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Original Research

Evolution of the “Panda–Rest–Bamboo” Ecosystem and Corridor Construction: A Case Study of Giant Panda National Park

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Abstract

Amid growing global efforts in biodiversity conservation, the protection of the giant panda in China has shifted from species-focused management to a holistic approach to ecosystem restoration. As one of the first designated national parks, the Giant Panda National Park (GPNP) plays a pivotal role in ecological conservation. Based on multi-source data from 2002 to 2022, this study examines the spatiotemporal evolution of giant panda habitats, rest spaces, and bamboo forests, and constructs an integrated ecological corridor system to evaluate changes in ecological connectivity and support conservation planning. The results show that: (1) Overall suitability remained stable, with increased habitat density in the Qinling and Daxiangling ranges, though bamboo resources in Daxiangling remained scarce; (2) Corridors were concentrated in Minshan, Qionglai, and Qinling, exhibiting short-distance and high-density patterns, while Daxiangling showed weaker connectivity; and (3) Declining ecological connectivity in some areas necessitates optimizing corridor structures, limiting disturbances, enhancing buffer zone management, and promoting the restoration and integration of source patches. This study provides a scientific foundation for optimizing ecological corridors and conserving giant panda habitats while promoting the coordinated management of habitat, rest space, and bamboo forest resources. It also contributes a replicable framework for advancing landscape-scale connectivity in global biodiversity conservation efforts.

Keywords: Giant Panda National Park, ecological corridor, habitat dynamics, ecological network, MaxENT model

Introduction

Habitat conservation has become a central issue in global biodiversity governance under the dual pressures of climate change and increasing ecosystem fragmentation [1]. The giant panda, widely recognized as both a flagship and umbrella species [2], plays a critical role in maintaining biodiversity within China’s protected areas [3]. However, large-scale deforestation during the 20th century severely reduced and fragmented panda habitats [4], causing the wild population to decline to around 1,000 individuals by the 1980s [5].

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In response, the Chinese government implemented a series of conservation policies [6], expanding nature reserves and restoring habitats [7]. According to the Fourth National Giant Panda Survey, the wild panda population has recovered to approximately 1,864 individuals, with the habitat area reaching 25,800 km² [8]. The establishment of the Giant Panda National Park (GPNP) in 2020 marked a new stage in conservation efforts, aiming to enhance ecological connectivity among fragmented populations and habitat patches [9, 10].

Existing research on GPNP mainly falls into two categories. The first focuses on spatial zoning and governance systems [11], which contribute theoretical insights but often lack empirical validation and spatial modeling. The second emphasizes habitat suitability assessment and spatial optimization [12], but such studies typically rely on static, single-species models [13], overlook bamboo resources as essential ecological dependencies [14], and pay insufficient attention to human disturbances [15]. These limitations restrict their practical applicability for guiding corridor construction.

This study addresses three major research gaps. First, few studies have simultaneously integrated panda habitats, bamboo forests, and recreational spaces, despite their ecological interdependence [16-20]. Second, there is a limited understanding of long-term spatiotemporal dynamics of suitability and connectivity, which are crucial for biodiversity management. Third, research on ecological corridors has largely focused on single dimensions, lacking composite corridor frameworks that balance ecological and human-use needs [21-24].

To fill these gaps, we applied the MaxENT model to integrate panda occurrence data, bamboo distribution, and recreational sites across five time points (2002, 2007, 2012, 2017, and 2022). We then construct a composite spatial network to reveal the coupling patterns of source areas. Using Linkage Mapper and the Minimum Cumulative Resistance (MCR) model, we identify both panda ecological corridors and composite corridors linking pandas with bamboo and recreation. Specifically, this study addresses the following questions:

1. How have the spatial distributions of giant pandas, recreational spaces, and bamboo forests evolved from 2002 to 2022?

2. What spatial and functional characteristics define the composite corridor network at each stage?

3. What correlations and synergistic mechanisms emerge among panda habitat, bamboo resources, and recreational spaces?

4. How can a human-nature coupled ecological network centered on panda conservation be constructed based on the spatiotemporal dynamics and interactions of these elements?

By combining multitemporal modeling with spatial-network analysis, this research develops a panda-centric, multifunctional ecological protection framework that balances ecological resources with human needs. The findings provide scientific guidance for China's national park management and species protection strategies, offering a transferable paradigm for the integrated conservation of other endangered species and their ecosystems worldwide.

Materials and Methods

Research Areas

Giant Panda National Park (GPNP), located in western China [25], was proposed in 2016 as one of the country's first pilot national parks. It integrates approximately 70 preexisting nature reserves distributed across Sichuan, Shaanxi, and Gansu provinces under unified management [26] (Fig. 1). The park covers an area of about 22,000 km², which is roughly three times the size of Yellowstone National Park in the United States [27]. GPNP comprises four major regions: the Minshan, Qionglai, Daxiangling, and Qinling subareas [28]. Among them, the Qionglai, Daxiangling, and Minshan subareas are located in the southern part (along the Sichuan-Gansu border), while the Qinling subarea lies at the northernmost boundary and represents the only distribution area of giant pandas in northern China [29]. The establishment of GPNP aims to strengthen the integrated conservation of giant pandas and other endemic species, enhancing the connectivity and sustainability of regional ecosystems. Additionally, this region is a global biodiversity hotspot that encompasses multiple priority conservation areas in China, conferring significant ecological protection value [30].

Data Collection

Data on the Giant Panda, the Bamboo Forest, and the Rest Sites

The giant panda occurrence data used in this study were derived from the third (1999-2003) and fourth (2012-2014) national giant panda surveys, which reported wild populations of 1,596 and 1,864 individuals, respectively. Species distribution data were preprocessed using the SDMToolbox, resulting in a final set of 215 validated occurrence points. Recreational site data were compiled by selecting national scenic area points, including A-level tourist attractions, national wetland parks, national forest parks, nature reserves, as well as township locations and key cultural heritage protection units, yielding a total of 58 representative sites. Bamboo distribution data were obtained from the Global Biodiversity Information Facility (GBIF) platform. All bamboo occurrence records within the spatial extent of GPNP were filtered, extracted, and cleaned to ensure geographic accuracy and ecological relevance. After removing redundant records, 82 bamboo distribution points were retained for further analysis.

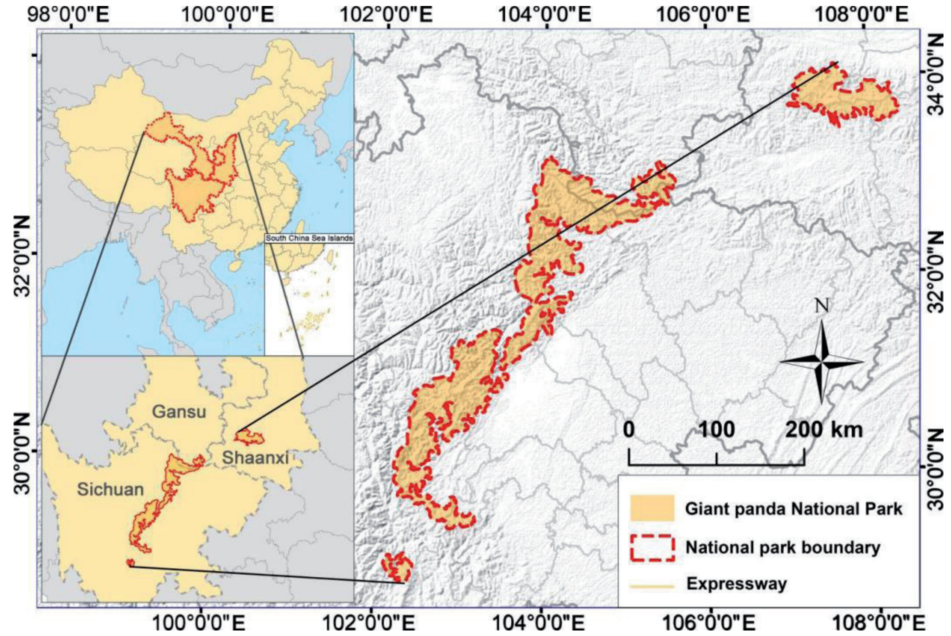

Fig. 1. Geographical location of China's Giant Panda National Park.

