversity pattern in this study, which conforms to the assertion that diverse and heterogeneous environments in mountainous areas can reduce the risk of climate-driven extinction by providing large quantities of alternative habitats within a short distance (Mosbrugger et al., 2018). Hence, these areas can serve as refuges for ancient species. Another interesting finding is that these diversity and protection hotspots were located in the northwestern part of the study area (Muli, Yangyuan, Dacheng, and Yajiang counties) in the Jinsha River basin (Yalong River DC). The geological evidence suggests that the climatic conditions in the river valley have been relatively stable since the Late Tertiary, which, together with the edge effect and channeling benefits, allowed new species to survive and reproduce, and species exchange was ensured (Zhu, 2014), giving rise to many endemic components, both paleo- and neo-endemic species. These results are also consistent with relevant flora studies in the Hengduan Mountains (Lang, 1990; Li & Li, 1993; Xu et al., 2014). These regions are priorities and core areas for orchid diversity conservation and potentially for new species diversification centers.

Differences between hotspot layers

It was clear that the differences between the layers were noticeable (Fig. 2), and there was a significant deviation between the habitat map and the diversity and protection hotspots. The highly suitable habitat in the southwest corner and west of the study area was not an essential diversity and protection core. The potential explanation is that these two parts belong to the Nujiang River basin, the Gaoligong Mountains, which is most strongly influenced by the habitat movement of the Himalayan orogeny, with younger geological age, shorter time of species formation and endemism (Li & Li, 1993), thus their species richness and protection value relatively low, even though the vertical variation is significant and enormous. Yet the high-quality habitat can provide sufficient space for current orchid diversification and development means that it would be an essential part of conservation planning. The situation may be dissimilar in the northeast corner, where there was no significant clustering about the richness or protection hotspot, despite the high predicted suitability. We speculate that these regions, a part of the Yunnan-Guizhou plateau, are faintly affected by river erosion, causing relatively less environmental heterogeneity (Sichuan Vegetation Cooperation Group, 1980), thus resulting in impacts on species diversity. At the same time, the relatively flat plateau surface has long been more susceptible to disturbance by human activities such as grazing, and it may be difficult for endangered species to remain. As a result, it is harder to generate diversity or protection hotspots. A particular situation arose in the northern part (Yajiang County), where protection hotspots appeared, but the model results did not show high-quality habitats. The possibility may be that for some endangered orchids, there are factors affecting survival, and targeted investigation and conservation efforts to address the causes of endangerment are formidable measures to avoid biodiversity loss.

Considering Fig. 3, all layer centers showed a gradually decreasing position change from east to west. One of the reasonable explanations is the retreating process of the ancient Mediterranean Sea from west to east (Sun, 2002). Other is that the changes in water and heat conditions brought about by the influence of the southeast monsoon are also possible causes. Another interesting finding is that the high-quality diversity and protection hotspots centers of mass were overall northward compared to other centers, and all located in Muli County (one of the counties with the highest orchid richness and endemism in China), which is closely related to the original forest vegetation preserved under stable geological conditions. According to our survey results and previous flora studies, Muli may be the central location for the evolution and diversification of one large flora of orchids. All of these imply that these hotspots maybe hold an equally important position in the whole of China, even Central Asia orchid floras.

Orchids multi-scenario conservation planning and applications

Multi-scenario conservation planning makes rational and effective utilization of resources, providing a reference basis for biodiversity conservation for different purposes at present and in the future. It was tough to cover all diversity and protection hotspots at any scale in our study if only habitat suitability predictions were used as the reference for conservation planning. This also proved our initial assumption, that the existence of species bias. Using the spatial overlay technology, we divided the biodiversity conservation plans corresponding to different scenarios. The strict conservation scenario (SS), based on the principle of protecting the most suitable habitat, the smallest buffer zones for diversity and protection hotspots, ensures the fundamental species pool of the region to a certain extent and is the bottom line to support the regional biodiversity (Catano et al., 2020). The economical conservation scenario (ES) is one of the most recommended methods under current conditions and is likely to be practiced. It protects the most suitable habitats and expands the scope of protection for the most endangered and richest areas to achieve the best protection effect. The positive conservation scenario (PS) is the most optimistic conservation plan, which can meet the maximum development of orchids in regional biodiversity hotspots. Undoubtedly, the managers will spend massive protection resources in choosing such a conservation scenario.

