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IMPLICATIONS OF CLIMATE CHANGE AND FORECASTING IMPACTS ON HABITAT CONSERVATION UNDER SDGS IN YUNNAN PROVINCE, CHINA

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Abstract: The projected gradual loss of biodiversity due to rising temperatures and decreasing precipitation poses a serious threat to biodiversity hotspots, such as Yunnan Province in China. These areas are rich in unique species and ecosystems, and their conservation has become a pressing global issue. As climate change continues to intensify, the challenge of conserving these vulnerable areas has become a focal point for environmental research and policy. The aim of this study was to assess and classify habitat fragmentation in core habitat areas of the province, and to model the specific values of temperature increase and precipitation sharp decrease predicted over the next 20 years in these areas. The systematic approach in this study places a strategic emphasis on identifying and establishing ideal routes that seamlessly connect high-quality habitats, ultimately enhancing biodiversity conservation efforts. Habitat quality was assessed and classified using the INVEST model combined with mean standard deviation analysis. Subsequently, core habitat areas were identified and classified by using the Morphospatial Pattern Analysis (MSPA) model. The Minimum Cumulative Resistance (MCR) model was used to construct 302 ecological corridors with a total length of more than 6,000 km to mitigate habitat fragmentation and to classify their importance in order to mitigate habitat loss of flagship species such as the Asian Elephants (Elephas maximus) and the Yunnan Snub-nosed Monkey (Rhinopithecus bieti) in the region. The findings of this study are contextualized within the framework of Sustainable Development Goals (SDGs), especially SDG 13 (Climate Action) and SDG 15 (Life on Land), which focus on biodiversity conservation and climate action. We discussed the implications of the study's findings for the future of the region, emphasizing the importance of sustainable development and the need to conserve biodiversity, maintain ecosystem stability, and contribute to the achievement of the SDGs.

Keywords: Biodiversity, Ecological Corridors, Climate Change, Yunnan Province, Habitat Fragmentation, Sustainable Development Goals (SDGs)

Introduction

The environment and human health relies on a diverse range of life forms—biodiversity (Cavender-Bares et al., 2024; Wood & Declerck, 2015). According to the United Nations Convention on Biological Diversity (CBD), biodiversity encompasses the vast variety of life on Earth, spanning across land, sea, and all aquatic environments, forming a complex web. This web, consisting of all living organisms and their interactions, defines biodiversity. It includes the unique traits of individual organisms, the extensive diversity of species, and the intricate ecosystems they establish (Opoku, 2019). Biodiversity, from genes to ecosystems, represents the rich tapestry of life on Earth, a concept integral to the UN's 2030 Sustainable Development Goals (SDGs)(Griggs et al., 2013).

China has emerged as a global leader in biodiversity, with three biodiversity hotspots and an astonishing 35,000 documented vascular plant species (Mi et al., 2021). This remarkable diversity

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thrives due to China's unique geographical landscape and complex ecological framework(Wang et al., 2011). However, this natural wealth is under threat. China's rapid economic growth and urbanization over recent decades have placed immense pressure on its biodiversity(Zhang et al., 2015).

Despite China's biodiversity initiatives, significant gaps remain, especially in the classification and mapping of habitats within biodiverse regions like Yunnan Province. While ecological corridors have gained attention to mitigate habitat fragmentation, studies specific to Yunnan's unique habitats, species requirements, and corridor effectiveness are limited. Most existing studies do not fully address the specific ecological requirements of key species or assess corridor design within Yunnan's distinct topography and climate. This lack of fine-scale habitat classification and corridor research hinders effective conservation efforts, as generalized models may fail to capture the nuanced needs of Yunnan's endemic species. This study aims to bridge these gaps by providing a focused examination of habitat connectivity for priority species in Yunnan, thereby enhancing the precision of conservation planning in this ecologically critical region.

Habitat fragmentation, resulting from habitat loss, threatens biodiversity worldwide(Fahrig, 2017). Population growth and urbanization are major drivers, reducing habitats and disrupting their structure and function(Bryant, 2006; Gomes et al., 2011; Syphard et al., 2011). China's urbanization exemplifies this challenge. Between 1978 and 2018, its urbanization rate has surged from 17.92% to 59.6%, with a particularly steep increase between 2000 and 2015(Bai et al., 2019). Projections indicate that urbanization will reach 75% by 2050(Zhang & Wang, 2006). This rapid development has the potential to cause habitat fragmentation and shrinkage, threatening China's rich biodiversity, which makes conserving it a huge challenge.

However, the impact of climate change on habitat fragmentation is significant. It has far-reaching impacts on global ecosystems, human societies, and economic progress, leading to higher global temperatures, rising sea levels, and an increasing frequency of extreme weather events such as floods and droughts. These effects ripple across various sectors, including agriculture, water resources, energy, and infrastructure. Moreover, climate change exacerbates biodiversity loss and disrupts ecosystem balance, posing significant threats to the sustainable development of both human societies and the natural environment(Malhi et al., 2020; Zhang et al., 2022).

The consequences of climate change include severe droughts, water scarcity, intense wildfires, rising sea levels, floods, polar ice melting, catastrophic storms, and a decline in biodiversity. Currently, Earth's average surface temperature is about 1.1°C higher than it was in the late 1800s, marking the warmest period in the last 100,000 years. The decade between 2011 and 2020 was the hottest on record, with each of the last four decades being warmer than any since 1850 (Intergovernmental Panel on Climate Change (IPCC), 2023). This temperature rise has contributed to glacier melting and a continuous increase in sea levels. Warmer temperatures also cause seawater expansion, further accelerating sea-level rise. As global warming progresses, it disrupts precipitation patterns by increasing atmospheric water capacity, heightening the likelihood of intense rainfall events. This shift increases the frequency of floods and expands drought-prone regions. Additionally, these climatic changes lead to significant alterations in regional precipitation patterns, resulting in more frequent droughts in some areas and an increase in flood-related events in others(Climate Change 2014: Impacts, Adaptation and Vulnerability, 2014; Trenberth et al., 2003; Zhan & Ren, 2023).

In recent years, ecological corridors have become a key strategy, gaining widespread adoption across various regions for their potential to mitigate biodiversity loss(Beazley et al., 2023; Liu et al., 2023a; Xu et al., 2023; Yang et al., 2022). These designated pathways reconnect fragmented habitats, serving as bridges for species movement across the landscape(Bennett et al., 2006; Peng et al., 2018a). By enhancing connectivity, ecological corridors counteract the isolation effects of habitat loss, promoting biodiversity and ecosystem stability. They facilitate gene flow, recolonization of suitable habitats, and escape from disturbances (Li et al., 2022; Yuan et al., 2022).

Study area and data sources

Yunnan Province, located in southwestern China (~ 394,100 km², 97°31'–106°11'E, 21°8'–29°15'N; Figure 1), is a biodiversity-rich region. The province's mountainous terrain, complex topography, and varied climate create a unique ecological environment (Yang et al., 2004). Despite the surrounding arid regions, Yunnan is abundant in rivers, lakes, and lush vegetation, including well-preserved tropical rainforests. As a biodiversity hotspot, it is home to a quarter of China's wildlife and a fifth of its plant species, making it a critical area for conservation (Hui et al., 2024). However, rapid urbanization and the expansion of roads and railways are leading to habitat loss and fragmentation, threatening the rich biodiversity of the region. The sources of data employed in this study are detailed in Table 1.

