

Habitat degradation assessment and restoration framework for the giant panda (*Ailuropoda melanoleuca*) in the Shimian section of the Giant Panda National Park (GPNP), China

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ABSTRACT

Anthropogenic activities and environmental changes have historically impacted the habitat quality of the giant panda (*Ailuropoda melanoleuca*). This study introduces the concepts of “theoretical habitat” and “actual habitat” and integrates disturbance factors to assess habitat degradation in the Shimian section of Giant Panda National Park (GPNP). The MaxEnt model and ArcGIS were employed to quantify habitat suitability, identify degraded habitat, rank environmental drivers and develop restoration scenarios. The results indicated that the theoretical habitat area was 33671.97 ha, whereas the actual habitat area was 25624.44 ha, with 10424.07 ha identified as degraded. In the theoretical habitat model, elevation was the most significant factor (23.2%), followed by vegetation type (22.6%) and distance to water (16.4%). In the actual habitat model, grazing intensity was the predominant factor (46.8%), surpassing infrastructure (11.8%), distance to water (6.8%) and vegetation type (6.0%). Grazing intensity also emerged as the primary factor affecting habitat quality among the controllable variables. Consequently, this study advocates for prohibiting or controlling grazing intensity and restoring habitat vegetation as critical strategies for rehabilitating degraded panda habitats in Shimian. The methodologies

provide a framework for broader ecological sustainability and establish a replicable approach for habitat restoration in similar regions, contributing to global conservation efforts.

Keywords: Degraded habitats identification; Giant Panda National Park (GPNP); Grazing intensity; Habitat suitability assessment; Restoration strategies

INTRODUCTION

Habitat suitability assessment is paramount for wildlife conservation and ecological restoration (Loke & Chisholm, 2022; Pullin, 2002). The giant panda (*Ailuropoda melanoleuca*), recognized as a flagship and umbrella species for conservation in China, has garnered global attention. Conservation efforts have successfully increased the wild panda population, leading to its status being reclassified from Endangered to Vulnerable (IUCN, 2025; Li & Pimm, 2016). Despite these advancements, the giant panda habitats continue to face degradation and fragmentation (Yang et al., 2020). According to the Fourth National Giant Panda Survey (the Fourth Survey for short), there are currently 1864 wild giant pandas (*Ailuropoda melanoleuca*) that are fragmented into at least 33 distinct local populations. Notably, 25 of these populations are considered too small to be self-sustaining, particularly given ongoing anthropogenic disturbances such as grazing, gathering, deforestation, and historical human encroachment activities (National Forestry and Grassland Administration, 2021). Additionally, environmental changes,

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including climate fluctuations, further exacerbate habitat quality disparities, highlighting the critical need for habitat conservation efforts (Kong et al., 2021; Xu et al., 2022).

The establishment of the Giant Panda National Park (GPNP) marks a conservation milestone, protecting core habitats in Southwest China's biodiversity hotspot and the last refuge for threatened species (Xu et al., 2022; Zhang et al., 2022). Meanwhile, as part of this initiative, the need for a rigorous scientific assessment of habitat quality and the accurate identification of degraded areas is underscored (Huang et al., 2020). Understanding the drivers of habitat degradation and identifying impacted areas within the park are vital for ensuring the long-term persistence of this iconic species (Kang, 2022). Despite extensive global efforts to conserve the giant panda, a notable gap remains in comprehensive studies addressing habitat degradation, particularly in the Xiaoxiangling mountain range, which suffers from severe fragmentation and an elevated risk of local extinction (Xu et al., 2022; Zhu et al., 2011a, 2011b). Furthermore, the low genetic diversity among pandas, coupled with the division of the Xiaoxiangling mountain range into isolated subpopulations due to human infrastructure, further highlights the urgency of habitat conservation (Li et al., 2021; Qing et al., 2016a; Zhao et al., 2013).

Quantifying habitat degradation is crucial for prioritizing conservation actions (Betts et al., 2024; Guisan et al., 2013). Recent advancements in remote sensing and Geographic Information System (GIS) technologies have enabled more precise monitoring and assessment of habitat changes (Erena & Yesus, 2021). For instance, Bosso et al. (2024) concluded that human activities, particularly fishing, significantly impact the habitat suitability of both *Hippocampus guttulatus* and *Hippocampus hippocampus*, affecting 42% and 38% of their habitats, respectively, while only 25% and 30% of their potential distributions are protected. In the Wanglang region of the GPNP, free-ranging livestock, particularly horses, significantly degrade giant panda habitats and bamboo resources, leading to a 34% reduction in usable habitat and forcing pandas to higher elevations, which has critical implications for conservation strategies and policies (Li et al., 2017). The Maximum Entropy (MaxEnt) model is a powerful tool in wildlife research for modeling species distributions and habitat suitability (Rehan et al., 2024; Roshani et al., 2024; Wang et al., 2024a). This method estimates the most likely species distribution by maximizing entropy under given constraints, relying solely on presence data, and is particularly advantageous when absence data are lacking or unreliable, given its robustness against spatial errors in location data (Chen et al., 2012; Sun et al., 2021). Previous studies have demonstrated that MaxEnt is effective in discerning habitat preferences and identifying areas of high quality and conservation value (Baldwin, 2009; Hua et al., 2023; Liu et al., 2024; Qin et al., 2023a). By comparing current habitat suitability with historical conditions or future projections, MaxEnt results can reveal areas of declining habitat quality, thereby aiding in the prioritization of conservation efforts to protect and restore critical habitats (Abedin et al., 2024; Buonincontri et al., 2023; Qiao et al., 2024).

However, for species like the giant panda, where habitat degradation has occurred over an extended period, accurate historical data are frequently unavailable (Zhu et al., 2013). Consequently, many studies have focused solely on current habitats, designating areas of low quality as degraded (Liu

et al., 2024; Qin et al., 2023b). Although using similar methods for habitat assessment is common, this approach risks misidentifying degraded habitats without addressing the underlying causes, potentially leading to ineffective or counterproductive restoration efforts. For instance, if low habitat quality is primarily due to topographical constraints, restoration initiatives might not yield the desired outcomes. Meanwhile, the direct and indirect effects of topography and human activities on habitat quality within the GPNP have yet to be comprehensively quantified. To bridge this knowledge gap, our study introduces the concepts of "theoretical habitat" and "actual habitat". The theoretical habitat, constructed using only intrinsic variables that are not easily modified by human intervention, focuses on the habitat's natural state as influenced by inherent environmental factors. It serves as a surrogate for historical habitats when precise data are unattainable, thereby enhancing the accuracy of degradation identification and improving the guidance of restoration efforts, unlike the "potential niche". When human controllable factors are considered, the resultant habitat is defined as "actual habitat", which aligns to a certain extent with the "realized niche" (Laughlin & McGill, 2024). Likewise, where "degraded habitat" refers to areas negatively impacted by anthropogenic activities (Salmaniw et al., 2022), the difference between actual habitat and theoretical habitat is defined as degraded habitat, which requires focused restoration and conservation efforts.