Environmental Data

This study selected a total of 22 environmental variables for giant panda habitat suitability modeling (Table 1), encompassing topographic and climatic factors, human disturbance, and landscape structure. Topographic and climatic variables include elevation, slope, aspect, temperature, precipitation, humidity, and normalized difference vegetation index (NDVI). Human disturbance factors consist of distances to roads, rivers, mines, power stations, neighborhood/village committees, and urban built-up areas, as well as nighttime light intensity and population distribution. Landscape structure and land-use variables included land-use types and distances to cropland, forest, green space, shrubs, water sources, and wasteland. For modeling the suitability of recreational space within GPNP, 18 environmental variables were selected. Natural environmental factors included elevation, temperature, humidity, precipitation, NDVI, and distance to water sources. Socioeconomic factors comprise population density, gross domestic product (GDP) distribution, and nighttime light intensity. Spatial accessibility factors cover distances to roads, urban built-up areas, residential settlements, A-level scenic spots, and rivers. Additionally, land cover characteristics were represented by distances to cropland, forest, green space, water sources, and wasteland. In bamboo forest distribution suitability modeling, 16 environmental variables were incorporated, representing natural terrain, climatic conditions, and vegetation landscape. Natural terrain variables include elevation, slope, aspect, and distance to rivers, reflecting the geomorphological basis for bamboo growth. Climatic variables (Table 2) encompass wind speed, temperature, humidity, and precipitation, indicating the influence of climate on bamboo distribution. Vegetation landscape factors include NDVI, distance to mines, and distances to cropland, forest, green space, shrubs, water sources, and wasteland, collectively characterizing the adaptation of bamboo forests to surrounding ecological patterns.

The System and Path of the Comprehensive Ecological Protection Corridor Network of the Giant Panda, Recreation Spaces, and the Bamboo Forest

Ecological corridor networks serve multiple functions, including biodiversity conservation, ecological recreation, and cultural heritage preservation [31]. As an effective approach to mitigating habitat fragmentation, these networks play a crucial role in enhancing habitat connectivity and facilitating the flow of natural elements [32]. In the current context of highly differentiated ecosystems and human activity spaces, single-function corridors are insufficient for integrating ecological and social components, thereby limiting the compound benefits of overall ecological governance [33]. Therefore, constructing a composite ecological corridor network that integrates giant panda habitats, recreational spaces, and bamboo forest resources by connecting both supply and demand sides of ecosystem services helps establish an ecological supply-demand network linking society and ecosystem services. This promotes an organic unification of species conservation, ecological experience, and sustainable utilization. By integrating biological habitats, ecological recreation nodes, and key vegetation resources, the network forms spatial pathways of ecological–social–cultural interactions, providing strategic support for the coordinated development of "conservation and utilization" within national parks. The following aspects characterize the ecological spatial system of GPNP:

Table 1. All environmental factors.

Environmental predictor	Description	Data source
Elevation	Altitude above sea level in kilometers	Geospatial Data Cloud (GSCloud) – Elevation, Slope, Aspect. (https://www.gscloud.cn)
Slope	Rate of elevation change over distance, expressed as a percentage	Geospatial Data Cloud (GSCloud) – Elevation, Slope, Aspect. (https://www.gscloud.cn)
Aspect of slope	Azimuth of slope orientation	Geospatial Data Cloud (GSCloud) – Elevation, Slope, Aspect (https://www.gscloud.cn)
Distance to roads	Euclidean distance to major transportation networks	OpenStreetMap. Open-source geographic data (https://www.openstreetmap.org)
Distance to waterway	Euclidean distance to main rivers	OpenStreetMap. Open-source geographic data (https://www.openstreetmap.org)
Distance from mine	Euclidean distance from mine point	Gaode Map (AutoNavi). Mapping and POIdata (https://www.amap.com)
Distance from power station	Euclidean distance from power station	Data is from the paper "Global dataset combining open source hydropower plant and reservoir data" (https://www.nature.com/articles/s41597-025-04975-0)
GDP distribution	Gross Domestic Product density and spatial pattern	National Bureau of Statistics of China (http://www.stats.gov.cn)
Distance to attractions	Euclidean distance to nationally-rated tourist attractions	Gaode Map (AutoNavi). Mapping and POIdata (https://www.amap.com)
Distance to community/village committees	Euclidean distance to local governance units	Shaanxi Provincial Government Portal (https://www.shaanxi.gov.cn)
Nighttime light data	Intensity of artificial light at night, proxy for human activity	NOAA VIIRS Nighttime Lights Dataset (https://eogdata.mines.edu/products/vnl/)
NDVI	Indicator of vegetation density and health	NASA MODIS NDVI Product (MOD13A3) (https://www.earthdata.nasa.gov)
Population spatial distribution	Population density and spatial pattern	WorldPop Project. Global population spatial datasets (https://hub.worldpop.org)
Wind speed	Airflow velocity over a unit of time	WorldClim – Global Climate Data (https://www.worldclim.org)
Humidity	Relative humidity expressed as a percentage	WorldClim – Global Climate Data (https://www.worldclim.org)
Temperature	Annual average air temperature	WorldClim – Global Climate Data. (https://www.worldclim.org)
Rainfall	Average annual rainfall	WorldClim – Global Climate Data (https://www.worldclim.org)
Land use type	Distribution of different types of land use	Chinese Land Cover Dataset (CLCD), Wuhan University (https://doi.org/10.5194/essd-13-3907-2021)
Distance to cropland	Euclidean distance to agricultural land	Chinese Land Cover Dataset (CLCD), Wuhan University (https://doi.org/10.5194/essd-13-3907-2021)
Distance to forest	Euclidean distance to forest-covered areas	Chinese Land Cover Dataset (CLCD), Wuhan University. (https://doi.org/10.5194/essd-13-3907-2021)
Distance to green spaces	Euclidean distance to public or natural green areas	Chinese Land Cover Dataset (CLCD), Wuhan University (https://doi.org/10.5194/essd-13-3907-2021)
Distance to shrubland	Euclidean distance to areas dominated by shrubs	Chinese Land Cover Dataset (CLCD), Wuhan University (https://doi.org/10.5194/essd-13-3907-2021)
Distance to water sources	Euclidean distance to surface water bodies	Chinese Land Cover Dataset (CLCD), Wuhan University (https://doi.org/10.5194/essd-13-3907-2021)
Distance to barren land	Euclidean distance to unused or degraded land	Chinese Land Cover Dataset (CLCD), Wuhan University (https://doi.org/10.5194/essd-13-3907-2021)
Distance to built-up areas	Euclidean distance to urbanized zones	PCL StarCloud Data Center (https://data-starcloud.pcl.ac.cn)

Table 2. Climate variables in the dataset.