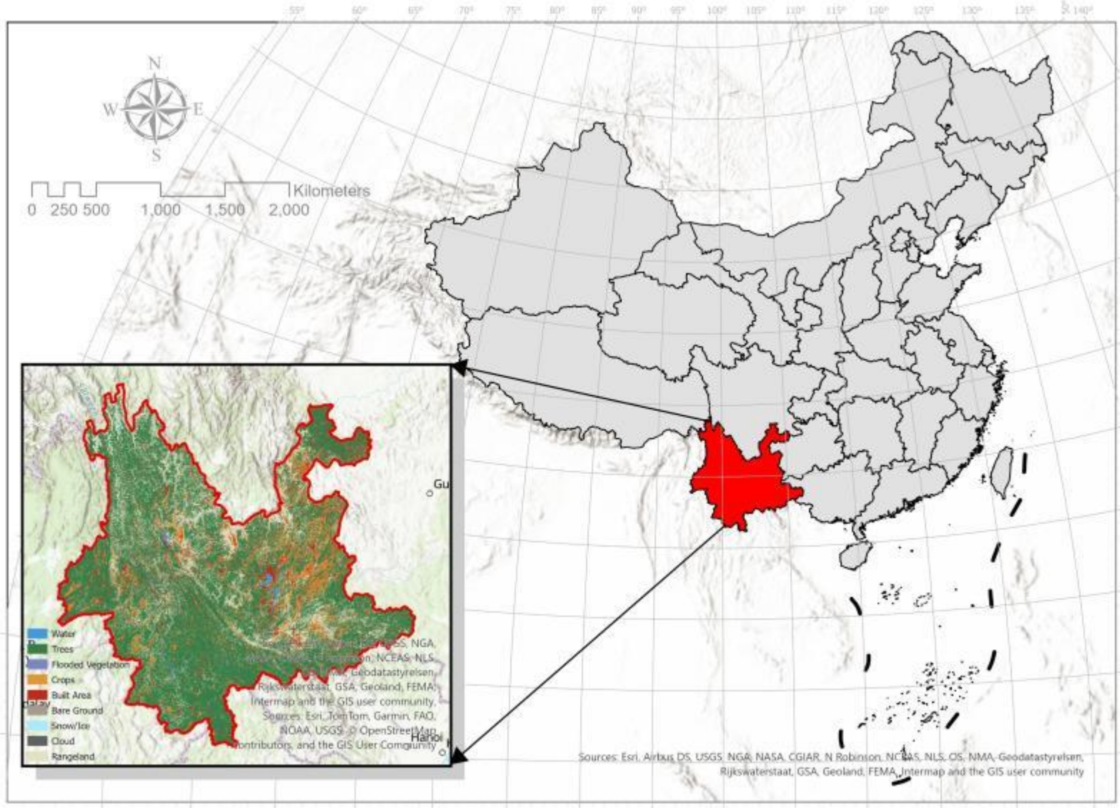


Figure 1.Land cover and geographical location of Yunnan province, China.

Table 1. Data sources.

Data	Description	Year	Spatial	Source

			resolution	
Land cover (LC)	Obtained from the Sentinel-2 dataset, generated by the Esri.	2022	10 m	https://livingatlas.arcgis.com
DEM	Derived from the digital elevation dataset SRTM GL3.	2014	30 m	https://srtm.csi.cgiar.org
Nighttime light	Derived from the worldwide NPP-VIIRS-like nighttime light dataset.	2020	500 m	An extended time-series (2000-2018) of global NPP-VIIRS-like nighttime light data - Harvard Dataverse
Annual average NDVI	Derived from the MODIS NDVI product (MOD13Q1), aggregated on the Google Earth Engine (GEE) platform.	2020	250 m	https://lpdaac.usgs.gov/products/mod13q1v006/
Road	Derived from the National Catalogue Service for Geographic Information.	2020	Polyline	www.webmap.cn

The land use/land cover (LULC) dataset includes eight main classes: Water, Trees, Flooded Vegetation, Crops, Built Area, Bare Ground, Snow/Ice, and Rangeland, along with an unused category. The annual average Normalized Difference Vegetation Index (NDVI) was calculated using the MOD13Q1 product (Ding et al., 2023a), with data captured at 16-day intervals. The nighttime light dataset, obtained from the Harvard Dataverse (Chen et al., 2021), was created through a cross-sensor calibration process, offering superior spatial and temporal resolution compared to other products. All spatial datasets were converted to raster format with a spatial resolution of 100 m × 100 m. These datasets were stored in the World Geodetic System (WGS) 1984 World Mercator coordinate system, and this process was carried out using ArcGIS Pro software version 3.1.0.

Methodology

In recent years, significant progress has been made in the study of biodiversity conservation and climate adaptation, with many approaches focusing on habitat classification, ecological corridor identification, and sustainable development. However, several critical gaps remain. Existing studies often focus on the static characterization of ecological networks without adequately addressing the dynamic and predictive aspects of climate change impacts. Furthermore, while methodologies such as the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) and MSPA (Morphological Spatial Pattern Analysis) models have been extensively applied in conservation planning, their combined use for habitat core classification and corridor identification under climate scenarios remains underexplored.

To address these gaps, our study integrates the InVEST and MSPA models to provide a novel methodological framework for classifying habitat cores and identifying ecological corridors in Yunnan Province. This integration enables a more nuanced understanding of habitat connectivity and biodiversity conservation in the face of climate change. By applying these tools, we offer predictive insights into the impacts of climate change on ecological networks, aligning our findings with Sustainable Development Goals (SDGs) that emphasize biodiversity preservation and climate adaptation.

Moreover, this study highlights how methodological advancements can contribute to practical conservation strategies. By incorporating future climate projections, we provide a forward-looking approach that bridges theoretical frameworks and actionable insights. This synthesis addresses the need for scalable, policy-relevant conservation strategies that can be adapted to other regions. Thus, our work not only fills critical gaps in the literature but also sets the stage for future research and pilot applications in biodiversity conservation and climate adaptation.

Figure 2 introduces a robust framework for crafting and assessing ecological corridors in Yunnan Province, effectively addressing the challenge of habitat fragmentation. This framework prioritizes identifying the ideal routes connecting high-quality habitats. The process starts with evaluating habitat quality across the entire province using the InVEST model (Sharp et al., 2015), which factors in land use types and threats like croplands and roads. High-quality habitats are then identified using the mean-standard deviation method. Moreover, the Morphological Spatial Pattern Analyst (MSPA) was employed to detect core areas within the habitat, utilizing advanced morphological analysis techniques to identify distinctive spatial patterns indicative of crucial ecological zones. Connectivity analysis ranks these core areas based on their potential for connection. To identify the most suitable corridors, a resistance surface is created by integrating diverse data sources such as night lights, roads, land cover, slope, and vegetation (NDVI). These data layers are then weighted based on their influence on animal movement, utilizing techniques like fuzzy membership and the Analytic Hierarchy Process (AHP). This surface is used with the Minimum Cumulative Resistance (MCR) model, a landscape ecology concept. MCR identifies corridors that minimize movement difficulty for species across fragmented landscapes. Additionally, the Gravity Model (GM) prioritizes corridors based on factors like habitat size and distance between cores. This model reflects the principle that larger and closer habitats have stronger natural connections.