Consequently, this study targets the Shimian section of the GPNP in Sichuan, China, to address challenges in understanding habitat quality for the giant panda. The Shimian section is a core distribution area and critical habitat for the isolated small population of giant pandas in the Xiaoxiangling mountain range and is home to China's first giant panda wild training and reintroduction base (Li et al., 2025). Given its critical role as a biodiversity hotspot and the pressing need for habitat degradation assessment and restoration, this region is pivotal for panda conservation efforts (Qin et al., 2019). By integrating both intrinsic and human controllable environmental variables, we seek to scientifically evaluate the habitat quality of the giant panda. The MaxEnt model was utilized to simulate both theoretical and actual habitats to gain a comprehensive understanding of habitat quality. This strategy will guide targeted conservation efforts and optimize the effective allocation of scarce habitat resources. Moreover, identifying and restoring degraded panda habitats can also enhance conservation benefits for other species, extending the protective 'umbrella' effect of the giant panda. In addition, developing a replicable framework for identifying degraded habitats not only aids in recognizing such areas but also serves as a foundation for extensive habitat degradation analysis and restoration efforts.

MATERIALS AND METHODS

Study area

The Shimian section of the GPNP is located in the upper reaches of the Dadu River, at the southwestern periphery of the Sichuan Basin, within the administrative boundaries of Shimian County (N28°51'02"–29°08'42", E102°10'33"–102°29'07"). Situated in the Xiaoxiangling mountain range, this area serves as both a critical habitat core and an essential ecological corridor for the small, genetically limited giant panda population in Xiaoxiangling (He, 2019). The Shimian

section of the GPNP extends 23 km from north to south and 17.8 km from east to west, covering a total area of 46 777.23 ha. The region primarily falls within the Nanya River catchment, a first-order tributary of the Dadu River, with a minor section in the Xiaoshui River basin to the northwest. It encompasses three townships named Liziping, Anshunchang, and Huilong. According to the Fourth Survey, the current giant panda population in the Shimian section of the GPNP consists of 22 individuals, characterized by small population size and low genetic diversity (Sichuan Forestry Department, 2015). Notably, China National Highway 108 bisects the region, fragmenting the giant panda population into the Gongyihai area to the east of the highway, the Zimaping area to the west, and the centrally positioned Pusagang area (Figure 1).

Giant panda distribution data

The giant panda occurrence data utilized in this study were obtained from the Fourth Survey, supplemented by ongoing daily field monitoring. The Fourth Survey dataset provides a comprehensive record of giant panda presence and distribution from 2011 to 2014. Because the giant panda's digestive system cannot fully digest plant fiber, well-preserved bamboo stems retaining their original length and shape remain in feces. Consequently, the Bamboo Stem Fragment (BSF) identification method served as a primary tool for professional investigators during the Fourth Survey and remains widely applied in current population surveys (Huang & Hu, 1989). Additionally, investigators collected evidence such as hair, footprints, feeding traces, resting traces, and birthing-den traces to assist in identifying giant pandas and sympatric

species (Li et al., 2018). The detailed methodologies employed during the survey were documented in relevant literature (Fu et al., 2022; Wang et al., 2024c; Xu et al., 2022; Yang et al., 2020). Routine field monitoring integrates direct observations by professional researchers with data from 320 infrared camera-traps. These camera-traps are distributed at a density of approximately one camera per square kilometer, ensuring comprehensive spatial coverage across the study area. The datasets for the giant panda comprised 62 points from the Fourth Survey and 51 points from daily field monitoring during 2018–2023, yielding a total of 113 points. To mitigate potential overfitting in the MaxEnt model caused by spatial autocorrelation from repeated sampling, duplicate occurrence points within 1 km were removed (Dhami et al., 2023; Xu et al., 2024b), resulting in a final dataset of 41 unique giant panda distribution points for model construction (Figure 1).

Environment variables data

This study employed 12 environmental variables: Elevation data were obtained from a Digital Elevation Model (DEM) with a 30 m spatial resolution, provided by the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (<http://www.resdc.cn/>, accessed on 25 October 2024). Slope and solar radiation layers were derived from this DEM using ArcGIS v.10.8. Additional environmental data, including vegetation type, forest canopy density, tree diameter at breast height (DBH), distance to water sources, grazing intensity, agricultural intensity, distance to roads, plant gathering, and infrastructure were extracted from the natural