Our conservation plan formed four distinct clusters that contained divergent geographical attributes and conservation priorities. For Cluster   and Cluster , although the diversity and protection value were less prominent than those of Cluster , there still exists a diverse and heterogeneous environment brought about by the enormous altitude difference, which, together with the warm and humid airflow brought about by the southwest monsoon, provides favorable conditions for the development and breeding of orchids, as well as numerous tropical orchid components have been developed here(Acharya et al., 2011; Perez-Escobar et al., 2017). Cluster II was the core of orchid biodiversity conservation for the south of the Hengduan Mountains. It has a long history of formation and stable climatic conditions that permit ample time for plants to enter, diversify, speciation, and spread. The complex mountainous environment with significant changes in vertical climate zones, frequent glacier movements, and upward and downward climatic shifts make the region include massive unique species, and many endangered plants can flourish here (Zhu, 2014). In the above three clusters, we propose to use the current protected areas as the basis and expand to hot spots outside the region. For Cluster IV, setting a string of protected sites to compose conservation corridors is a good choice. When facing global climate change threats, they provide vital migration corridors for the orchid population dispersal and are conducive to other species groups (Keeley et al., 2018; Pellerin et al., 2022). It is also a critical channel for species diversification centers to spread in all directions.

Considerations for future research

While our study affords a valuable framework for assessing the suitability of orchids in biodiversity hotspots and the results should provide significant information for investigating orchid distribution patterns in the Hengduan Mountains, there are several considerations when migrating to other scales or geographic regions for biodiversity studies. The orchid protection evaluation is currently based on the attributes of the species. We recommend that obtain enough survey data, such as the number of species, threat factors, and levels, to conduct more detailed conservation assessments, which would be more meaningful. Although these data are hard to obtain at large scales, we suggest that researchers try them at small scales. Of course, using separate or local lists for evaluation is valuable for local conservation efforts to advance in any case. Secondly, our quantification of species diversity did not address the issue of diversity weights within the cell grid, and being able to take β diversity into account in future studies would be a substantial expansion of this research. In addition, finer remote sensing data, acquisition of environmental variables (Krner, 2007), and fine gradient delineation of variables would facilitate the study of corresponding geographic attributes of target species within hotspots and will facilitate conservation efforts.

Conclusion

The extensive ecological suitability and advanced biological evolution status of orchids make it possible that they could be used to identify conservation priorities and analysis biogeographic patterns in biodiversity hotspots. When orchids are planned for this role, this study provides a method to address the species bias caused by the unequal conservation status between species and using SDMs in heterogeneous environments. The south of Hengduan Mountain is a hot region of great significance and value for global biodiversity conservation. We used the suitability map of orchids and combined the diversity and protection hotspots to generate the multi-scene biodiversity conservation spatial patterns. It is not only conducive to promoting the protection of orchids but also has significance for understanding the biogeographic patterns of the region and facilitating the protection of other groups. This study emphasizes that species bias cannot be ignored when conducting a suitability analysis of multiple species or a certain group in biodiversity hotspots to guide regional conservation planning. The extensive ecological suitability and advanced biological evolution status of orchids make it possible that they could be used to identify conservation priorities and analysis biogeographic patterns in biodiversity hotspots. When orchids are planned for this role, this study provides a method to address the species bias caused by the unequal conservation status between species and using SDMs in heterogeneous environments. The south of Hengduan Mountain is a hot region of great significance and value for global biodiversity conservation. We used the suitability map of orchids and combined the diversity and protection hotspots to generate the multi-scene biodiversity conservation spatial patterns. It is not only conducive to promoting the protection of orchids but also has significance for understanding the biogeographic patterns of the region and facilitating the protection of other groups. As our research may be applied to planning practice, any possible omission of valuable species or regions will cause an unbearable loss of diversity. We hope this study will help researchers and conservation practitioners take necessary steps toward preserving orchids and biological diversity.

Declarations

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Data Availability: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request