Environmental predictor	Description	Data source
Bio1	Temperature Seasonality	Sciencedatabank data platform (https://www.scidb.cn/en/detail?dataSetId=cece16f1863b4ebd839894f6df26f8ac&version=V5)
Bio2	Isothermality	
Bio3	Max Temperature of Warmest Month	
Bio4	Min Temperature of Coldest Month	
Bio5	Temperature Annual Range	
Bio6	Mean Temperature of Wettest Quarter	
Bio7	Mean Temperature of Driest Quarter	
Bio8	Mean Temperature of Warmest Quarter	
Bio9	Mean Temperature of Coldest Quarter	
Bio10	Annual Precipitation	
Bio11	Precipitation of Wettest Month	
Bio12	Precipitation of Driest Month	
Bio13	Precipitation Seasonality	
Bio14	Precipitation of Wettest Quarter	
Bio15	Precipitation of Driest Quarter	
Bio16	Precipitation of Warmest Quarter	
Bio17	Precipitation of Warmest Quarter	
Bio18	Precipitation of Coldest Quarter	
Bio19	Accumulated Growing Degree Days of Daily Temperature >0ºC	
Bio20	Accumulated Growing Degree Days of Daily Temperature >5ºC	
Bio21	Annual Potential Evapotranspiration	
Bio22	Moisture Index	
Bio23	Temperature Seasonality	

1. Structural connectivity: ecological corridors link giant panda habitats, bamboo forest distributions, and recreational spaces to form an integrated network of habitat patches and corridors, thereby enhancing spatial connectivity among habitats;

2. Functional integration: the system centers on species conservation while also maintaining bamboo forest resources and promoting public ecological awareness, emphasizing habitat protection, scientific monitoring, and the dissemination of giant panda culture;

3. Spatial organization: ecological corridors serve as key connecting units that coordinate different ecological functional zones to establish a stable, continuous conservation pattern with educational and outreach functions.

Method Overview

This study employs the MaxEnt model [34] in conjunction with ArcMap spatial analysis [35], Linkage Mapper, and the Minimum Cumulative Resistance (MCR) model [36] to construct a comprehensive ecological corridor network integrating giant panda habitats, recreational spaces, and bamboo forests. The overall methodology consists of three steps. First, occurrence data for both giant pandas and recreational sites, as well as spatial distribution data for bamboo forests, along with natural and socio-environmental variables, were collected and preprocessed. Second, the MaxEnt model was used to analyze the spatial suitability distributions of these three components, with optimal suitability areas identified as source regions. Based on the suitability maps, resistance surfaces were generated in ArcMap, where higher suitability corresponded to lower resistance values. Third, ecological corridors for giant pandas were delineated using the Linkage Mapper tool. The MCR model was applied to identify the least-cost paths, thereby constructing composite corridors that link giant pandas with bamboo forests and recreational spaces. Finally, the three corridor types were optimized in ArcMap to establish the ecological spatial system of GPNP (Fig. 2).

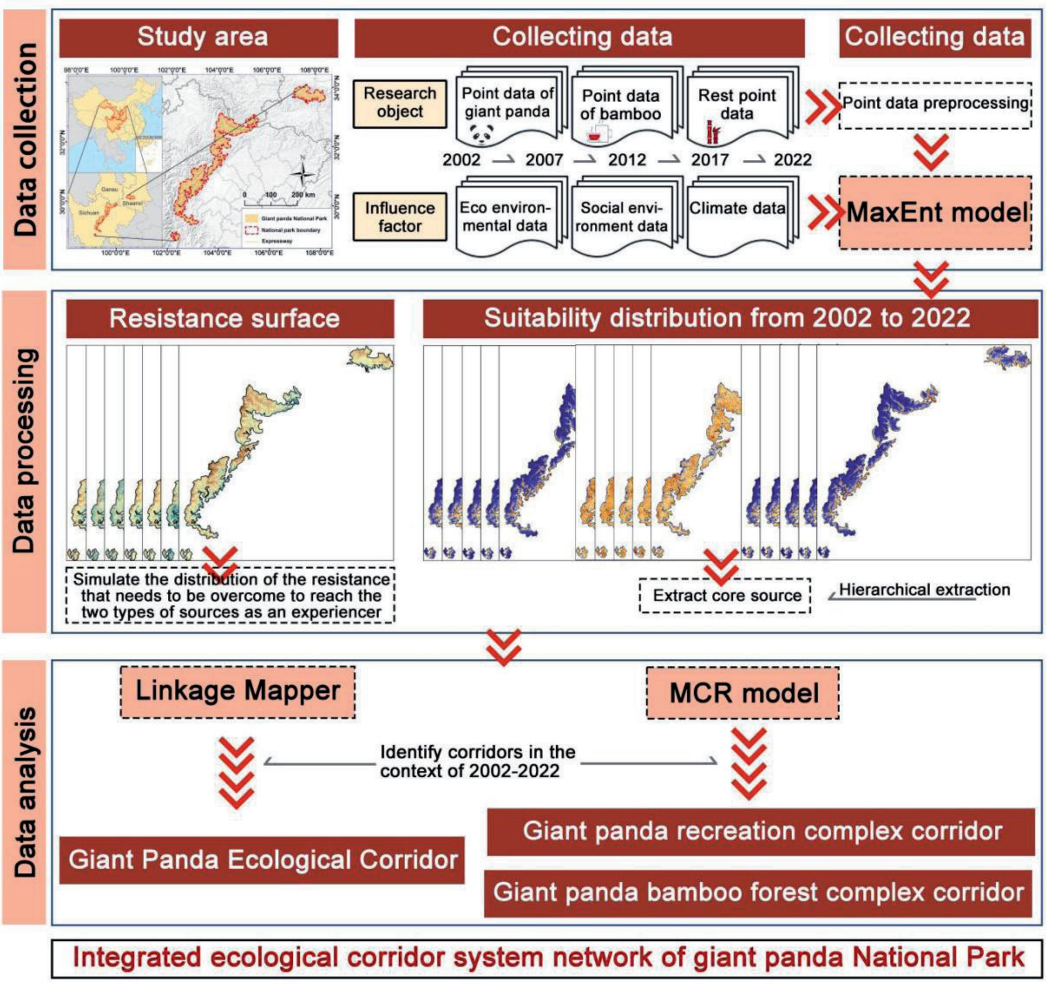

Fig. 2. Research framework of the integrated ecological corridor network in the Giant Panda National Park.

Suitability Prediction Model of Temporal Evolution in the Giant Panda Bamboo Forest Recreation Space

The MaxEnt model is an ecological suitability modeling approach based on species occurrence data and environmental variables to predict the potential spatial distribution patterns of species within a region. As a conservation-oriented tool, MaxEnt is widely applied in spatial predictions of species distributions and habitat quality. In this study, datasets for giant pandas, bamboo forests, and recreational nodes were used as the primary data sources, combined with environmental factor data to predict the spatial distributions of these three components using the MaxEnt model. The predictive performance of MaxEnt is typically evaluated by the area under the receiver operating characteristic curve (AUC), with values ranging from 0 to 1, where higher values indicate stronger predictive ability.