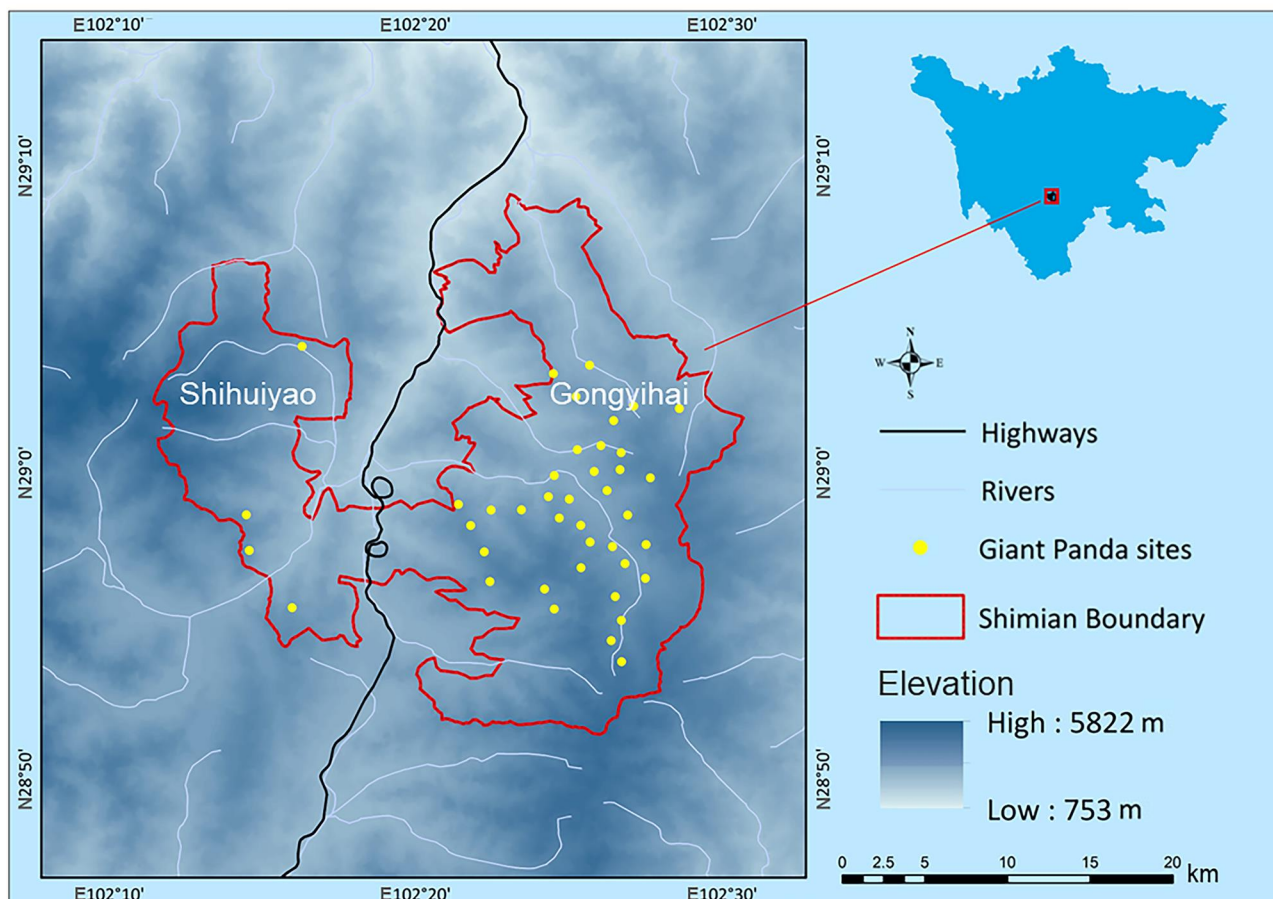


Figure 1 Location and elevation map of the study area of the Giant Panda National Park (GPNP) in Shimian, Sichuan, China. The yellow dots indicate giant panda occurrence records used in the MaxEnt model

resource survey of the GPNP in the Shimian region (Data from the Sichuan Forestry and Grassland Ecological Environment Monitoring Center).

These variables were selected based on their documented influence on giant panda habitat quality and bamboo distribution. Ideal giant panda habitat consists of mixed coniferous and broadleaf forests dominated by tree species such as *Abies fabri*, *Picea asperata*, *Acer* spp., *Schima sinensis*, *Corylus ferox*, *Viburnum dilatatum*, *Sorbus alnifolia*, *Enkianthus chinensis*, and *Aesculus chinensis* (Qin et al., 2023b). These forests typically exhibit a canopy density of 20%–80% and are often characterized by the presence of bamboo groves (Zhang et al., 2011). However, given that county-wide bamboo distribution maps with species-level resolution are unavailable and considering that bamboo is inherently linked to other vegetation types and forest canopy density, these associated environmental factors significantly influence the DBH and height of bamboo, as well as the number of bamboo shoots and other growth indicators, which in turn affect habitat structure and food availability for pandas (Qin et al., 2023b). Therefore, we have included the growth environment for bamboo as part of environmental variables to indirectly reflect its presence and health (Qin et al., 2024, 2025; Yang et al., 2025a).

Excessive grazing can cause vegetation degradation and soil erosion, reducing food resource availability and increasing the risk of habitat fragmentation. This not only negatively impacts the giant panda habitat suitability but also leads to a decline in biodiversity (Chen et al., 2021; Tian et al., 2025). Quantifying grazing intensity facilitates the development of targeted restoration strategies aimed at mitigating these negative impacts and promoting habitat recovery (Fei et al., 2024). Additionally, distance to water, distance to roads, agricultural intensity, potential plant gathering pressure, and infrastructure presence are commonly reported factors influencing habitat suitability (Chen et al., 2021; Fei et al., 2024; Yang et al., 2025b). Grazing intensity was quantified using inverse distance weighting (IDW) interpolation (Kearney et al., 2023), based on the average daily counts of grazing events by cattle, sheep, and goats captured by infrared cameras (Lti Acorn, China). Distance to water sources was calculated by analyzing the Euclidean distance from water bodies identified in the land use category of the natural resource survey using ArcGIS v.10.8. To avoid spatial autocorrelation among environmental variables, a Moran's *I* correlation analysis was performed (Supplementary Table S1). Data compilation and preliminary analysis were conducted using Excel 2016, followed by statistical calculations in R v.4.3.3.

Habitat prediction analysis

To quantify habitat degradation, the 12 environmental variables were partitioned into intrinsic and controllable factors to construct the “theoretical habitat” and “actual habitat” layers. Elevation, slope, solar radiation, distance to water sources, vegetation type, tree diameter at breast height, and forest canopy density were categorized as intrinsic factors, as they are subject to limited modification through human intervention (Mehmood et al., 2024; Yang et al., 2025b). In contrast, variables such as grazing intensity, agricultural intensity, distance to roads, plant gathering, and infrastructure—which can be influenced by human activities—were considered controllable factors. For instance,

grazing intensity can be managed through conservation measures within protected areas. Accordingly, the habitat constructed using only intrinsic variables was designated as the “theoretical habitat”, whereas the habitat incorporating all variables was defined as the “actual habitat”. Finally, by overlaying the theoretical and actual habitats, areas where the actual habitat did not meet the potential of the theoretical habitat were identified as degraded habitats.

The MaxEnt v.3.4.3 model was employed to simulate the Habitat Suitability Index (HSI) for giant panda habitats, based on species distribution data and a suite of environmental variables. Habitats with HSI values exceeding the threshold determined by the maximum Youden's index were classified as suitable. During model calibration, 75% of the occurrence points were randomly allocated for training, with the remaining 25% reserved for validation, aligning with common practices to balance model training and validation (Su et al., 2021). To mitigate potential sampling bias, the model was iterated 10 times, and the final results represented the average of these 10 replicates. A jackknife test was used to assess the relative importance of environmental variables, while all other parameters remained at software defaults. Model prediction accuracy was evaluated using the receiver operating characteristic (ROC) area under the curve (AUC) and the true skill statistic (TSS). AUC values range from 0 to 1, with scores of 0.5 to 0.6 indicating inadequate models, 0.6 to 0.7 indicating poor performance, 0.7 to 0.8 considered acceptable, 0.8 to 0.9 rated as good, and values above 0.9 deemed excellent (Costa et al., 2015; Hameed et al., 2020). TSS ranges from −1 to 1, with values above 0.4 indicating acceptable predictive performance and values exceeding 0.8 representing excellent model discrimination (Allouche et al., 2006).