References

1. Acharya KP, Vetaas OR & Birks HJB (2011) Orchid species richness along Himalayan elevational gradients. J Biogeogr 38: 1821-1833. https://doi.org/10.1111/j.1365-2699.2011.02511.x
2. Anderson ER, Cherrington EA, Tremblay-Boyer L, Flores AI & Sempris E (2008) Identifying critical areas for conservation: Biodiversity and climate change in central America, Mexico, and the Dominican Republic. Biodivers 9: 89-99. https://doi.org/10.1080/14888386.2008.9712912
3. Anibaba QA, Dyderski MK & Jagodzinski AM (2022) Predicted range shifts of invasive giant hogweed (Heracleum mantegazzianum) in Europe. Sci Total Environ 825: 154053. https://doi.org/10.1016/j.scitotenv.2022.154053
4. Araújo MB & Guisan A (2006) Five (or so) challenges for species distribution modelling. J Biogeogr 33: 1677-1688. https://doi.org/10.1111/j.1365-2699.2006.01584.x
5. Bernardos S, Garcia-Barriuso M, Angeles Sanchez-Anta M & Amich F (2007) Composition, geographical affinities and endemism of the Iberian Peninsula orchid flora. Nord J Bot 25: 227-237. https://doi.org/10.1111/j.0107-055X.2007.00123.x
6. Borrero H, Alvarez JC, Prieto RO & Liu H (2022) Comparisons of habitat types and host tree species across a threatened Caribbean orchid's core and edge distribution. J Trop Ecol 38(3): 134-150 https://doi.org/10.1017/s0266467421000572
7. Brooks TM, Mittermeier RA, da Fonseca GA, Gerlach J, Hoffmann M, Lamoreux JF, ... Rodrigues AS (2006) Global biodiversity conservation priorities. Science 313: 58-61. https://doi.org/10.1126/science.1127609
8. Cañadas EM, Fenu G, Peñas J, Lorite J, Mattana E & Bacchetta G (2014) Hotspots within hotspots: Endemic plant richness, environmental drivers, and implications for conservation. Biol Conserv 170: 282-291. https://doi.org/10.1016/j.biocon.2013.12.007

9. Catano CP, Grman E, Behrens E & Brudvig LA (2020) Species pool size alters species–area relationships during experimental community assembly. Ecology 102. https://doi.org/10.1002/ecy.3231
10. Chen YS, Deng T, Zhou Z & Sun H (2018) Is the East Asian flora ancient or not? Natl Sci Rev 5: 920-932. https://doi.org/10.1093/nsr/nwx156
11. Crain BJ & Fernandez M (2020) Biogeographical analyses to facilitate targeted conservation of orchid diversity hotspots in Costa Rica. Divers Distrib 26: 853-866. https://doi.org/10.1111/ddi.13062
12. Crain BJ, Tremblay RL & Rouget M (2014) Do richness and rarity hotspots really matter for orchid conservation in light of anticipated habitat loss? Divers Distrib 20: 652-662. https://doi.org/10.1111/ddi.12179
13. Crain BJ & White JW (2013) A checklist and floristic summary of the vascular plants of Napa County, California. Phytotaxa 95. https://doi.org/10.11646/phytotaxa.95.1.1
14. Djordjevic V, Tsiftsis S, Lakusic D, Jovanovic S, Jakovljevic K & Stevanovic V (2020) Patterns of distribution, abundance and composition of forest terrestrial orchids. Biodivers Conserv 29: 4111-4134. https://doi.org/10.1007/s10531-020-02067-6
15. Dodson CH (2003) Why are there so many orchid species? Lankesteriana 7: 99-103.
16. Evans A, Janssens S & Jacquemyn H (2020) Impact of Climate Change on the Distribution of Four Closely RelatedOrchis(Orchidaceae) Species. Diversity-Basel 12. https://doi.org/10.3390/d12080312
17. Eyre AC, Briscoe NJ, Harley DKP, Lumsden LF, McComb LB, Lentini PE & Leroy B (2022) Using species distribution models and decision tools to direct surveys and identify potential translocation sites for a critically endangered species. Divers Distrib 28: 700-711. https://doi.org/10.1111/ddi.13469
18. Faruk A, Papikyan A & Nersesyan A (2021) Exploring Effective Conservation of Charismatic Flora: Orchids in Armenia as a Case Study. Diversity 13. https://doi.org/10.3390/d13120624
19. Fick SE & Hijmans RJ (2017) WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. Int J Climatol 37: 4302-4315. https://doi.org/10.1002/joc.5086
20. Figura T, Weiser M & Ponert J (2020) Orchid seed sensitivity to nitrate reflects habitat preferences and soil nitrate content. Plant Biology 22: 21-29. https://doi.org/10.1111/plb.13044
21. Gogol-Prokurat M (2011) Predicting habitat suitability for rare plants at local spatial scales using a species distribution model. Ecol Appl 21(1): 33-47. https://doi.org/10.1890/09-1190.1
22. Sichuan Vegetation Cooperation Group (1980). Vegetation in Sichuan province. Sichuan Renmin Press, Chengdu.
23. Guisan A & Thuiller W (2005) Predicting species distribution: offering more than simple habitat models. Ecol Lett 8: 993-1009. https://doi.org/10.1111/j.1461-0248.2005.00792.x
24. Han TS, Hu ZY, Du ZQ, Zheng QJ, Liu J, Mitchell-Olds T & Xing YW (2022) Adaptive responses drive the success of polyploid yellowcresses (Rorippa, Brassicaceae) in the Hengduan Mountains, a temperate biodiversity hotspot. Plant Diversity 44(5): 13. https://doi.org/10.1016/j.pld.2022.02.002