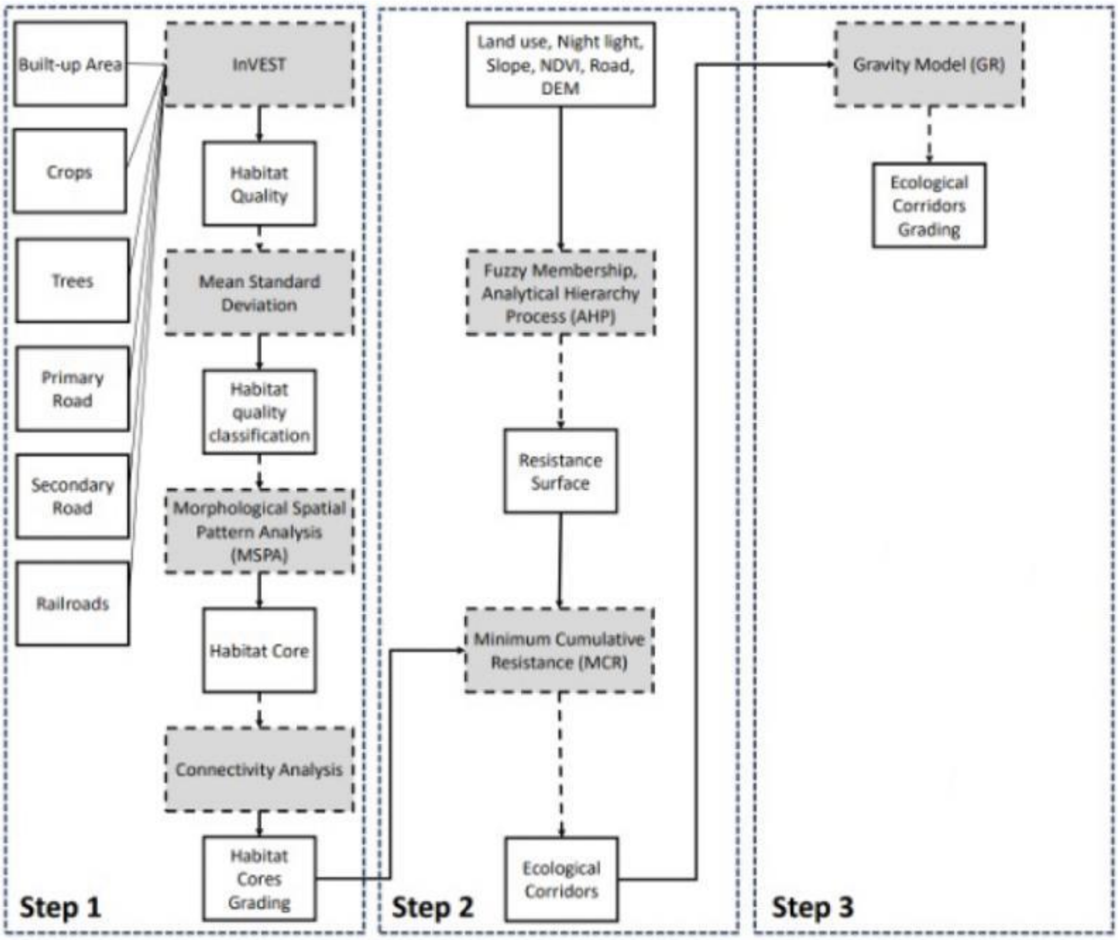


Figure 2.Framework for research.

Habitat quality

The InVEST model, version 3.14.1 developed by the Natural Capital Project at Stanford University (Sharp et al., 2015), was employed to evaluate habitat quality and degradation in Yunnan Province. The habitat quality module was utilized to assess the impact of human activities on the ecological environment, drawing insights from previous studies (Ding et al., 2023b; Pu et al., 2024; Wei, et al., 2022). As human activity intensifies, existing habitats face increased pressure, leading to declines in biodiversity and habitat quality. The model integrates raster data of LULC with information on habitat threats, including their impact range and intensity (Pu et al., 2024). Details regarding the necessary data for the model, such as LULC data, threat factors, and spatial decay types, are provided in Table 2 and Table 3 (Zhang et al., 2020).

Table 2.The weight of threat factors and the spatial decay types.

THREAT	Description	Decay	Maximum Distance	Weight
Crops	Agricultural lands	linear	8	0.7
Railroad	Railroad lines	exponential	5	0.6
Built-up	Urban/developed	exponential	10	1
Road1	Primary roads	linear	3	1
Road2	Secondary roads	linear	1	0.7

Table 3.Sensitivity of various habitat types to threat factors.

NAME	**HABITAT**	**Crops**	**Railroad**	**Built-up**	**Road1**	**Road2**
Built Area	0	0	0	0.00	0	0
Railroad	0	0	0	0.00	0	0
Primary roads	0	0	0	0.00	0	0
Secondary roads	0	0	0	0.00	0	0
Flooded vegetation	1	0.7	0.75	0.90	0.7	0.6
Barren	0	0	0	0.00	0	0
Trees	1	0.7	0.75	0.90	0.7	0.6
Water	1	0.5	0.55	0.70	0.5	0.4
Rangeland	1	0.3	0.35	0.50	0.3	0.2
Field crop	0	0	0	0.00	0	0

Habitat quality is evaluated through:

$$Q_{xj} = H_j\left[1 - \left(\frac{D_{xj}^{x}}{D_{xj}^{x} + k^{z}}\right)\right]$$

Habitat quality within each LULC category is represented by Q_{xj} for grid cell x in category j. Habitat suitability (*Hj*) plays a critical role, ranging from 0 (no suitability) to 1 (highest suitability) for each LULC category. A normalization constant (*z*), typically set at 2.5, is used in the calculation.

Additionally, a half-saturation constant (k) is adjusted to reflect half of the maximum habitat degradation value observed within the study area. Importantly, a higher *Qxj* value indicates a better-quality habitat (Zhang et al., 2020).