Habitat restoration model construction

The relative influence of each environmental factor on giant panda habitat suitability was quantified by its percentage contribution to the MaxEnt model. Notably, grazing intensity, a significant anthropogenic factor, profoundly affects habitat quality, particularly regarding vegetation-related variables. Restoration strategies targeting the three vegetation-related variables that include vegetation type, forest canopy density, and tree diameter at breast height adhere to the Guidelines for the Restoration of Giant Panda National Park Habitats in Sichuan Province (Giant Panda National Park Sichuan Provincial Administration, 2022).

The overall analytical framework and associated methods are summarized in Figure 2.

RESULTS

MaxEnt model results

The MaxEnt model yielded AUC values of 0.843 (Figure 3A) for the theoretical habitat and 0.930 (Figure 3B) for the actual habitat, with corresponding mean TSS scores of 0.642 and 0.689. Both metrics exceeded the thresholds generally considered acceptable in species distribution modeling, demonstrating high predictive reliability and justifying the use of the model in subsequent analyses.

Based on the established classification threshold, the theoretical habitat for the giant panda was estimated at 33 671.97 ha, encompassing 72.0% of the study area (Figure 4A). The actual habitat was identified as 25 624.44 ha,

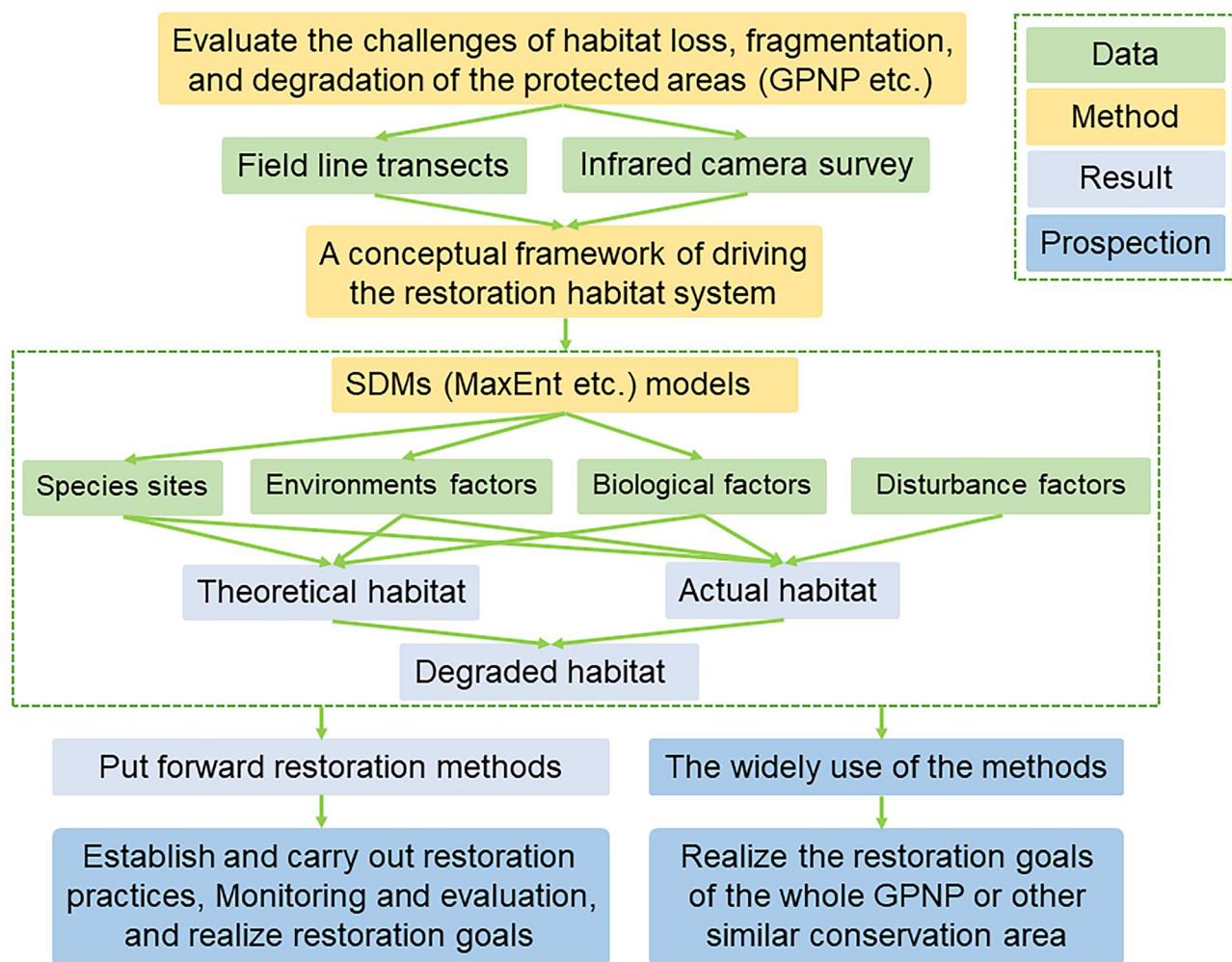


Figure 2 Conceptual and analytical framework used to identify degraded giant panda habitat and develop restoration strategies

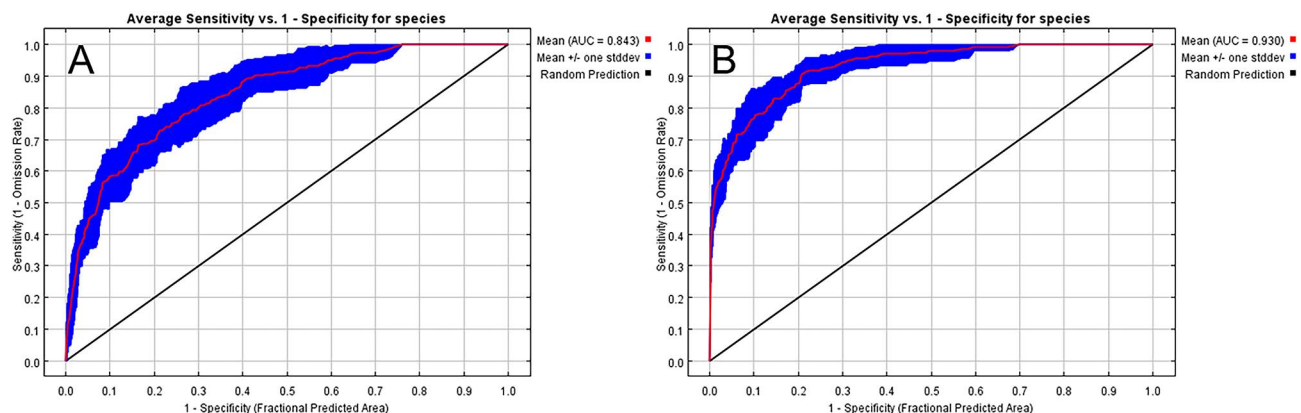


Figure 3 The ROC curves for the MaxEnt model of the GPNP in Shimian, Sichuan, China