25. Hemrova L, Kotilinek M, Konecna M, Paulic R, Jersakova J, Tesitelova T, ... Munzbergova Z (2019) Identification of drivers of landscape distribution of forest orchids using germination experiment and species distribution models. Oecologia 190: 411-423. https://doi.org/10.1007/s00442-019-04427-8
26. IUCN (2021) The IUCN Red List of Threatened Species. Version 2021-3. https://www.iucnredlist.org.
27. Jacquemyn H, Brys R, Adriaens D, Honnay O & Roldán-Ruiz I (2008) Effects of population size and forest management on genetic diversity and structure of the tuberous orchid Orchis mascula. Conserv Genet 10: 161-168. https://doi.org/10.1007/s10592-008-9543-z
28. Jaynes ET & Cummings FW (1963) Comparison of quantum and semiclassical radiation theories with application to the Bean Maser. P Ieee 51(1): 89-109.
29. Jenkins CN, Pimm SL & Joppa LN (2013) Global patterns of terrestrial vertebrate diversity and conservation. Pnas 110: E2602-10. https://doi.org/10.1073/pnas.1302251110
30. Kaur J, Phillips C & Sharma J (2021) Host population size is linked to orchid mycorrhizal fungal communities in roots and soil, which are shaped by microenvironment. Mycorrhiza 31: 17-30. https://doi.org/10.1007/s00572-020-00993-5
31. Keeley ATH, Basson G, Cameron DR, Heller NE, Huber PR, Schloss CA, ... Merenlender AM (2018) Making habitat connectivity a reality. Conser Biol 32: 1221-1232. https://doi.org/10.1111/cobi.13158
32. Kelly MM, Toft RJ & Gaskett AC (2013) Pollination and insect visitors to the putatively brood-site deceptive endemic spurred helmet orchid,Corybas cheesemanii. New Zeal J Bot 51: 155-167. https://doi.org/10.1080/0028825x.2013.795905
33. Kirby SH (2011) Activemountain building and the distribution of "core" maxillariinae species in tropical Mexico and Central America. Lankesteriana 11(3): 275-291.
34. Krner C (2007) The use of 'altitude' in ecological research. Trends Ecol Evol 22(11): 569-574. https://doi.org/10.1016/j.tree.2007.09.006
35. Lang KY (1990) Notes on the orchid flora in the Hengduan Mountain region, China. J Syst Evol 28 (5): 356-371.
36. Lefcheck JS, Byrnes JEK, Isbell F, Gamfeldt L, Griffin JN, Eisenhauer N, ... Duffy JE (2015) Biodiversity enhances ecosystem multifunctionality across trophic levels and habitats. Nat Commu 6: 6936. https://doi.org/10.1038/ncomms7936
37. Li XW & Li J (1993) A preliminary floristic study on the seed plants from the region of Hengduan Mountain. Plant Diversity 15 (3): 217-231.
38. Loiselle BA, Jørgensen PM, Consiglio T, Jiménez I, Blake JG, Lohmann LG & Montiel OM (2007) Predicting species distributions from herbarium collections: does climate bias in collection sampling influence model outcomes? J Biogeogr 35(1): 105-116. https://doi.org/10.1111/j.1365-2699.2007.01779.x
39. Luo YB, Jia JS & Wang CL (2003) A general review of the conservation status of Chinese orchids. Biodivers Sci 11(1): 70-77. https://doi.org/1005-0094 2003 01-0070-08