Habitat degradation for each grid cell (*x*) within a LULC category (*j*) is represented by *Dxj*. This value ranges from 0 to 1, with values closer to 1 signifying a higher degree of habitat degradation. The mathematical formula for *Dxj* is presented in the equation (2):

$$D_{xj} = \sum_{r=1}^{R}\sum_{y=1}^{Y_r}\left(\frac{\omega_r}{\sum_{r=1}^{R}\omega_r}\right) r_y i_{rxy} \beta_x S_{jr}$$

Several factors contribute to habitat degradation. The total number of threats is denoted by *R*, with each individual threat factor represented by *r*. These threats are considered across all grid cells (*y*) within the threat map for each factor (*r*). A weight (*ωr*) is assigned to each threat factor based on its importance, while β_x represents the inherent resilience of the habitat in grid cell *x*. Additionally, S_{jr} captures the sensitivity of LULC category *j* to specific threat factor *r*. The intensity of threat factor *r* itself is denoted by *ry*. Equations (3) and (4) detail how to calculate the influence (*irxy*) of threat r originating in grid cell *y* on the habitat in grid cell *x*.

$$i_{rxy} = 1 - \left(\frac{d_{xy}}{d_{r\,max}}\right)$$

$$i_{rxy} = exp\left(-\left(\frac{2.99}{d_{r\,max}}\right)d_{xy}\right)$$

Within this scenario, "d_{rmax}" signifies the maximum impact range of threat factor "r". Meanwhile, "d_{xy}" represents the straight-line distance separating grid cells x and y. Equation (3) governs how the impact of "r" diminishes linearly with distance, while Equation (4) dictates its exponential decay.

Morphological spatial pattern analysis

Morphological Spatial Pattern Analysis (MSPA) is a methodology designed to identify patches exhibiting significant morphological characteristics as determined by algorithms (Wei et al., 2022a). It has been demonstrated as a powerful tool for examining the geometric properties, spatial arrangements, and connectivity within images, while also facilitating the identification of structural connections (Soille & Vogt, 2009). Originally introduced in 1967 for the field of landscape ecology (Carlier & Moran, 2019) , the MSPA approach has subsequently been applied in a wide range of disciplines. These applications include the development and refinement of ecological security patterns, the planning and management of corridor construction, and the assessment of connectivity within landscapes (Carlier & Moran, 2019). Furthermore, MSPA methodology has been utilized in research investigating the phenomenon of habitat fragmentation (Ding et al., 2023a; Wei et al., 2022b; Wei et al., 2023).

In this study, the spatial pattern of Habitat Core (HC) was analyzed using the Guidos Toolbox tool. Specific parameters, such as "edge width," which corresponds to the established Euclidean distance threshold, were defined by the user (Lin et al., 2021), require user specification. The MSPA classification employed the default 8-neighborhood rule, with the edge width set to its default value of "1". Transition and intext parameters were also maintained at their pre-set values. Ultimately, the classification of HC involved assigning a value of 2 to pixels located within the HC area, effectively designating them as foreground, while pixels situated outside the HC were considered background and assigned a value of 1.

By utilizing the MSPA method, crucial spatial patches and pivotal nodes within the region can be subjected to visual examination and analysis (Wei et al., 2022a). The dominant spatial pattern associated with the most significant type of HC is typically identified as the core area, recognized for its stable and effective ecological impact (Qiu et al., 2023).

Connectivity analysis

Landscape connectivity is a concept centered on understanding how the movement of ecological processes between distinct land patches is either facilitated or hindered (Wang et al., 2022; Xiang et al., 2023; Yu et al., 2021). In the field of connectivity analysis, various indices are employed to evaluate the role played by specific areas in sustaining landscape connectivity (Saura & Pascual-Hortal, 2007). This analytical approach is widely utilized across diverse fields, with landscape ecology being a prime example (Qiu et al., 2023).

Conefor 2.6 software (Saura & Torné, 2009) was employed to compute the integral index of connectivity (IIC) and the probability of connectivity (PC) indices for the Habitat Cores (HCs). These indices are commonly used in connectivity analysis (Pascual-Hortal & Saura, 2006; Saura & Pascual-Hortal, 2007). The specific calculations used to determine these indices are presented in the equation (5) and (6):

$$dIIC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{Ai \times Aj}{1+Cij}}{A_L^2}$$

$$dPC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} Ai \times Aj \times Pij^*}{A_L^2}$$

Where *dIIC* represents the *HC* connectivity importance index, *dPC* is the *HC* connectivity probability index, *AL* is the total area of the HCs, n is the total number of patches in the HCs surface *L*, *Ai* and *Aj* are the areas of HC patches *i* and *j*, *Cij* is the total number of connections between HC patches *i* and *j* under the shortest path, and *Pij∗* is the probability of the maximum connection between HC patches *i* and *j* (Herrera et al., 2017). To formulate the integrated importance index (*III*) of HCs, the *IIC* and *PC* indices underwent min-max normalization and were assigned a weight of 0.5.

Constructing the resistance surface

The resistance surface reflects the difficulty for biodiversity to move horizontally across a landscape, connecting different habitats (Qiu et al., 2023; Xiang et al., 2023; Yu et al., 2021). In this study, a comprehensive resistance model for animal migration was developed using raster data as the base unit. This model assigns higher values to areas that hinder movement and lower values to areas that facilitate it. Considering both human activities, identified as the primary disturbance in earlier research (Peng et al., 2018b; Wang et al., 2020), and natural factors, four key indicators were chosen to build the model: LULC, NDVI, slope, and night light intensity. Building upon past research that identified human activity as the main obstacle to animal migration, areas with higher night light and lower NDVI were assigned higher resistance values (Peng et al., 2018b; Wang et al., 2020). Conversely, forests, grasslands, and water bodies, recognized as prime ecological habitats, received lower resistance values (Cunningham et al., 2014). Croplands and built-up areas, representing zones of high human activity, respectively, were assigned progressively increasing resistance values (Ding et al., 2023a).

Weights for each factor were determined using the Analytical Hierarchy Process (AHP) (Ding et al., 2023a; Liu et al., 2023b; Wang et al., 2022), facilitated by Expert Choice software (Ishizaka & Labib, 2009). This software ensured consistency within acceptable limits, with a CR value below 0.1. The assigned weights were: LULC (0.58), NDVI (0.23), slope (0.05), and night light (0.13). To quantify resistance values, the fuzzy membership toolbox in ArcGIS Pro was employed, transforming the input raster into a scale ranging from 0 to 1. This scale denoted the degree of membership in a set based on a specified fuzzification algorithm.

Building ecological corridors for optimal regional connectivity

This study investigated the use of the Minimum Cumulative Resistance (MCR) method to establish corridors connecting high-quality habitat patches. MCR excels at identifying the most efficient pathways for movement between multiple areas, making it ideal for this purpose (Dai et al., 2021). Resistance surfaces, which depict the difficulty species encounter while traversing their habitat, are commonly employed to identify ecological corridors (Peng et al., 2022; Xiang et al., 2023). MCR model was utilized to establish corridors specifically aimed at enhancing connectivity between distinct habitat core areas, optimizing their spatial arrangement, and ultimately improving overall connectivity efficiency within the core habitat. Spatial analysis tools in ArcGIS Pro were then utilized to identify corridors that would facilitate optimal regional connections. This comprehensive approach promotes the development of more consistent and extensive high-quality habitat across the entire study area, effectively mitigating the negative impacts of habitat fragmentation. Consequently, it has the potential to significantly improve landscape connectivity, fostering healthy ecological processes and facilitating the movement of species throughout fragmented landscapes.