A: Theoretical habitat model; B: Actual habitat model

covering 54.8% of the study area (Figure 4B). In contrast, 10 424.07 ha were classified as degraded habitat. The theoretical habitat exhibited relatively low fragmentation, whereas the actual habitat was characterized by higher fragmentation. Notably, significant habitat degradation in the region extending from Zima village to Menghuo village bifurcated the actual habitat into two distinct regions in the eastern and western parts of the study area (Figure 4C).

Analysis of giant panda habitat range

The overlay analysis of the actual and theoretical habitats

revealed that 23247.90 ha of the predicted habitat coincided with the actual habitat, accounting for 69.0% of the theoretical habitat. Conversely, 10424.07 ha were identified outside the observed habitat, representing 31.0% of the theoretical habitat (Figure 4C). These findings highlight a substantial area of degraded habitat with potential restoration. However, the actual habitat outside the theoretical habitat encompassed only 2376.54 ha, representing 9.3% of the actual habitat, to some extent, indicating that meeting the habitat requirements of giant pandas through artificial restoration in areas beyond

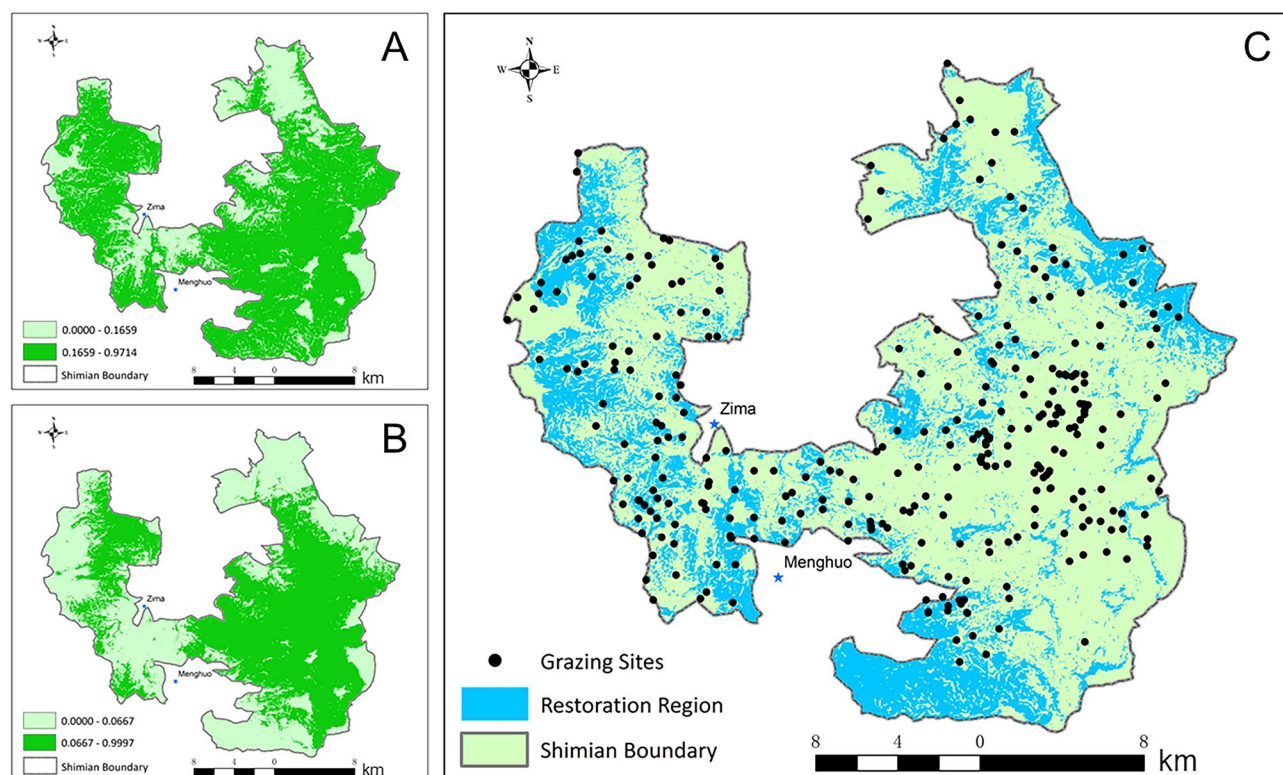


Figure 4 The habitat range for giant pandas of the GPNP in Shimian, Sichuan, China

A: Theoretical habitat; B: Actual habitat; C: Restoration habitat and grazing sites

the theoretical habitat is challenging.

The actual habitat of the giant panda was concentrated in three sectors: the Gongyihai area in the east, the Pusagang area in the center and the Zimaping area in the west. In Gongyihai, 14 376.39 ha were reclassified as actual habitat and 2 283.60 ha as degraded habitat, the latter corresponding to 15.2% of the theoretical habitat. In Zimaping, 4 058.82 ha remained as actual habitat, whereas 3 311.27 ha had become degraded, amounting to 45.5% of the theoretical habitat. Pusagang retained 3 743.43 ha of actual habitat and contained 2 718.23 ha of degraded habitat, representing 43.5% of the theoretical habitat. Thus, habitat degradation was markedly more severe in the Zimaping and Pusagang populations than in the Gongyihai population (Figure 4; Table 1).

Factors affecting giant panda habitat

In the theoretical habitat model, elevation emerged as the most significant factor, contributing 23.2%, followed by vegetation type (22.6%) and distance to water sources (16.4%). Meanwhile, tree diameter at breast height had the lowest impact, with a contribution of only 3.9%. This highlights

the critical role of elevation in defining the theoretical habitat suitability for giant pandas in this region. In contrast, the actual habitat model identified grazing intensity as the predominant factor, contributing 46.8%, followed by infrastructure (11.8%) and distance to water sources (6.8%). Among the controllable variables, grazing intensity was also the most influential factor for habitat suitability, followed by infrastructure (11.8%). Distance to roads and plant gathering each contributed 5.6% (Table 2).