Identify Giant Pandas and Bamboo Forests and Rest Corridors

Initially, core areas for giant pandas, bamboo forests, and recreational sites were extracted. Suitability distribution maps generated by MaxEnt for these three elements were imported into ArcMap, where the natural breaks classification method was applied to divide the suitability index into five levels. The highest suitability level (class 5) was extracted, and core patches smaller than 20 km² were excluded, resulting in the final core areas for giant pandas, bamboo forests, and recreational spaces. Simultaneously, resistance surface layers were constructed to represent the spatial intensity of resistance during migration and connectivity processes between core source areas. Finally, ecological corridors connecting giant pandas with bamboo forests and recreational sites were identified and analyzed using the Linkage Mapper tool. Based on circuit theory and least-cost path principles, Linkage Mapper effectively assesses connectivity among core areas and identifies potential ecological corridors. By inputting the previously generated resistance surfaces and core area data, Linkage Mapper calculates the minimum cumulative cost paths between giant panda core areas and bamboo and recreational core areas, thereby delineating potential corridors.

Identification of a Comprehensive Ecological Protection Corridor Network

The Minimum Cumulative Resistance (MCR) model identifies optimal ecological connectivity paths by calculating the least-resistance routes between ecological source areas and target regions under varying resistance conditions. This model has been widely applied in ecological corridor suitability analyses. It simulates the movement of ecological elements or ecosystem service users through space along paths of minimal resistance, effectively capturing spatial ecological connectivity. In this study, the MCR model is employed to identify integrated ecological protection corridors within GPNP. Given the core role of giant panda habitats in ecosystem conservation, these habitats are designated as ecological source areas, while recreational spaces and bamboo forest distribution areas represent ecosystem service demand sites and are thus set as target regions. The model is expressed as follows:

$$MCR = f_{\min} \sum_{n}^{i=m} D_{ij} \cdot R_i$$

Where MCR denotes the minimum cumulative resistance value; f is a function representing the ecological process, D_{ij} is the distance between ecological source j and target i (bamboo forest or recreational area); and R_i is the resistance coefficient imposed by environmental factors i on the spatial movement process between the ecological source and the target site.

Results

Model Performance Evaluation and the Relationship between Various Elements

The three statistical models developed for giant panda habitat, bamboo forest suitability, and recreational space suitability all yielded strong evaluation results. Across the five time periods, the AUC values for all datasets exceeded 0.7, indicating excellent model fit and high predictive reliability. The results show that the influence of environmental variables on the distributions of giant pandas, bamboo forests, and recreational spaces varies significantly across the five benchmark years. For the giant panda suitability model, the contribution rates of key factors varied by year (Fig. 3):

1. In 2002, distance to power stations had the greatest influence, followed by distance to wasteland (16.5%).

2. In 2007, precipitation was the dominant factor (40.2%), followed by NDVI (16.9%) and humidity (12.4%).

3. In 2012, similar to 2002, distance to power stations again ranked highest (46.4%), followed by distance to wasteland (20.4%).

4. In 2017, the distribution of neighborhood/village committees became the primary factor (24.8%), with distance to power stations (17.9%), land use type (17.3%), and humidity (10.6%) also contributing significantly.

5. In 2022, the influence of distance to power stations further increased to 61.6%, followed by humidity (7.2%) and distance to wasteland (7.0%).

For the bamboo forest suitability model, the dominant factor remained stable, while secondary factors fluctuated slightly. Elevation consistently had the highest contribution in all five periods – 76.1%, 75.0%, 74.9%, 70.4%, and 76.2% – indicating its continuous role in determining bamboo growth suitability. Temperature was the second most important factor, with contribution rates ranging from 9.0% to 11.7%. Farmland distribution ranked third in most years, with lower contribution rates (approximately 4%-5%). In 2017, precipitation contributed 5.6%, reflecting a period-specific influence. Overall, the bamboo forest suitability model was predominantly influenced by natural factors, with limited impact from socioeconomic variables. For the recreational space suitability model, the dominant influencing factors showed a shift from natural terrain to socioeconomic conditions.

1. From 2002 to 2017, elevation remained the primary factor, with contribution rates of 72.7% (2002), 72.2% (2007), 72.7% (2012), and 74.0% (2017). Meanwhile, GDP distribution, temperature, and farmland gradually increased in importance.

2. By 2022, GDP distribution became the leading factor (73.7%), followed by nighttime light intensity and temperature (both 6.5%), indicating an increasing influence of socioeconomic factors on recreational space suitability.

Spatial Distribution Characteristics under Different Time Nodes

The overall spatial distributions of giant panda habitat, recreational spaces, and bamboo forests across the five time points are shown in Fig. 4. Within the GPNP, habitat suitability for giant pandas is the most widespread. All four areas – the Qinling area, the Minshan district, the Qionglai mountain area, and the Daxiangling area –exhibit generally high suitability, with only limited low-suitability zones appearing along some peripheral edges. In contrast, recreational spaces and bamboo forests are primarily concentrated along the margins of the four areas.

Based on the data from 2002, 2007, 2012, 2017, and 2022, Fig. 5 presents the temporal dynamics of panda habitat density. In the Daxiangling area, density shows an overall increasing trend, rising from 0.75 in 2002 to 0.85 in 2022. The Qionglai mountain area consistently maintains a high density level with only minor fluctuations, remaining between 0.84 and 0.94.