Gravity Model

The gravity model, frequently employed to analyze relationships between distinct locations, is utilized in this study to assess the effectiveness of corridors (Rudd et al., 2002) and the importance of interconnected habitat cores (Godron, 1981; Sklar & Costanza, 1991). By gauging the level of interaction between these cores, the model helps us understand the significance of corridors (Kong et al., 2010; Xiang et al., 2023). Greater interaction signifies more effective and important corridors. The mathematical expression for calculating node interaction using the gravity model is as follows (Linehan et al., 1995; Rudd et al., 2002):

$$G_{ab} = \frac{N_a N_b}{D_{ab}^2}$$

In this equation, G_{ab} represents the gravitational force between habitat cores HCa and HCb. N_a and N_b denote the corresponding weights, calculated in section 3.3 as the integrated importance index (III) during the connectivity analysis, while D_{ab} signifies the normalized cost of movement between them through the connecting corridor.

Identifying the impact of future climate

In this study, future climate scenarios and their potential impact on habitats were assessed using WorldClim data. Climate projections for the year 2040 were accessed and processed through Geographic Information System (GIS) techniques, resulting in the creation of two prediction rasters: one for future temperature and another for future precipitation. These prediction rasters provide detailed insights into expected changes in climate variables with a 10-minute spatial resolution.

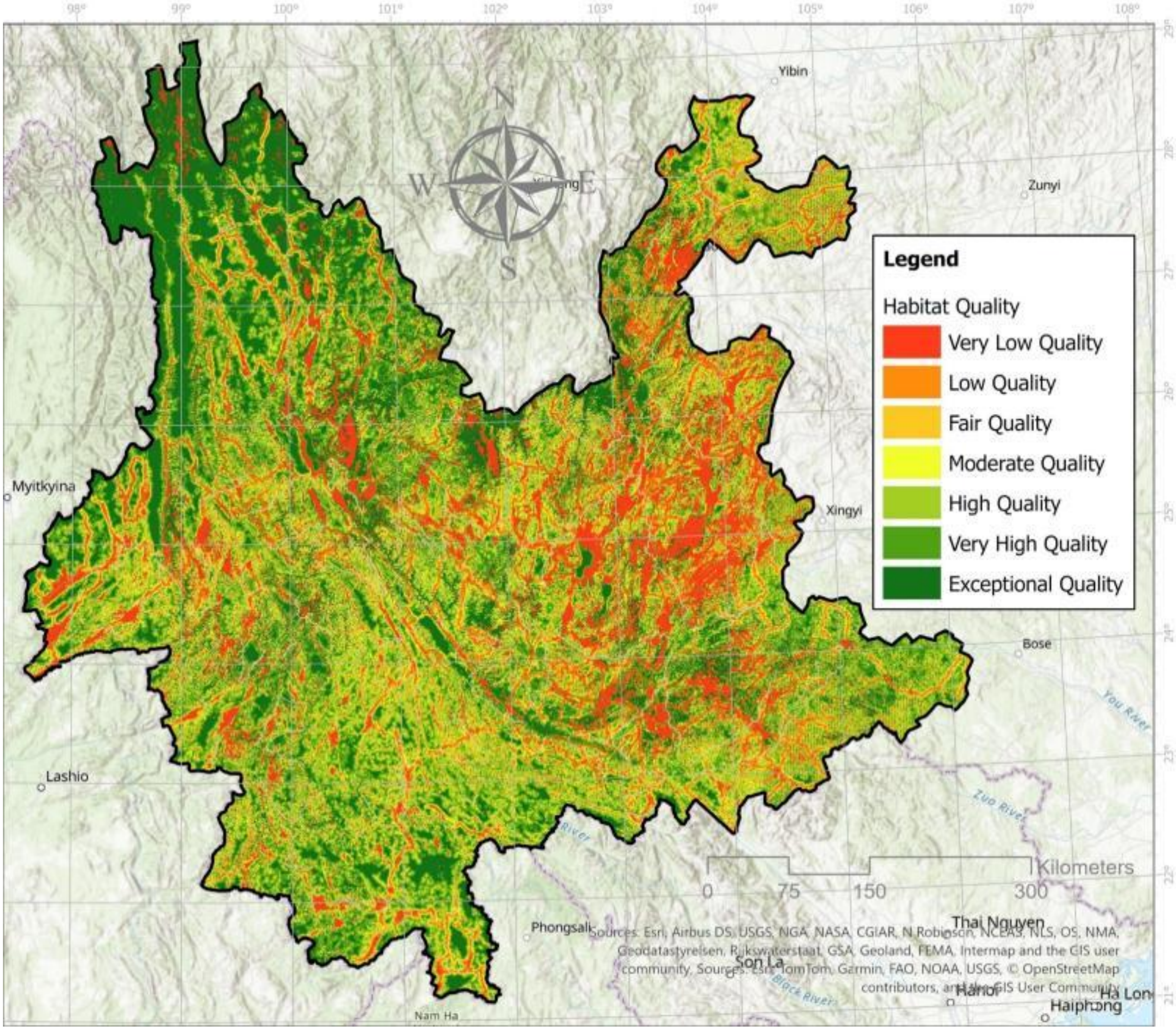
The study also compared current and future climate scenarios by integrating average temperature and precipitation data for each habitat. Using GIS techniques, researchers calculated these averages for both present and future conditions across various habitats. By overlaying and analyzing these datasets, they developed a comprehensive understanding of anticipated climate changes, leading to more accurate predictions of habitat alterations and ecological responses.

These changes are particularly concerning for species like the Asian elephant and the Yunnan snub-nosed monkey. Rising temperatures and shifting precipitation patterns could disrupt their habitats, potentially causing habitat loss or fragmentation, reducing food availability, and increasing human-wildlife conflict. As both species rely on specific ecosystems for survival, these climatic shifts could have severe consequences for their populations. Therefore, this study is especially important for the conservation of flagship species that inhabit this region, as it provides valuable insights for safeguarding their future in the face of climate change.

Results

Habitat quality

An advanced modeling approach was employed to evaluate habitat quality across Yunnan Province. As depicted in Figure 3, the analysis revealed that the highest quality habitats are concentrated in the northern and southwestern regions.



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 3. Habitat Quality of Yunnan province, InVEST model output.

To identify critical areas for conservation, a standard deviation model was utilized. This approach selected high-quality, very high-quality, and exceptionally high-quality habitats for further analysis. As shown in Figure 4, the MSPA model visually highlights the core areas essential for habitat preservation. These areas of high conservation value were recognized as vital for subsequent analyses and form the backbone of the conservation strategy. In total, 120 Habitat Cores (HCs) were identified, covering a combined area of 108,229 km², representing a significant portion of Yunnan Province's valuable ecological landscape.