40. Marchese C (2015) Biodiversity hotspots: A shortcut for a more complicated concept. Glob Ecol Conserv 3: 297-309. https://doi.org/10.1016/j.gecco.2014.12.008
41. McCune JL & Baraloto C (2016) Species distribution models predict rare species occurrences despite significant effects of landscape context. J Appl Ecol 53: 1871-1879. https://doi.org/10.1111/1365-2664.12702
42. Mosbrugger V, Favre A, Muellner-Riehl AN, Päckert M & Mulch A (2018) Cenozoic evolution of geo-biodiversity in the Tibeto-Himalayan region. Mountains, climate, and biodiversity 429.
43. Murray-Smith C, Brummitt NA, Oliveira-Filho AT, Bachman S, Moat J, Lughadha EM & Lucas EJ (2009) Plant diversity hotspots in the Atlantic coastal forests of Brazil. Conserv Biol 23: 151-63. https://doi.org/10.1111/j.1523-1739.2008.01075.x
44. O'Brien EM (2006) Biological relativity to water-energy dynamics. J Biogeogr 33: 1868-1888. https://doi.org/10.1111/j.1365-2699.2006.01534.x
45. Oliver TH, Heard MS, Isaac NJB, Roy DB, Procter D, Eigenbrod F, ... Bullock JM (2015) Biodiversity and Resilience of Ecosystem Functions. Trends Ecol Evol 30: 673-684. https://doi.org/10.1016/j.tree.2015.08.009
46. Parsons RF & Hopper SD (2003) Monocotyledonous geophytes: comparison of south-western Australia with other areas of mediterranean climate. Aust J Bot 51: 129-133.
47. Pellerin F, Bestion E, Winandy L, Di Gesu L, Richard M, Aguilee R & Cote J (2022) Connectivity among thermal habitats buffers the effects of warm climate on life-history traits and population dynamics. J Anim Ecol 91(11): 2301-2313. https://doi.org/10.1111/1365-2656.13814
48. Perez-Escobar OA, Chomicki G, Condamine FL, Karremans AP, Bogarin D, Matzke NJ, ... Antonelli A (2017) Recent origin and rapid speciation of Neotropical orchids in the world's richest plant biodiversity hotspot. New Phytol 215: 891-905. https://doi.org/10.1111/nph.14629
49. Reid WV (1998) Biodiversity hotspots. Trends Ecol Evo 13: 275-280. https://doi.org/10.1016/S0169-5347(98)01363-9
50. Rewicz A, Jaskula R, Rewicz T & Tonczyk G (2017) Pollinator diversity and reproductive success of Epipactis helleborine (L.) Crantz (Orchidaceae) in anthropogenic and natural habitats. PeerJ 5: e3159. https://doi.org/10.7717/peerj.3159
51. Seaton PT, Hu H, Perner H & Pritchard HW (2010) Ex Situ Conservation of Orchids in a Warming World. Bot Rev 76: 193-203. https://doi.org/10.1007/s12229-010-9048-6
52. Souza Rocha F & Luiz Waechter J (2010) Ecological distribution of terrestrial orchids in a south Brazilian Atlantic region. Nord J Bot 28: 112-118. https://doi.org/10.1111/j.1756-1051.2009.00500.x
53. Sun H (2002) Tethys Retreat and Himalayas-Hengduanshan Mountains Uplift and Their Significance on the Origin and Development of the Sino-Himalayan Elements and Alpine Flora. Plant Diversity 24(3): 273-288.
54. Timsina B, Rokaya MB, Munzbergova Z, Kindlmann P, Shrestha B, Bhattarai B & Raskoti BB (2016) Diversity, distribution and host-species associations of epiphytic orchids in Nepal. Biodivers Conserv 25: 2803-2819. https://doi.org/10.1007/s10531-016-1205-8