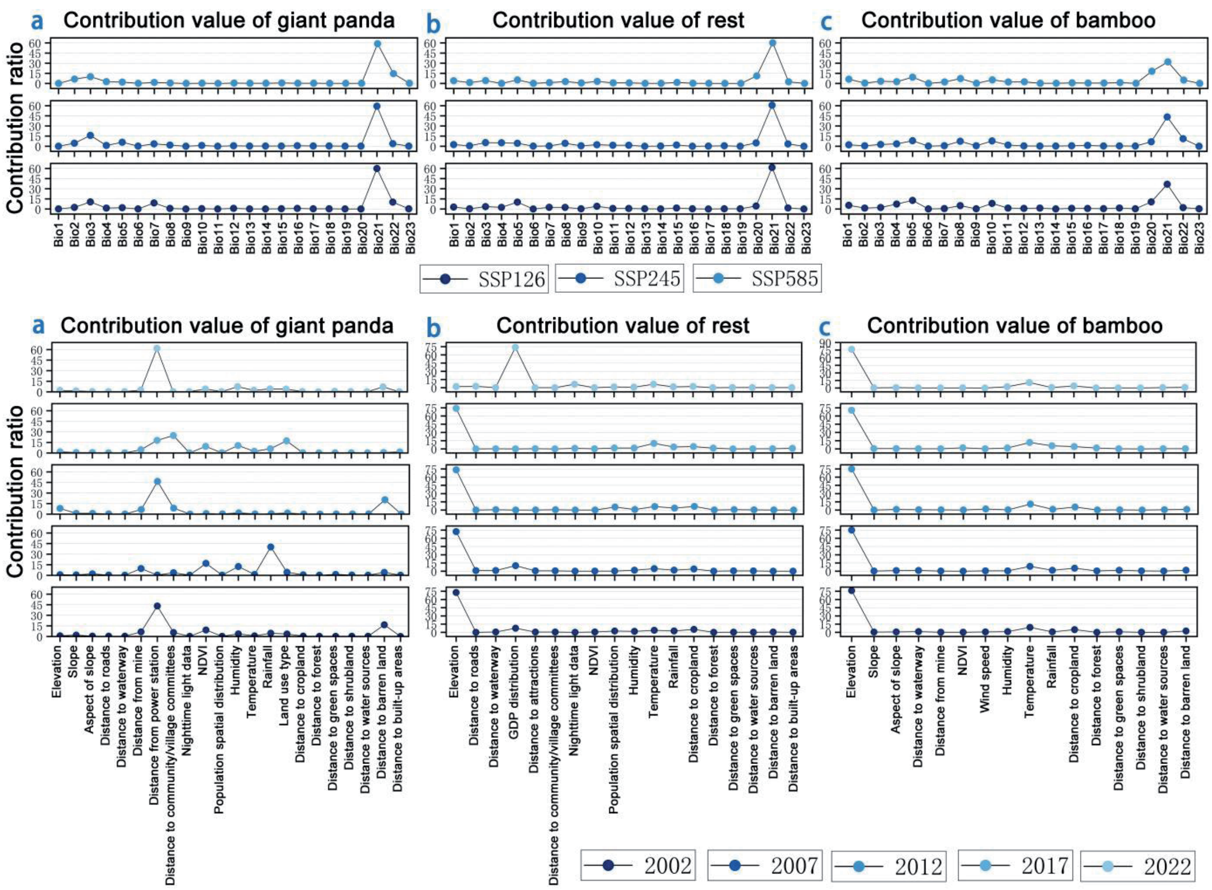

Fig. 3. Contribution rate of environmental variables under the SSP126-585 climate scenario from 2002 to 2022: a) Environmental variables in the habitat of giant pandas; b) Environmental variables of leisure habitats; c) Environmental variables in the bamboo habitat.

In the Minshan district, density peaked in 2012 at 0.98 before declining slightly in subsequent years. The Qinling area remained relatively stable throughout the period, with the 2022 value returning to the 2002 level (both 0.88). Moreover, the spatial distribution of panda habitat in the Qinling area shows a noticeable southward shift over time. The density of recreational spaces remains largely stable in all four areas. The Qinling area and Minshan district both maintain a constant density of 0.99, while the Qionglai mountain area remains stable at 1.00 across all years. Only the Daxiangling area shows a slight decline, from 0.99 (2002-2017) to 0.98 in 2022. The density of bamboo forests shows a similar trend to that of recreational spaces. In the Qinling area, Minshan district, and Qionglai mountain area, the density fluctuates slightly between 0.99 and 1.00, reaching 0.97, 0.99, and 0.99, respectively, in 2022. The Daxiangling area maintained a stable density of 1.00 in 2022, with minimal change in its spatial extent (Table 3).

Construction of Space Corridors under Different Time Nodes

Using a hierarchical extraction method, we delineated core source areas for giant panda habitat, recreational core areas, and core bamboo sources for each benchmark year from 2002 to 2022 (Fig. 4). In aggregate, the area of giant panda core sources fluctuated markedly, reaching a maximum of 3,641 km² in 2007 and a secondary peak of 2,548 km² in 2017. Within the Daxiangling area, no core panda sources were present in 2002; they emerged between 2007 and 2017 but disappeared again by 2022, whereas distributions in the other three areas remained relatively stable. Recreational sources exhibited a persistent decline in both number and area, decreasing from 34 sites (1,236 km²) in 2002 to 23 sites (971 km²) in 2022. These sources were largely concentrated along the south-eastern fringe of GPNP near densely populated zones, although a localized increase was observed in the Qinling area. Bamboo core sources showed comparatively stable spatial patterns, remaining clustered along the park's south-eastern edge with minimal change in number or area; notably, the Daxiangling area consistently lacked core bamboo sources larger than 20 km².

During source-area identification, we also calculated land-use composition for the giant panda, recreational, and bamboo core sources. As a protected area, GPNP is dominated by forest across all three source types. In the giant panda core sources, forest cover remained above 85% throughout 2002-2022, peaking at 94.36%

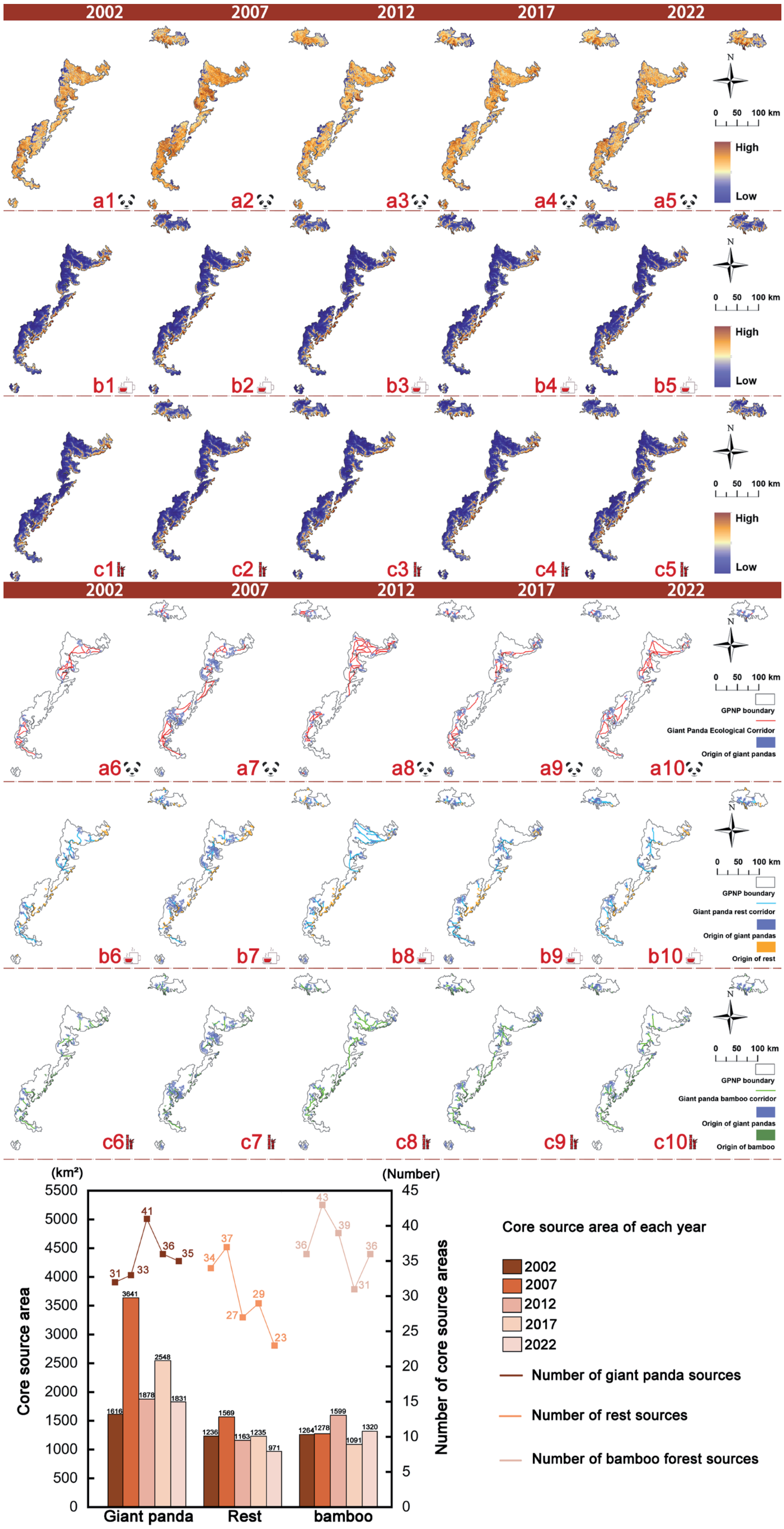

Fig. 4. Spatial suitability distributions and ecological corridors of giant panda habitat, recreation, and bamboo forest from 2002 to 2022, along with the number and area of core source patches in each period: (a1-a5) Habitat suitability; (b1-b5) Recreation suitability; (c1-c5) Bamboo forest suitability; (a6-a10) Giant panda ecological corridors; (b6-b10) Giant panda–recreation composite corridors; (c6-c10) Giant panda–bamboo composite corridors.