The response curves revealed how theoretical and actual habitats were shaped by different dominant environmental filters. For the theoretical habitat, the probability of occurrence rose steeply at 1500–3000 m, peaked at 3000–3500 m, and then declined; it followed a similar bell-shaped pattern along the forest canopy density gradient, with high suitability concentrated in vegetation types 5 and 8. In contrast, the actual distribution was governed primarily by grazing pressure, with habitat probability declining sharply as grazing intensity increased and then gradually approaching 0. Infrastructure acted as the second limiting factor for the actual habitat,

Table 1 Giant panda habitat distribution and degradation of the Giant Panda National Park (GPNP) in the Shimian region

Category	Theoretical habitat (ha)	Actual habitat (ha)	Percentage (%)
Total areas	33 671.97	25 624.44	76.1%
Inside actual habitat	23 247.90	–	69.0%
Outside actual habitat	10 424.07	–	31.0%
Gongyihai	15 015.46	14 376.39	95.7%
Pusagang	6 255.60	3 743.43	59.8%
Zimaping	7 282.14	4 058.82	55.7%
Gongyihai degraded area	2 283.60	–	15.2%
Pusagang degraded area	2 718.23	–	43.5%
Zimaping degraded area	3 311.27	–	45.5%

–: Not available.

Table 2 The contribution rate of environmental factors to the model results that affect the habitat of the GPNP in the Shimian region

Environmental factors		Contribution rate to theoretical habitat model (%)	Contribution rate to actual habitat model (%)
Intrinsic factors	Elevation	23.2%	3.2%
	Slope	12.7%	3.6%
	Solar radiation	8.2%	1.4%
	Distance to water sources	16.4%	6.8%
	Vegetation type	22.6%	6.0%
	Tree diameter at breast height	3.9%	3.2%
	Forest canopy density	13.0%	2.5%
	Grazing intensity	/	46.8%
	Agricultural intensity	/	3.6%
Controllable factors	Distance to roads	/	5.6%
	Plant gathering	/	5.6%
	Infrastructure	/	11.8%

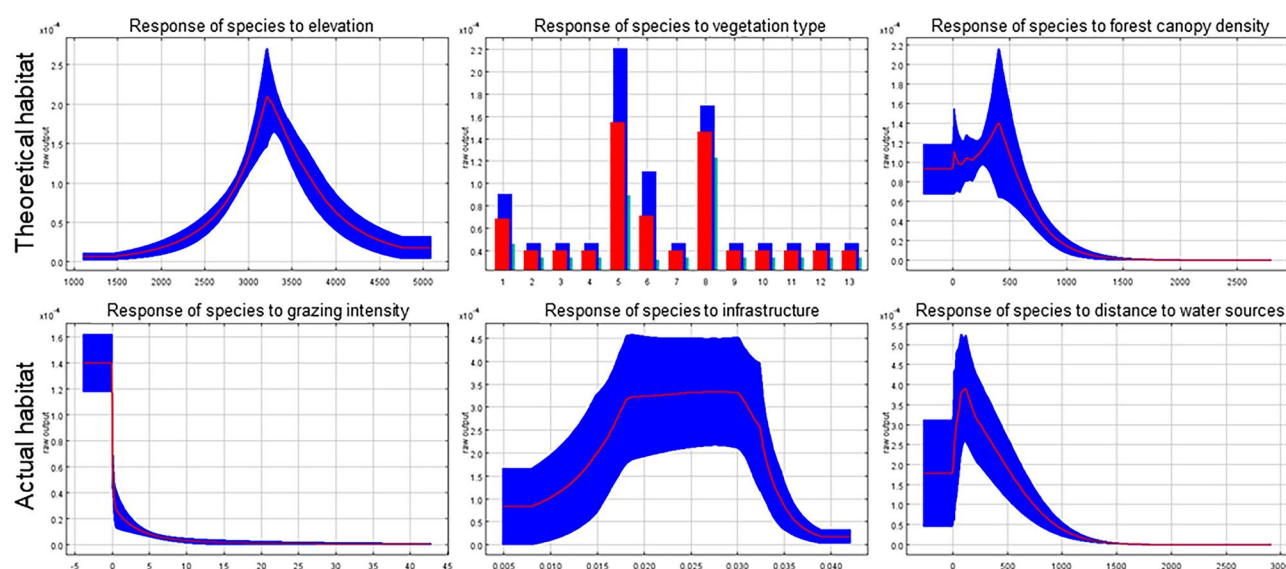


Figure 5 MaxEnt response curves of the top three dominant environmental variables in the theoretical and the actual habitat models

producing a humped response that initially rose, leveled off, and declined once density exceeded 0.03. Notably, distance to water sources maintained high probability within 200 m, after which suitability decreased significantly and approached 0 with further increases in distance (Figure 5).

Factors related to habitat restoration

Spatial overlay analysis revealed that agricultural and infrastructure lands together contributed less than 0.1% of the degraded habitat, confirming their negligible role. In contrast, grazing, which exerted the greatest impact on giant panda habitat, occurred across 850.9 ha and accounted for 8.2% of the total degraded area, with these areas concentrated along the boundary between Zimaping and Pusagang (Figure 4; Table 3). Although this proportion was relatively small, grazing was found to be widespread throughout the entire habitat and substantially reduced habitat connectivity, likely explaining its high weight in the model.

Further mapping of overlay analysis indicated that 4 078.69 ha of degraded habitat consisted primarily of sparse forest

with canopy density below 20% and an almost complete absence of arboreal trees, underscoring the importance of restoring native species such as maple (*Acer* spp.) and birch (*Betula* spp.). Additionally, the study identified 4 640.00 ha of degraded habitat with forest canopy density either below 20% or above 80% (Table 3).

DISCUSSION

Ecological interpretation of differences between theoretical and actual habitats

Habitats provide the essential conditions for species survival and reproduction. Habitat assessment is critical for identifying priority areas requiring strategic conservation efforts, thereby ensuring the long-term survival and health of emblematic species such as the giant panda (Mu et al., 2024; Pei et al., 2024). Quantifying habitat degradation is crucial for prioritizing conservation actions effectively. However, previous studies relying on traditional statistical analyses have primarily detected habitat degradation through statistical comparisons

Table 3 Categories of degraded habitat of the GPNP in the Shimian region

Category	Description	Area (ha)	Percentage of degraded habitat area (%)
Grazing activity area	Affects giant panda habitat primarily	850.90	8.2%
Artificial origin forest land	Mainly sparse forest land lacking arboreal trees	4 078.69	39.2%
Forest canopy density anomaly area	Canopy less than 20% or more than 80%	4 640.00	44.5%

of present and historical conditions, with limited exploration of the interplay among factors driving this degradation (de Fraga et al., 2023; Salmaniw et al., 2022).