55. Vollering J, Schuiteman A, de Vogel E, van Vugt R & Raes N (2016) Phytogeography of New Guinean orchids: patterns of species richness and turnover. J Biogeogr 43: 204-214. https://doi.org/10.1111/jbi.12612
56. Wallington TJ, Hobbs RJ & Moore SA (2005) Implications of Current Ecological Thinking for Biodiversity Conservation: a Review of the Salient Issues. Ecol Soc 10. https://doi.org/https://doi.org/10.5751/ES-01256 -100115
57. Wambulwa MC, Milne R, Wu ZY, Spicer RA, Provan J, Luo YH, ... Liu J (2021) Spatiotemporal maintenance of flora in the Himalaya biodiversity hotspot: Current knowledge and future perspectives. Ecol Evol 11: 10794-10812. https://doi.org/10.1002/ece3.7906
58. Wang E, Kirby E, Furlong KP, van Soest M, Xu G, Shi X, ... Hodges KV (2012) Two-phase growth of high topography in eastern Tibet during the Cenozoic. Nat Geosci 5: 640-645. https://doi.org/10.1038/ngeo1538
59. Wieder WR, Boehnert J, Bonan GB & Langseth M. (2014). Regridded Harmonized World Soil Database v1.2. Data set.
60. Xing Y & Ree RH (2017) Uplift-driven diversification in the Hengduan Mountains, a temperate biodiversity hotspot. PNAS 114: E3444-E3451. https://doi.org/10.1073/pnas.1616063114
61. Xu B, Li ZM & Sun H (2014) Plant diversity and floristic characters of the alpine subnival belt flora in the Hengduan Mountains, SW China. J Syst Evol 52: 271-279. https://doi.org/10.1111/jse.12037
62. Yu H, Miao S, Xie G, Guo X, Chen Z & Favre A (2020) Contrasting Floristic Diversity of the Hengduan Mountains, the Himalayas and the Qinghai-Tibet Plateau Sensu Stricto in China. Front Ecol Evol 8. https://doi.org/10.3389/fevo.2020.00136
63. Zhang S, Yang Y, Li J, Qin J, Zhang W, Huang W & Hu H (2018) Physiological diversity of orchids. Plant Divers 40: 196-208. https://doi.org/10.1016/j.pld.2018.06.003
64. Zhang Y, Du H, Jin X & Ma K (2015a) Species diversity and geographic distribution of wild Orchidaceae in China. Chin Sci Bull 60: 179-188.
65. Zhang Y, Qian L, Spalink D, Sun L, Chen J & Sun H (2021) Spatial phylogenetics of two topographic extremes of the Hengduan Mountains in southwestern China and its implications for biodiversity conservation. Plant Divers 43: 181-191. https://doi.org/10.1016/j.pld.2020.09.001
66. Zhang Z, Yan Y, Tian Y, Li J, He JS & Tang Z (2015b) Distribution and conservation of orchid species richness in China. Biol Conserv 181: 64-72. https://doi.org/10.1016/j.biocon.2014.10.026
67. Zhu XX (2014) The Flora of Seed Plants in Three Rivers Valley of SW China. Dissertation, University of Chinese Academy of Science.
68. Zizka A & Antonelli A (2018) Mountains of diversity. Nature 555: 173-174. https://doi.org/10.1038/d41586-018-02062-6