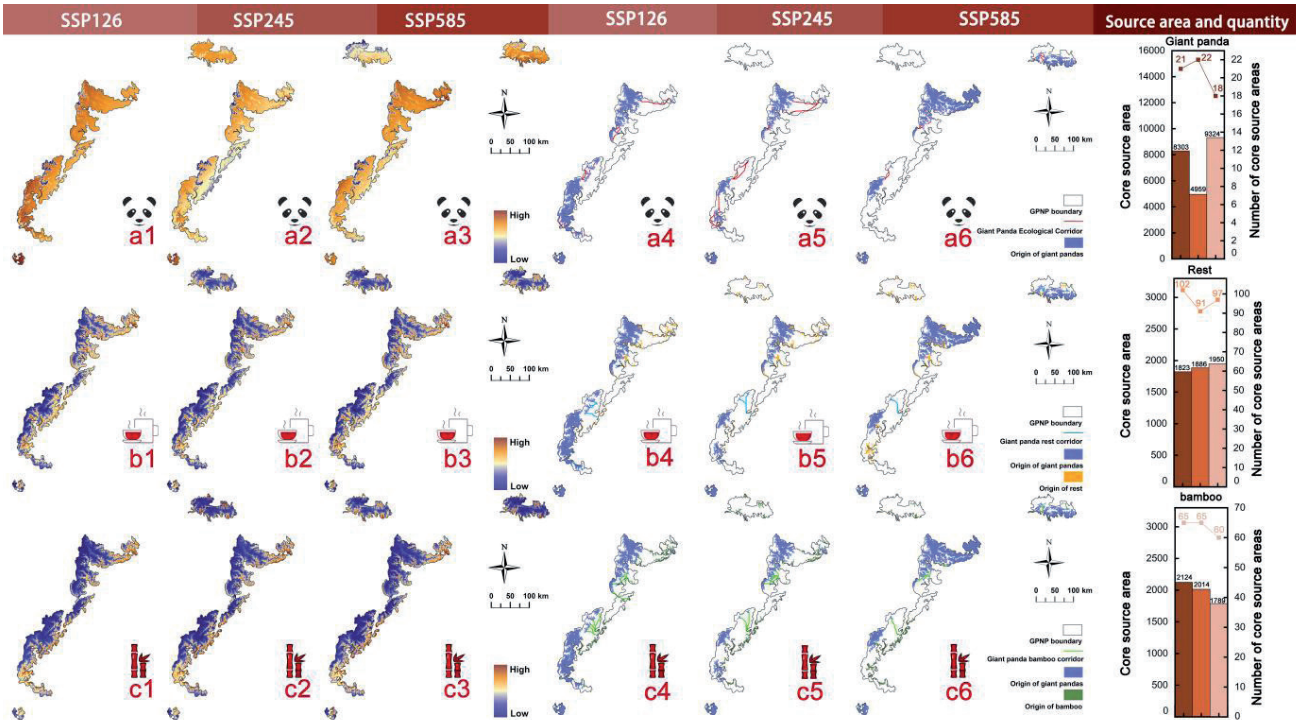

Fig. 5. Spatial suitability of giant panda habitat, recreation, and bamboo forest under future climate scenarios (SSP126–SSP585, 2041-2070), along with ecological corridors and the quantity and area of core source patches: (a1-a3) Giant panda habitat suitability; (b1-b3) Recreation suitability; (c1-c3) Bamboo forest suitability; (a4-a6) Giant panda ecological corridors; (b4-b6) Giant panda–recreation composite corridors; (c4-c6) Giant panda–bamboo composite corridors.

(3,434.34 km²) in 2007 and reaching its lowest level of 86.65% (1,622.99 km²) in 2012; grassland was secondary, holding steady at 5% -10% . In recreational core sources, the forest proportion was generally stable – 87.38% (1,043.19 km²) in 2002 and 89.99% (847.48 km²) in 2022 – with a maximum of 92.88% in 2017. Cropland ranked second but declined from 10.75% in 2002 to 7.96% in 2022. In bamboo core sources, forest cover rose annually from 86.27% in 2002 to 91.53% in 2022, while cropland fell from 11.90% to 6.52%. Overall, forests consistently accounted for the largest share in all three source types, with the strongest afforestation trend in bamboo sources and a noticeable reduction of cropland in recreational sources.

Using Linkage Mapper, we delineated giant panda ecological corridors, identifying 49, 46, 70,

Table 3. Suitability density variation under five time periods (2002-2022) and three future climate scenarios.

Type	Area	2002	2007	2012	2017	2022	SSP126	SSP245	SSP585
Giant panda	Qinling	0.88	0.76	0.77	0.79	0.88	0.52	0.57	0.63
	Minshan	0.92	0.84	0.98	0.90	0.85	0.66	0.85	0.84
	Qionglai	0.93	0.84	0.93	0.94	0.93	0.76	0.77	0.70
	Daxiangling	0.75	0.8	0.76	0.86	0.85	0.80	0.81	0.71
Rest	Qinling	0.99	1	0.99	0.99	0.97	0.84	0.87	0.85
	Minshan	0.99	1	1	1	0.99	0.87	0.90	0.92
	Qionglai	0.99	1	0.99	0.99	0.99	0.98	0.90	0.95
	Daxiangling	0.99	1	0.99	1	1	0.91	0.80	0.92
Bamboo	Qinling	0.99	0.99	0.99	0.99	0.99	0.82	0.78	0.71
	Minshan	0.99	0.99	0.99	0.99	0.99	0.89	0.89	0.92
	Qionglai	1	1	1	1	1	0.90	0.96	0.94
	Daxiangling	0.99	0.99	0.99	0.99	0.98	0.90	0.94	0.92

48, and 49 corridors in 2002, 2007, 2012, 2017, and 2022, respectively, with total lengths of 915.91 km, 1,145.08 km, 1,562.24 km, 923.12 km, and 1,364.01 km. The MCR model was then applied to generate composite corridors linking giant pandas with recreational spaces and bamboo resources (Fig. 4). The giant panda–recreational composite corridors numbered 28, 30, 34, 29, and 34 across the five years, with total lengths of 737.29 km, 919.61 km, 901.68 km, 768.59 km, and 657.27 km. The giant panda–bamboo composite corridors totaled 29, 31, 31, 30, and 32, with corresponding lengths of 512.76 km, 402.11 km, 910.22 km, 699.47 km, and 612.25 km. Giant panda ecological corridors are concentrated in the Minshan district, Qionglai mountain area, and Qinling area; the Daxiangling area shows only a few corridors in 2012 and 2017. In 2007, the larger extent of panda core sources yielded a compact, highly connected corridor pattern across the park, although no corridors formed in Daxiangling that year. In other years, most corridors extended linearly over greater distances, reflecting more dispersed core-source configurations. Giant panda–recreational composite corridors also lie mainly in the Minshan district, the Qionglai mountain area, and the Qinling area for all five time points; except for 2007, none were identified in the Daxiangling area, indicating a lack of stable, suitable recreational sources there. Giant panda–bamboo composite corridors display stronger spatial heterogeneity: in Minshan and Qionglai, corridors cluster at the northern and southern ends with sparse coverage in the central zone, producing a "sandwich-like" pattern with some long links; in Qinling, corridors are densely arranged around southern core sources, forming a compact bamboo–habitat network. Because the Daxiangling area lacks extensive, high-suitability bamboo, no composite corridors were detected there, highlighting limited bamboo resource support in that area.