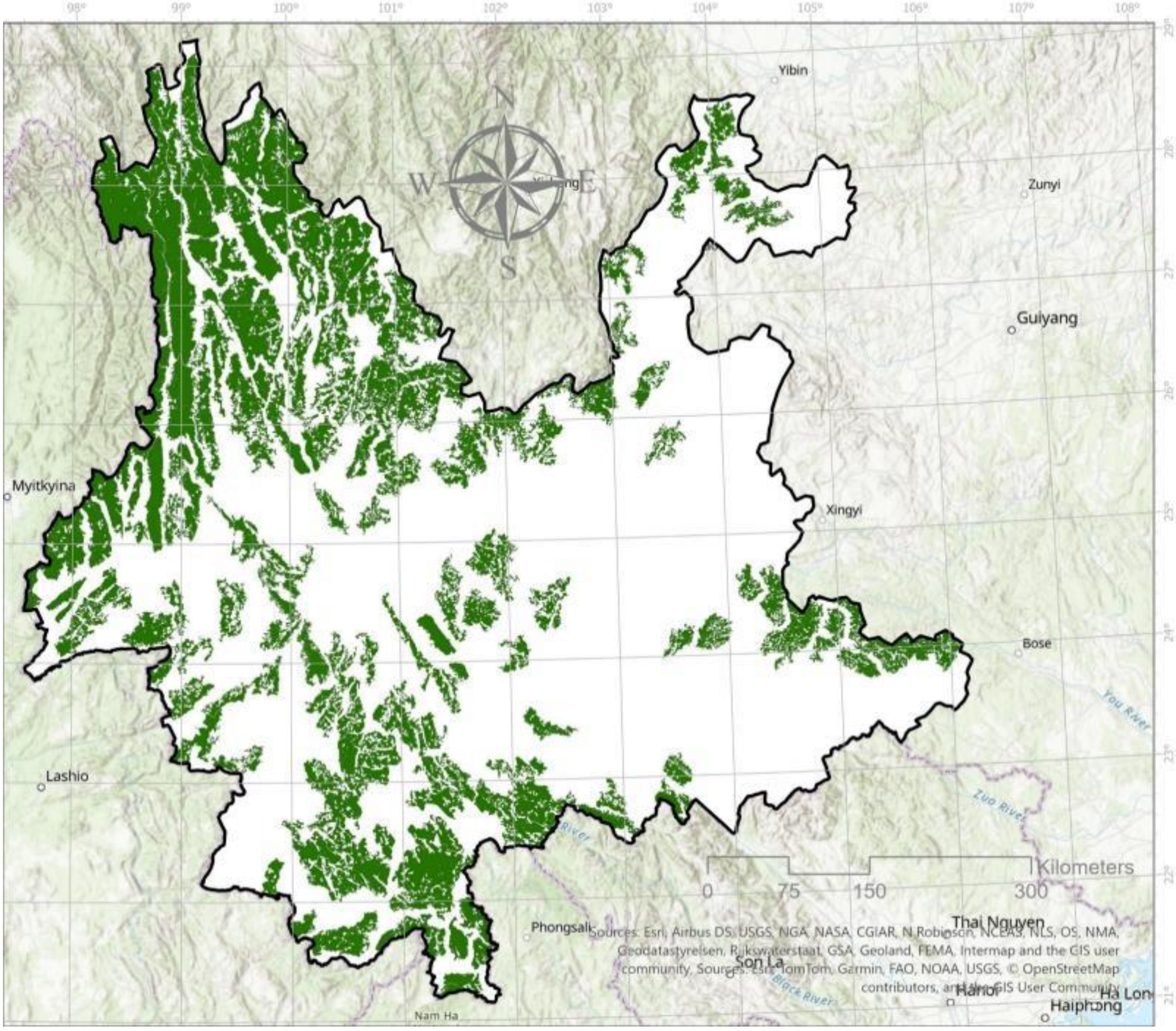


Figure 4. Habitat Cores of Yunnan province, MSPA output.

Grading of habitat cores

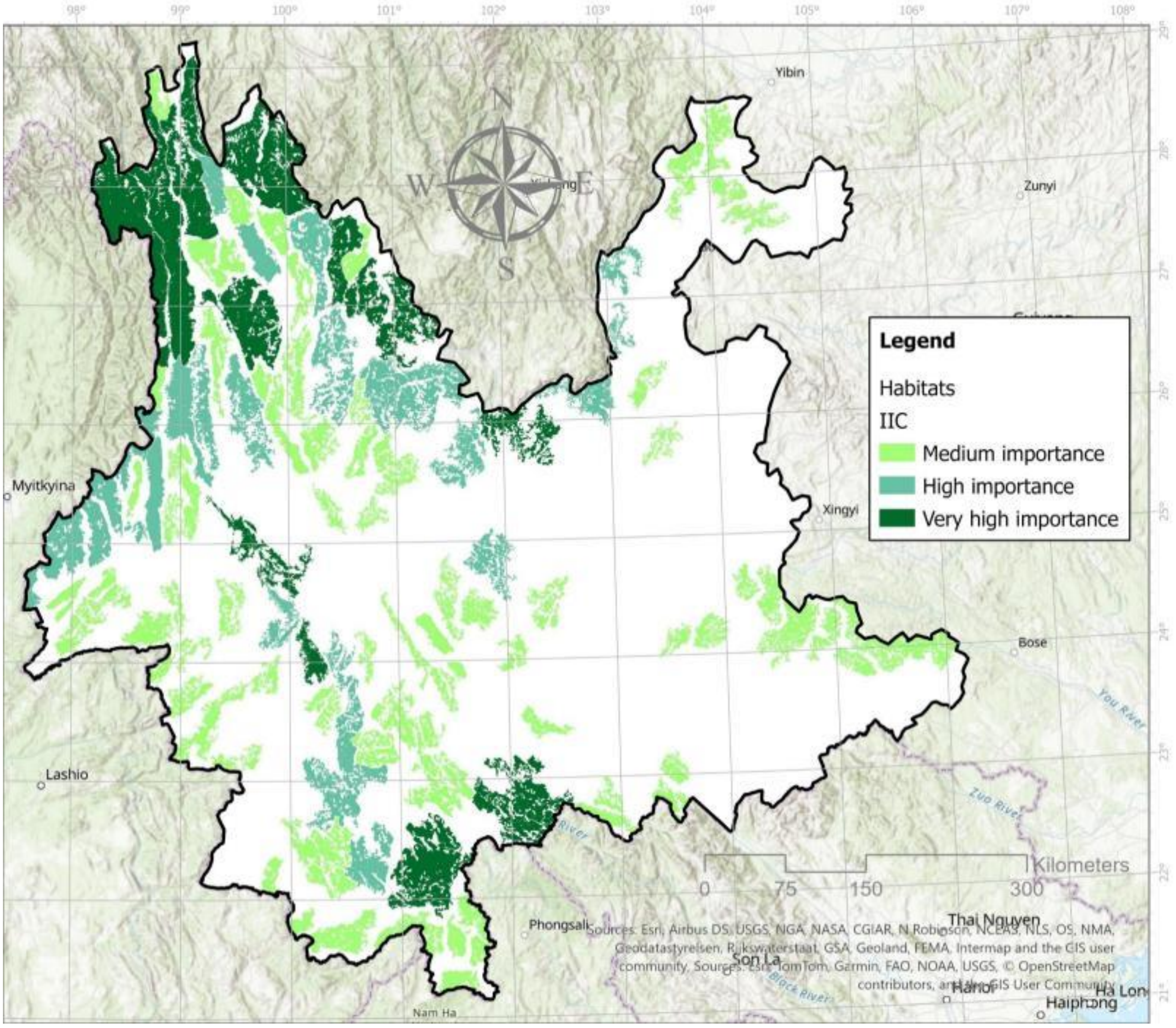
The results of a connectivity analysis conducted on 120 Habitat Cores (HCs) within Yunnan Province are summarized in Table 4. Figure 5 visually presents these findings, highlighting 11 HCs of very high importance, which collectively cover a substantial area of 33,460 km².