Figures

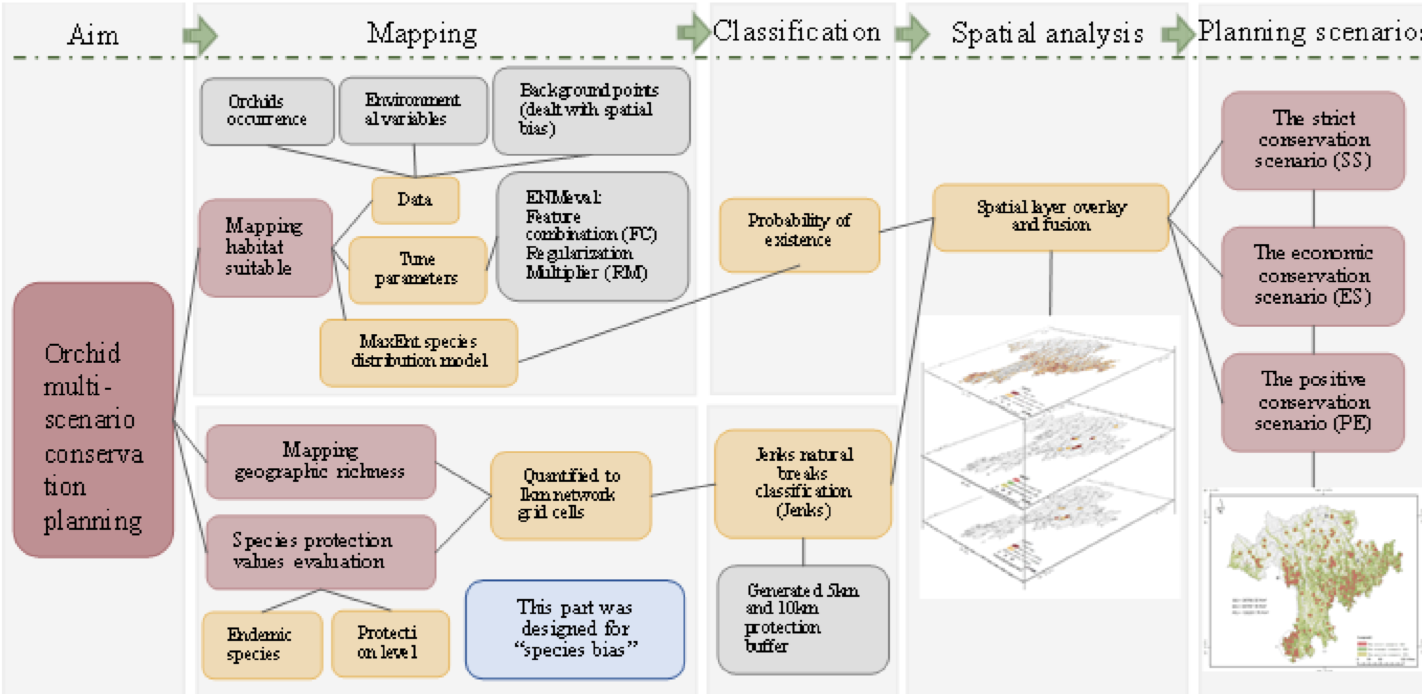

Figure 1

An overview of the study design across four parts: 1. mapping the habitat suitability, geographical richness, and protection hotspots, 2. classification for subsequent conservation scenarios, 3. spatial analysis to obtain their deviation, 4. multi-scenario conservation plannings, including associated geographical attributes analysis.

Figure 2

The maps of habitat suitability, richness hotspot, and protection hotspot (from left to right). The red represents the most priority, the yellow represents the secondary, and the grey represents the lowest level.