Discussion

Protection of the Giant Panda Ecological Habitat

Ecological conservation serves as the fundamental basis for maintaining global biodiversity, while ecosystem services – through climate regulation, water supply maintenance, and habitat provision – directly or indirectly enhance human well-being [37]. A strong interdependence exists between the two: the healthy functioning of ecosystems supports the stability of natural systems and, in turn, directly influences the quality of human life [38]. Effective environmental governance should thus foster a positive synergy between ecosystem services and human well-being [39]. As one of China's first ten pilot national parks [40], the GPNP aims to achieve large-scale conservation of the giant panda population through an integrated and standardized spatial management framework.

However, in recent years, human activities have increasingly disrupted the integrity of habitats. According to the Fourth National Survey Report on Giant Pandas [41], the park contained over 1,300 roads at the time of the survey, which increased to 2,909 by 2022, along with 320 hydropower stations, 980 residential settlements, and 520 agricultural land-use areas. Previously continuous forest–bamboo corridors have been replaced by bare land, farmland, residential zones, and secondary vegetation. This has significantly reduced ecological connectivity and limited the movement of pandas across habitats.

Constructing ecological corridors has thus become a critical strategic measure. These corridors connect isolated core panda habitats, restoring landscape connectivity and providing pathways for migration, foraging, breeding, and gene exchange. Previous studies in GPNP identified 24 ecological sources and 55 corridors, highlighting 23 priority corridors and 14 restoration nodes [42]. These findings suggest that corridor planning should focus on high-leverage links rather than uniform interventions. Moreover, feasibility assessments around GPNP emphasize that human disturbances are the main limiting factor and that priority corridor construction and habitat restoration are key strategies in highly fragmented areas [43]. Therefore, ecological corridors are central to overcoming population isolation, increasing genetic diversity, and enhancing species resilience to environmental change.

Optimizing corridor width and structural configuration is essential. Priority should be given to areas with mixed forest and bamboo coverage to ensure both concealment and continuity of food sources. Ecological stations should be established along fragmented or long-distance corridors to enhance movement accessibility and connectivity. In parallel, human activities around corridors should be restricted by implementing buffer zone management, controlling new roads and agricultural expansion, and reducing disturbances such as herb and bamboo harvesting, which cause vegetation loss and soil compaction, thereby degrading habitat quality. Although agricultural activity has contributed to habitat reduction and increased fragmentation, transforming steep-slope farmland back into forest has helped restore key habitats and re-establish ecological corridors. By integrating existing protected areas and forest resources, a multi-level ecological network has been established, improving both regional ecological suitability and overall habitat quality for giant pandas.

Ecological Benefits of Resting and the Construction Strategy of the Bamboo Forest

Ecological Corridor in GPNP

Using the core sources of giant panda habitat, recreational spaces, and bamboo distribution within GPNP, this study identified corresponding composite ecological corridors. Over the course of five benchmark years, both suitable recreational areas and bamboo-forest core sources remained relatively stable. These areas were mainly concentrated along the south-eastern edges of the Minshan district, the Qionglai mountain area, the Daxiangling area, and the southern Qinling region.

In recreational core sources, forest and cropland consistently occupied the largest land-use shares, highlighting the influence of human activity. Cropland is typically located near settlements, roads, and water bodies. Its accessibility and infrastructure make it suitable for conversion into leisure sites, such as scenic platforms, agritourism zones, or eco-experience areas. Moreover, the generally level terrain reduces development costs, allowing for low-intensity recreational facilities that balance ecological protection and human use [44]. Under the park's "ecological restoration + moderate utilization" policy, portions of cropland can be reallocated to ecological recreation, facilitating a shift from agricultural production to ecosystem service provision.

In areas with concentrated recreational activities, constructing giant panda–recreational composite corridors is critical. These corridors help mitigate habitat fragmentation and promote recovery. To counter cropland expansion and agricultural disturbances, measures such as converting cropland to forest or bamboo and establishing ecological transition zones are recommended. Intensive harvesting and grazing disrupt arrow bamboo and compact soils, accelerating habitat degradation and resource competition. Furthermore, comparative studies have shown that plantation forests within nature reserves often exhibit excessively high tree density, limited bamboo resources, and reduced understory biodiversity compared to natural forests. Such conditions cannot fully meet the ecological requirements of giant pandas, and habitat differences between plantations and natural forests are often difficult to detect with conventional suitability models. Therefore, incorporating microenvironmental indicators, particularly bamboo density, is essential for designing effective corridors and delineating core conservation areas [45].

Optimizing corridor alignment, integrating existing forest resources, and using mixed forest–bamboo cover can enhance concealment, maintain food continuity, and improve ecological connectivity. Bamboo remains the primary food source for giant pandas. Similarly, in bamboo core sources, forest and cropland dominate land use. Constructing giant panda–bamboo composite corridors requires a systematic approach, focusing on bamboo distribution, enhancing ecological functions, and improving landscape connectivity.

Priority should be given to connecting areas near giant panda core sources where bamboo density and connectivity are high, forming bamboo-based ecological pathways. Degraded lands, including bare ground, shrub-grassland, bamboo stands, monoculture plantations, and secondary forests, should be rehabilitated. Restoration methods include installing soil bunds, planting bamboo, or creating mixed shrub–bamboo mosaics. Bamboo stand management should apply uniform or strip thinning to reduce stem density and canopy closure, ensuring adequate light and nutrients. Excess shrubs and lianas should be pruned or girdled to limit regrowth and competition. In liana-rich secondary forests, selective thinning can promote the growth of bamboo and native, fast-growing trees, thereby enhancing ecological function and supporting long-term management effectiveness.

Suitability Analysis of GPNP under Different Climate Change Scenarios

Building on the temporal and spatial analysis of giant panda habitat, recreational spaces, and bamboo forests from 2002 to 2022, and the construction of ecological corridors, this study further incorporates three Shared Socioeconomic Pathways (SSP126, SSP245, SSP585) recently released by the IPCC. Twenty-three bioclimatic variables were used as environmental drivers to predict and simulate potential suitability distributions and changes in ecological connectivity of giant panda habitats, bamboo resources, and recreational spaces within the GPNP for the period 2041-2070 (Table 2). This approach supports the exploration of ecosystem responses under future climate scenarios. As shown in Fig. 5, the overall spatial patterns of suitability for giant panda habitat, recreational spaces, and bamboo under all three future scenarios show limited changes. However, density variations among the four areas reveal a sensitive response to climate change. In the Daxiangling area, the suitability density of giant pandas initially rises from 0.80 to 0.81 before declining to 0.71. The Minshan district stabilizes around 0.84 after reaching 0.85 under SSP245. The Qionglai mountain area declines from 0.76 to 0.70, whereas the Qinling area shows a continuous increase from 0.52 to 0.63. Recreational space density fluctuates slightly. The Qinling area gradually declines from 0.82 to 0.71, while the Minshan district and Qionglai mountain area maintain high levels (≥0.89). In the Daxiangling area, density slightly increases before stabilizing between 0.90 and 0.92. Bamboo suitability exhibits regional variation. It generally increases in the Minshan district and Daxiangling area, decreases, then rises in the Qionglai mountain area (0.98-0.90-0.95), and fluctuates slightly in the Qinling area (0.84-0.85) (Table 3).