In the present study, the introduction of “theoretical habitat” and “actual habitat” provides a robust framework for current and future research, enhancing the precision of habitat degradation assessments and the effectiveness of conservation strategies. The theoretical habitat serves as a proxy for historical conditions when precise data are unattainable, a common scenario in long-term habitat degradation studies such as those involving the giant panda. This concept facilitates more accurate identification of degraded areas by comparing the current, human-influenced actual habitats against this theoretical baseline. By integrating these comparisons, targeted restoration efforts can be designed to reverse or mitigate the impacts of habitat degradation. Consequently, this study identified the theoretical and actual habitats for the giant panda at 33671.97 ha and 25624.44 ha, respectively, with 23247.90 ha (69.0%) remaining functional and 10424.07 ha (31.0%) classified as degraded habitat, and the spatial distribution of degradation was explicitly mapped. Meanwhile, it is important to acknowledge the potential limitations of these concepts, particularly regarding data availability, as the accuracy of the theoretical habitat as a historical proxy depends on the quality and comprehensiveness of the data used for modeling.

The United Nations Environment Programme World Conservation Monitoring Center (UNEP-WCMC) emphasizes the need for strategic leadership and evidence-based support for effective ecosystem restoration and species recovery, which aligns with the goals of this study. The introduction of a definition for “actual habitat” in terms of human controllable factors, and its contrast with the intrinsic factors of “theoretical habitat” to identify habitat degradation not only aids in recognizing degraded habitats but also establishes a foundation for extensive habitat degradation analysis and restoration efforts, providing a replicable framework for future research and conservation practices. Furthermore, the integration of ecological theories into practical habitat restoration is gaining traction, as discussed by Loke & Chisholm (2022). This integration is vital for enhancing restoration success and provides a strong support system for habitat restoration initiatives, which can be further developed and tested in future studies.

Habitat restoration and habitat capacity

MaxEnt is a widely recognized approach for modeling species distributions and habitat suitability, enabling the simulation of both theoretical and actual habitats to identify degradation and inform strategic restoration and conservation for species such as the giant panda (Fei et al., 2024). Previous research by Zhang et al. (2023) used the MaxEnt model to highlight the fragmentation of suitable giant panda habitats in the Meigu Dafengding National Nature Reserve, where only a small proportion of highly suitable habitat remains, emphasizing the urgent need for in-situ conservation measures to enhance habitat connectivity and ensure species survival. Similarly, the present research revealed considerable areas of degraded habitat within and beyond the actual habitat, particularly in the Gongyihai area, where habitat restoration is imperative to support the giant panda population. The Zimaping population, although smaller, faces more severe degradation, underscoring the need for focused restoration efforts in this

context.

Referring to the minimum habitat area requirement of 3.7 km² for giant pandas (Hu & Xia, 1985), the current actual habitat of the GPNP in the Shimian region can support approximately 69 giant pandas. Recent research indicates that 33 giant pandas currently inhabit the area (He, 2019). Without considering habitat fragmentation, the existing habitat can sustain the current population; however, the potential expansion of the giant panda population is constrained by the total available habitat (Qing et al., 2016b; Wang et al., 2024b). A notable example is the migration of Zhang Xiang and Zhang Meng, who traveled a round-trip distance of more than 100 km from the Liziping release site to the territory of Mianning County, likely in search of optimal home ranges (Chen, 2022). Artificial intervention to restore degraded habitat could substantially increase carrying capacity, thereby facilitating a self-sustaining population.

The Tuowushan corridor, which links the eastern and western giant panda populations in Liziping (Huang et al., 2017a; Qing et al., 2016a), is primarily located within the degraded habitat. Restoring this degraded habitat is vital for enhancing connectivity and biodiversity in the Shimian region, which serves as a crucial corridor for the Liziping giant panda subpopulation. These findings are particularly significant for the habitat restoration and management strategies within the GPNP in the Shimian region. The implications of degraded habitat in Tuowushan for connectivity are substantial. Degradation can lead to habitat fragmentation, which may reduce the movement and gene flow between panda populations, potentially leading to inbreeding and a decline in genetic diversity (Wang et al., 2024b). Conservation efforts should focus on restoring the connectivity of the Tuowushan corridor to ensure the long-term viability of the giant panda populations. This could involve reforestation efforts, the creation of wildlife corridors, and the reduction of human disturbances within the corridor to facilitate panda movement, thereby enhancing genetic diversity and the overall health of the species.

Grazing dominated habitat degradation

Among the 12 environmental variables examined, grazing intensity emerged as the dominant factor, contributing 46.8% to habitat degradation in the Shimian section of the GPNP. This finding is consistent with previous studies demonstrating that excessive livestock grazing adversely affects ecosystems, leading to vegetation degradation and reduced biodiversity (Ran et al., 2005; Serrano et al., 2023). MaxEnt response curves show that the probability of species occurrence drops sharply as livestock density increases, corroborating the significant influence of grazing pressure on habitat suitability. Although degraded habitat caused by grazing accounted for only 8.2% of the total degraded area, grazing was widespread throughout the entire habitat and substantially reduced habitat connectivity. Grazing not only directly disturbs giant pandas but also indirectly diminishes habitat quality by altering vegetation types and impeding bamboo growth (Huang et al., 2017b).

Among the seven intrinsic variables, vegetation type and forest canopy density rank as the second and third most influential natural filters. However, their actual contributions shrink markedly, along with that of the dominant factor elevation, which drops from 23.2% in the theoretical model to 3.2% in the actual model, suggesting that controllable factors

rather than physiography now limit actual habitat suitability. Meanwhile, shifts in vegetation types and road segmentation effects resulting from human activities affect not only the food sources for giant pandas but also the structure and function of their habitats (Xu et al., 2024a). Among the five controllable variables, infrastructure accounted for 11.8%, while plant gathering and distance to roads each contributed 5.6%, and agricultural intensity only 3.6%, values consistent with the spatial pattern. As a protected area, the region experiences minimal road disturbance beyond the G108 highway, and although this corridor fragments adjacent vegetation, the overall disturbance density remains low, consistent with the limited road impacts identified in Shimian (Qin et al., 2022). Agricultural and infrastructure lands within degraded habitats account for less than 0.1% of the total degraded area, constituting a negligible driver of degradation. Given agricultural land protection and local livelihoods, excluding these variables from active restoration will likely leave outcomes largely unaffected.