Table 4. Ranking of Habitat Cores connectivity index.

ID	dIIC	dPC	Area (km^2)	importance	ID	dIIC	dPC	Area (km^2)	importance
1	0.74	0.89	524.09	Medium	61	0.90	0.73	622.95	Medium
2	0.45	0.67	316.46	Medium	62	0.14	0.28	661.12	Medium
3	0.70	0.88	481.17	Medium	63	1.52	2.01	890.74	Medium
4	0.62	0.78	436.68	Medium	64	0.68	0.84	440.96	Medium
5	1.74	2.02	1194.00	Medium	65	3.46	4.00	1956.81	High
6	0.60	0.75	413.20	Medium	66	2.74	1.54	1056.47	High
7	0.86	1.19	604.87	Medium	67	0.06	0.15	338.76	Medium
8	0.44	0.52	324.26	Medium	68	1.85	13.33	766.03	Very high
9	6.48	7.31	3456.67	Very high	69	1.68	3.45	939.74	High

10	0.73	0.96	486.36	Medium	70	1.75	12.59	639.47	Very high
11	0.49	0.65	328.00	Medium	71	2.88	3.44	1417.94	High
12	0.49	0.58	355.17	Medium	72	1.28	1.81	634.10	Medium
13	2.29	3.24	1397.11	High	73	1.55	3.33	849.50	High
14	1.18	1.61	775.72	Medium	74	0.85	0.67	363.77	Medium
15	0.61	1.19	378.27	Medium	75	0.56	0.65	309.75	Medium
16	6.59	8.21	3046.86	Very high	76	0.72	1.26	361.86	Medium
17	0.65	1.39	496.72	Medium	77	0.58	0.63	307.08	Medium
18	1.47	3.05	871.11	High	78	1.91	2.16	973.75	Medium
19	0.48	0.78	431.29	Medium	79	2.22	2.64	813.81	High
20	1.12	1.43	665.73	Medium	80	3.53	3.55	1239.41	High
21	0.47	0.58	310.27	Medium	81	4.11	3.80	1818.61	High
22	0.80	1.99	468.74	Medium	82	0.77	0.77	368.06	Medium
23	3.84	4.64	1576.21	High	83	1.01	1.07	519.88	Medium
24	0.61	1.33	355.63	Medium	84	1.97	1.80	903.68	Medium
25	0.43	0.60	395.15	Medium	85	3.97	3.29	1630.72	High
26	0.88	0.75	415.29	Medium	86	1.65	1.67	803.06	Medium
27	0.69	0.87	436.24	Medium	87	2.46	2.38	1073.06	High
28	1.11	1.64	735.90	Medium	88	7.85	5.67	1517.49	Very high
29	0.77	1.88	445.53	Medium	89	0.46	0.43	375.64	Medium
30	0.57	1.74	352.69	Medium	90	4.47	5.45	2144.10	High
31	0.59	1.72	349.49	Medium	91	2.39	2.47	1193.47	High
32	0.85	0.71	454.14	Medium	92	0.64	0.69	330.17	Medium
33	1.02	6.37	596.82	High	93	3.94	3.72	1757.25	High
34	0.98	1.12	562.30	Medium	94	5.58	4.31	1068.72	High
35	1.01	2.08	584.16	Medium	95	2.05	1.79	884.18	Medium
36	1.12	1.05	594.76	Medium	96	1.94	1.79	827.17	Medium
37	0.54	1.42	325.32	Medium	97	0.70	1.51	343.05	Medium
38	1.01	1.57	584.87	Medium	98	0.56	0.72	458.35	Medium
39	0.76	1.66	401.76	Medium	99	0.71	0.70	345.64	Medium
40	1.04	1.08	633.43	Medium	100	7.14	5.82	2893.58	Very high
41	0.52	0.59	306.21	Medium	101	9.45	10.10	4222.44	Very high
42	1.25	12.11	715.06	Very high	102	19.93	20.85	8502.47	Very high
43	1.71	2.64	376.68	High	103	3.30	1.92	333.96	High
44	0.09	0.17	454.14	Medium	104	1.34	1.28	615.38	Medium
45	0.05	0.12	301.13	Medium	105	3.17	5.81	1528.13	High
46	0.75	0.71	410.19	Medium	106	2.97	1.76	587.39	High
47	0.85	0.45	371.51	Medium	107	1.50	1.58	736.35	Medium
48	0.36	0.65	1709.70	Medium	108	2.18	2.06	987.59	High
49	0.28	0.75	1267.06	Medium	109	1.07	1.14	545.24	Medium
50	0.11	0.20	525.22	Medium	110	1.00	0.98	470.52	Medium
51	0.05	0.21	310.05	Medium	111	1.37	1.38	657.31	Medium
52	0.78	0.91	489.89	Medium	112	7.06	10.18	3390.11	Very high
53	0.79	1.20	515.60	Medium	113	0.58	0.47	653.63	Medium
54	1.36	9.82	718.53	High	114	1.15	1.23	547.69	Medium
55	0.10	0.30	543.08	Medium	115	2.48	1.32	916.22	Medium

56	1.46	1.60	875.89	Medium	116	1.62	4.85	801.10	High
57	1.04	1.40	658.27	Medium	117	9.40	9.90	4309.54	Very high
58	1.26	1.07	627.72	Medium	118	0.42	0.49	471.50	Medium
59	0.61	0.57	335.44	Medium	119	0.78	0.75	873.85	Medium
60	1.04	0.94	652.44	Medium	120	0.95	1.08	512.78	Medium