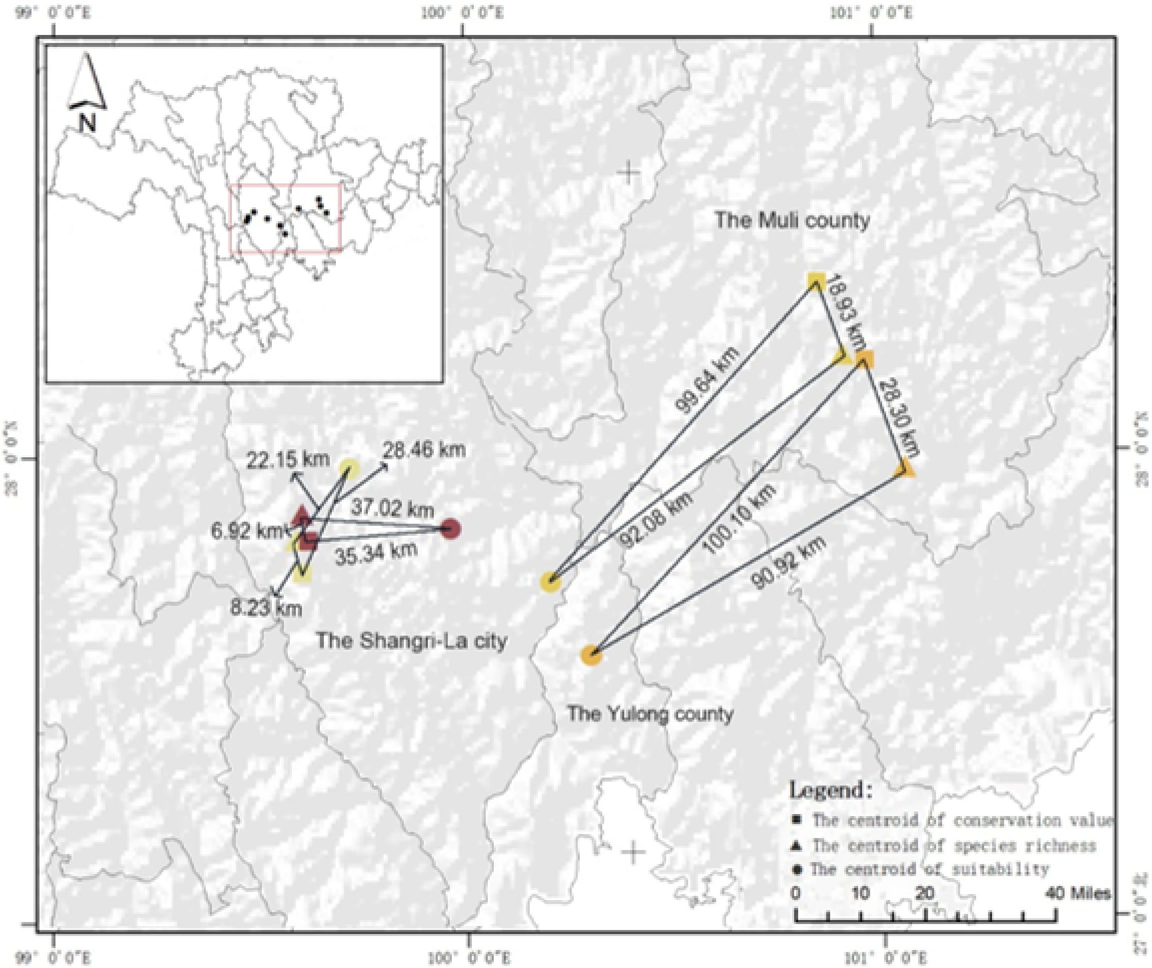

Figure 3

Centroid position of different layers. Shapes represent different attributes, and the color becomes lighter as the level decreases. Red means the total centroid of the attribute.

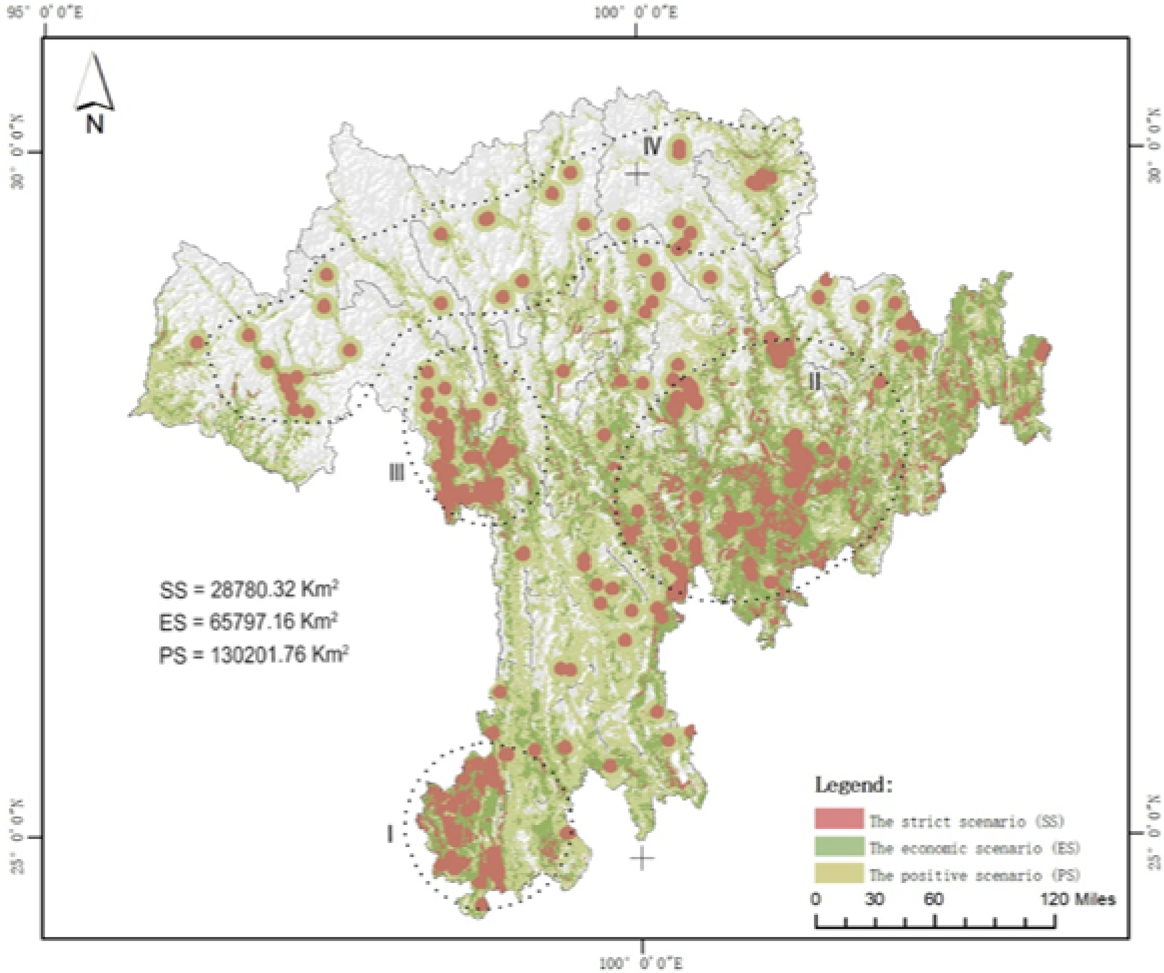

Figure 4

The spatial range of different protection scenarios. The black dotted line shows the grid cell clusters in the figure.

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