Feasibility and constraints of the proposed restoration strategies

This study demonstrates that habitats are at imminent risk of continued degradation without enhanced management and that restoration feasibility is highest where controllable drivers can be rapidly reversed. Grazing pressure, the dominant driver of giant panda habitat degradation, is spatially restricted to 850.9 ha, representing 8.2% of the degraded area. Livestock exclusion and stall-feeding would regenerate sub-adult bamboo and restore connectivity between the habitat blocks of Gongyihai and Zimaping. Therefore, eliminating or markedly reducing grazing intensity is the primary restoration need, especially in the continuous high-intensity belt extending from Zima village to Menghuo village. However, the traditional reliance on grazing as a primary income source for local communities presents significant challenges to conservation management, rendering a simple ban or mere regulation of grazing intensity insufficient.

To mitigate the critical impacts of grazing on habitat degradation, a comprehensive management plan is required. Such a plan should scientifically assess the area's livestock carrying capacity, support local communities in developing environmentally sustainable alternative industries, and manage grazing activities to balance ecological conservation with local economic development (Banks-Leite et al., 2020). Furthermore, it is essential to explore alternative livelihood strategies that reduce reliance on livestock grazing. One such strategy involves promoting agricultural practices less dependent on grazing, such as agroforestry and the cultivation of high-value crops that require minimal land and cause minimal ecosystem disruption (Roe et al., 2015). These practices not only provide economic incentives for local communities to decrease grazing intensity but also support habitat conservation by maintaining vegetation cover and soil health. Additionally, developing ecotourism and nature-based tourism can offer alternative income sources with lower environmental impacts. By providing targeted training and institutional support, local communities can be encouraged to shift from traditional grazing toward more sustainable livelihoods that are compatible with habitat conservation.

Meanwhile, the effects of other factors including vegetation type and forest canopy density must not be overlooked, as they affect habitat quality and connectivity, which are vital for

giant panda survival and reproduction. Degraded areas comprising 4078.69 ha of sparse forest have been identified as requiring vegetation restoration. The Guidelines for the Restoration of Giant Panda National Park Habitats in Sichuan Province (Giant Panda National Park Sichuan Provincial Administration, 2022) stipulate the use of native tree species as a fundamental requirement, given their adaptability to local environments and the reduced risk of monoculture formation or invasive species. Owing to the limited efficacy of tree species replacement in naturally regenerated stands and its potential for unintended impacts on other native flora and fauna, restoration efforts considered tree species replacement only in areas of artificial origin. Meanwhile, tree species selection should be based on the native taxa identified in vegetation surveys, with priority given to native species. However, current market supplies mainly consist of economic or ornamental tree seedlings, while native seedlings are scarce. Prioritizing the cultivation of native seedlings is therefore essential for restoration work, rather than relying on readily available non-native seedlings. Although the slower growth of native trees often requires several decades to reach ecological functionality, and cultivating native seedlings may postpone immediate restoration benefits, their superior adaptability is expected to enhance long-term habitat recovery.

Tree diameter at breast height contributed only 3.9% in the theoretical model and 3.2% in the actual model; thus, restoration can safely focus on canopy structure rather than waiting for large-diameter stems, thereby accelerating the timeline. Degraded habitat covering 4640.00 ha displayed canopy densities either below 20% or above 80%. Since giant pandas prefer stands with canopy densities within the 20%–80% range (Ran et al., 2005), these stands require silvicultural adjustment to meet the physiological and behavioral optimum of the species. To counteract these degradation drivers, the primary strategy entails artificial restoration methods, such as hillside closure for natural regeneration coupled with afforestation and artificial seeding to raise canopy density or reconstruct plant communities. It is essential to establish specific timelines and benchmarks for measuring the success of these restoration efforts. For instance, a target should be established to achieve the desired canopy density within a defined period, such as 10–15 years, providing a clear benchmark for success. Assessing progress through remote sensing and field surveys conducted annually or biennially tracks restoration performance and allows for necessary strategy adjustments (Lindenmayer, 2020). Through these methods, restoration efforts are directed toward achieving desired outcomes and allow for flexibility under changing conditions, thereby supporting trajectory alignment and adaptive management.

CONCLUSION

The application of MaxEnt modeling to assess giant panda habitats within the GPNP in the Shimian region has yielded significant insights with broader conservation implications. The identification of extensive degraded habitat underscores an urgent need for targeted restoration efforts. It is imperative to allocate resources for restoring these areas through targeted reforestation and sustainable land management, as grazing regulations that reconcile local livelihoods with conservation objectives remain indispensable. Furthermore, enhancing habitat connectivity through habitat restoration and the

creation of wildlife corridors, particularly in critical corridors, is essential for facilitating genetic exchange and population viability of giant pandas. Additionally, vegetation recovery should be prioritized in areas with low forest canopy density, accompanied by regular monitoring to assess restoration effectiveness and adjust strategies as needed. Integrating these scientific findings into policy development and on-the-ground conservation practices is necessary, including updating land-use plans and engaging with local communities to ensure sustainable development that benefits both wildlife and people.

The replicable framework established by this research for identifying degraded habitats is not only effective within the GPNP but also adaptable to other regions. This transferability is underpinned by species distribution modeling, which can be applied to various ecosystems by incorporating specific environmental and spatial data, thereby allowing for the customization of habitat assessment and restoration strategies to local conditions. By adopting this approach, conservation practitioners can enhance the understanding of habitat distribution and dynamics, ensuring effective measures for species coexistence with their natural environment. Furthermore, this research contributes to broader conservation efforts by providing a science-based approach to wildlife habitat conservation and restoration initiatives globally.

DATA AVAILABILITY

The data presented in this study are available on request from the corresponding author.

COMPETING INTERESTS

The authors declare that they have no competing interests.

AUTHORS' CONTRIBUTIONS

W.L.: Data curation, Formal analysis, Methodology, Writing—original draft. Q.W.: Validation, Writing—original draft, Writing—review & editing. J.L.: Investigation, Methodology. H.P.: Investigation. X.C.: Methodology. Q.D.: Investigation. L.H.: Investigation. Z.Y.: Investigation. L.L.: Writing—review & editing. B.Y.: Conceptualization, Funding acquisition, Methodology, Supervision, Visualization, Writing—review & editing. All authors read and approved the final version of the manuscript.

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