Using a multi-level extraction method, the core source areas of giant panda habitat, recreational spaces, and bamboo forests were identified for 2041-2070 (Fig. 5). Under SSP245, the highest number of giant panda core source areas was found (22), whereas SSP585 had the fewest (18). Nevertheless, the total area was largest under SSP585 (9,324 km²), indicating spatial concentration under high-emission conditions. The number of recreational core areas was 102, 91, and 97 under SSP126, SSP245, and SSP585, respectively, with the total area gradually increasing from 1,823 km² to 1,950 km². Bamboo forest core areas remained stable in number but decreased to 60 under SSP585, accompanied by a corresponding reduction in area, indicating a higher sensitivity to climate change. Spatially, the giant panda core source areas shifted northward to the Minshan district and Qionglai mountain area, appearing only under SSP585 in the Qinling area. Recreational and bamboo forest core areas remained concentrated along south-eastern margins, with relatively stable spatial patterns.

For ecological corridors (Fig. 5), the highest number and longest total connectivity length were observed under SSP245, with 26 corridors spanning 514.55 km. SSP126 and SSP585 each identified 18 corridors, with total lengths of 236.58 km and 104.23 km, respectively. This is lower than the historical average for the 2002-2022 period. Giant panda–recreation composite corridors showed minimal variation in number, but length decreased from 236.58 km under SSP126 to 172.34 km under SSP585. Giant panda–bamboo composite corridors performed best under SSP126 (472.93 km) but were significantly shorter under SSP245 and SSP585.

Overall, under future climate impacts, the distribution of all corridor types becomes sparser, with reduced connectivity strength. Corridors are mainly concentrated in the Minshan district and Qionglai mountain area, characterized by short-distance, high-density connections. In the Daxiangling area, corridors remain scarce, while in the Qinling area, they form limited connections only under SSP585 due to a southward shift of the core source areas.

Response of Giant Panda Habitat to Future Climate Change

Under future climate scenarios SSP126, SSP245, and SSP585 for the period 2041-2070, the overall spatial pattern of suitable core habitat within the GPNP remains relatively stable. However, density changes within the four areas reveal a sensitive response to climate change. In the Daxiangling area, habitat density under SSP585 declines markedly from 0.81 to 0.71. The Minshan district and Qionglai mountain area also show fluctuations or decreases, indicating a decline in habitat quality. In contrast, the Qinling area exhibits a gradual increase from 0.52 to 0.63, suggesting potential improvements in suitability. Simultaneously, both the number and length of composite corridors decrease under the high-emission scenario, reflecting reduced ecological connectivity. This may limit the movement of giant pandas and their future dispersal. To address the weakened connectivity and spatial restructuring of suitable habitats, it is crucial to develop a climate-adaptive ecological corridor network. Priority should be given to constructing short-distance, high-density corridors with mixed forest, bamboo, and resting spaces. In particular, north-south ecological transition buffers in the Minshan and Qionglai mountain areas should be strengthened to maintain resource continuity and enhance population resilience under extreme climate conditions. Small core habitat nodes can be established at corridor fragmentation points to serve as stepping stones during migration, improving survival stability under high temperatures and drought.

In climatically stable regions, such as Qinling, core habitats should be prioritized for protection and restoration to reinforce their central role within the ecological network. In areas like Daxiangling, where density declines continuously, management should focus on restoring degraded forests, planting suitable vegetation, and restricting agricultural disturbances to enhance climate adaptation and recovery.

Overall, integrating climate projections with corridor layout models allows the development of a dynamic, temporally flexible corridor system. Such a system can sustain ecological function, maintain connectivity, and provide long-term support for giant panda populations under changing climate scenarios. These findings underscore the need for adaptive management strategies in future conservation planning, emphasizing both structural and functional resilience.

Limitations and Future Directions

This study constructed an integrated corridor network linking giant panda habitats, recreational spaces, and bamboo forests within the Giant Panda National Park while projecting their distributions under future climate scenarios. While addressing key conservation gaps, several limitations remain. Historical data limitations, including monitoring accuracy and spatial resolution, may introduce uncertainties in identifying core areas and assessing habitat suitability. Corridor design focused primarily on spatial connectivity and did not fully consider cumulative human disturbances or socioeconomic drivers, potentially overestimating effectiveness. Moreover, simplified models for future projections may not capture multi-scale ecological dynamics, species adaptation, or landscape feedbacks. Future research should integrate multi-source data, finer-scale ecological indicators (e.g., bamboo density), and dynamic modeling, combining long-term monitoring with scenario simulations to improve predictions and provide adaptive guidance for park management. These reflections emphasize that corridor planning must account for ecological complexity, human influence, and the need for adaptive management.

Conclusions

Using data from 2002 to 2022, this study constructed integrated ecological corridors for the giant panda habitat, recreational space, and bamboo forest within GPNP at five historical time points. By moving beyond traditional single-corridor approaches, the research captures temporal shifts in panda–human–nature interactions. Giant panda occurrence records, recreational-space distributions, and bamboo-cover data were combined to generate suitability maps with the MaxEnt model, from which core source areas were extracted. Giant panda corridors were delineated with Linkage Mapper, while composite corridors linking pandas with recreational areas and bamboo forests were identified using the Minimum Cumulative Resistance model. The resulting panda–recreation–bamboo corridor network connects source patches to the broader conservation system. Key findings are as follows: (1) Between 2002 and 2022, the three source types followed distinct trajectories. Giant panda core-source density fluctuated and contracted in some zones, whereas recreational and bamboo sources remained relatively stable along the park's south-eastern margin. (2) Corridor identification across the five periods revealed an overall southeastward concentration with dense, short-range links; the Minshan district and Qionglai mountain area emerged as priority zones for corridor development. Composite corridors retained strong connectivity potential and should be reinforced by expanding forest–bamboo mixed cover to improve concealment and food continuity. (3) Based on temporal change, corridor structure should be optimized, core sources reinforced, and human activity coordinated with ecological restoration to enhance connectivity and system stability. Recommended measures include restoring degraded cropland, restricting agricultural expansion and other disturbances, and integrating fragmented habitat patches to create a protection pattern anchored by core sources and tied together by composite corridors.

In conclusion, this study provides a spatially explicit framework that integrates giant panda habitat, recreational use, and bamboo resources, thereby supporting comprehensive conservation planning in GPNP. By strengthening coordination between human activities and natural ecosystems, the framework achieves ecological connectivity, promotes sustainable resource use, and supports recreational functions within a single network, offering differentiated strategies for future climate scenarios. The findings are significant for improving ecological protection efficiency and disseminating cultural value in GPNP, providing transferable insights for protected-area management and ecosystem-service planning worldwide, especially in developing countries.

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Conflict of Interest

The authors declare that there are no competing interests associated with this manuscript.

Author Contributions

L.Q. made substantial contributions to the conception and design of the work; the acquisition, analysis, and interpretation of data; and the development of the spatial modeling and corridor construction framework. R.P. contributed to the refinement of the research design and supported the interpretation of key findings; L.Q. drafted the manuscript and was responsible for the preparation of all figures and tables. R.P. critically revised the manuscript for important intellectual content and provided academic supervision throughout the writing process; both authors approved the final version of the manuscript to be published; both authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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