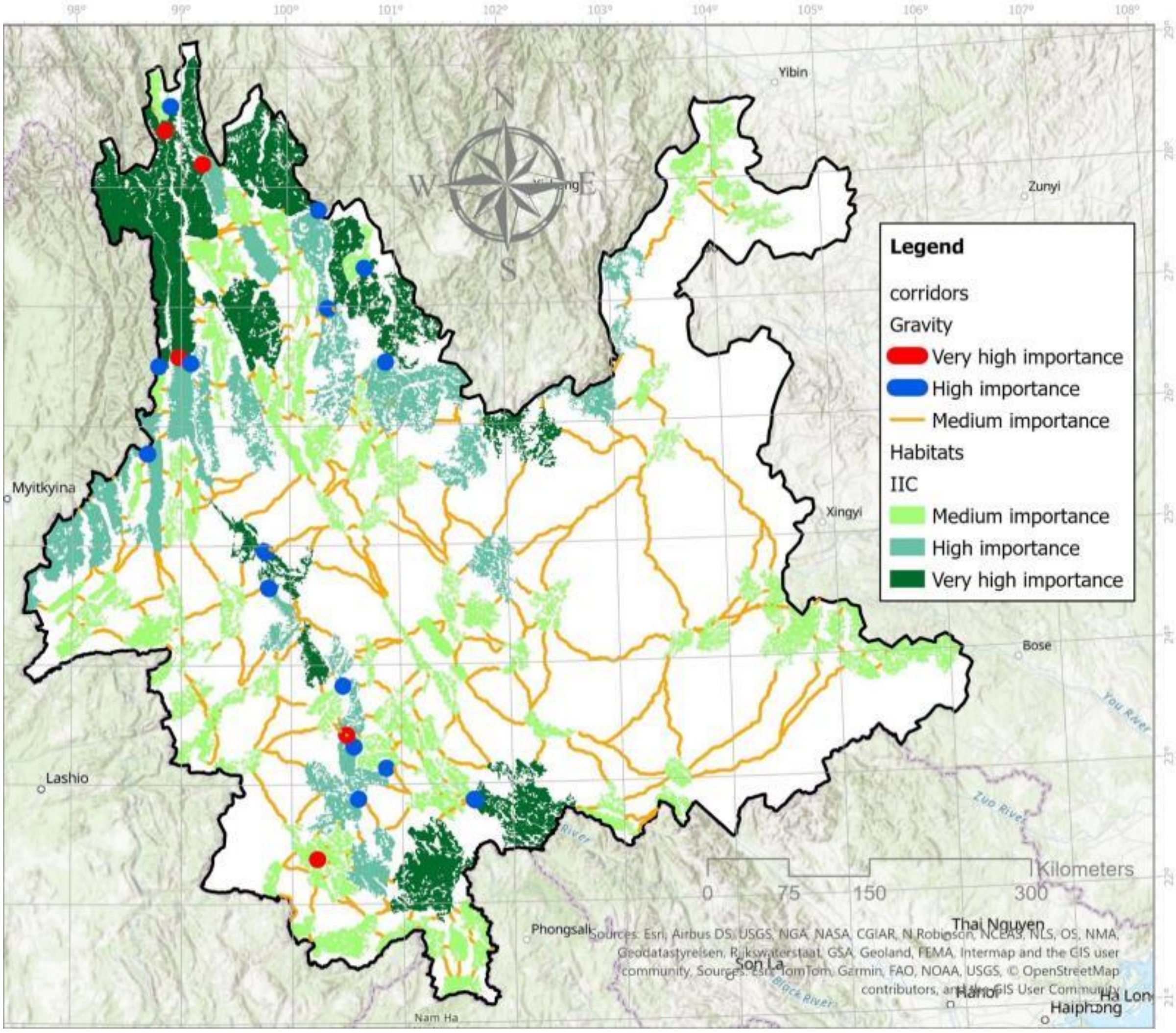
Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 5. Ranking of Habitat Cores connectivity index of Yunnan province.

These critical areas are mainly concentrated in the northern and southern regions of Yunnan Province, where extensive and continuous vegetation cover is maintained due to their distance from urban centers. The analysis also identifies 25 HCs of high importance, spanning 28,734 km², primarily located in the northern part of the region. Additionally, 84 HCs of medium importance, covering 46,035 km², are scattered throughout the study area. Despite their dispersed distribution, these medium-importance HCs are essential for mitigating habitat fragmentation. Their proximity to other HCs enhances connectivity, contributing to the overall cohesion and integrity of the landscape in Yunnan Province.

Identification and grading of corridors

Figure 6 illustrates the outcomes of the MCR model used to identify Habitat Cores (HCs) and the gravity model applied for their grading. This analysis resulted in the creation of a network consisting of 302 corridors, which extend across an impressive 6,320 km throughout Yunnan Province.



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 6.MSPA, MCR and connectivity analysis of Habitat Cores. The figure shows 302 proposed corridors spanning over 6,000 km, connecting various habitat cores (HCs) of differing levels of importance across Yunnan Province.

These corridors predominantly trace the edges of major urban areas characterized by high development and population density. The analysis identified five key corridors with a combined length of 1.87 km (averaging 373 ± 49.2 m). These corridors typically connect zones of high and very high importance, bridging areas of medium and very high importance HCs, and even linking geographically close areas of high and medium importance.

Furthermore, the study identified fifteen high-importance corridors totaling 9.8 km in length. Additionally, 282 corridors with a medium importance index were revealed, collectively spanning an extensive 6,310 km.

Addressing these identified corridors offers a significant opportunity to reduce overall fragmentation and enhance the ecological integrity of habitats across Yunnan Province. However, it is crucial to recognize that identifying optimal corridors is a vital step in mitigating habitat fragmentation and implementing a strategy to connect separate habitat cores. This approach is essential for facilitating species movement between isolated areas, thereby promoting genetic diversity and strengthening ecosystem resilience.

Future climate and impact

The prediction raster for future temperature highlights areas where significant increases are expected, suggesting potential shifts in climate zones and habitats. These changes could have profound effects on species distributions, phenology, and overall ecosystem functioning, underscoring the need for adaptive strategies to address the challenges these alterations may bring.

Similarly, the future precipitation prediction raster offers insights into anticipated changes in precipitation levels by 2040. Shifts in precipitation patterns can significantly impact habitat suitability, water availability, and species diversity. Regions projected to change precipitation regimes may face various challenges, such as droughts, floods, or shifts in vegetation composition, all of which may require adaptive management strategies.

By integrating future temperature and precipitation predictions, a comprehensive assessment of habitat suitability under changing climate conditions can be conducted. Areas identified as experiencing significant alterations in climate variables may require prioritized conservation efforts or habitat restoration initiatives. Understanding how habitats are likely to evolve enables stakeholders to proactively develop strategies that mitigate adverse impacts and promote ecosystem resilience.

Through the utilization of WorldClim data and GIS techniques, this study provides valuable insights into future climate scenarios and their potential implications for habitats. The prediction rasters offer valuable tools for informing conservation and management strategies, enabling stakeholders to develop adaptive solutions that safeguard biodiversity and ecosystem services in the face of a changing climate.

Figure 7 illustrates the annual temperature variation across Yunnan Province for the year 2020. It is evident from the graph that the northern region experiences comparatively lower temperatures, while the southern part registers higher temperatures throughout the year. The temperature gradient spans from a minimum of -21 degrees Celsius in the coldest months to a maximum of 19.2 degrees Celsius during the warmest periods. This disparity in temperatures across the province underscores the diverse climatic conditions prevalent within Yunnan, ranging from sub-zero chill in the north to milder subtropical climates in the south. Such climatic diversity has significant implications for various aspects of life, including agriculture, tourism, and local ecosystems, shaping the socio-economic and environmental dynamics of the region.

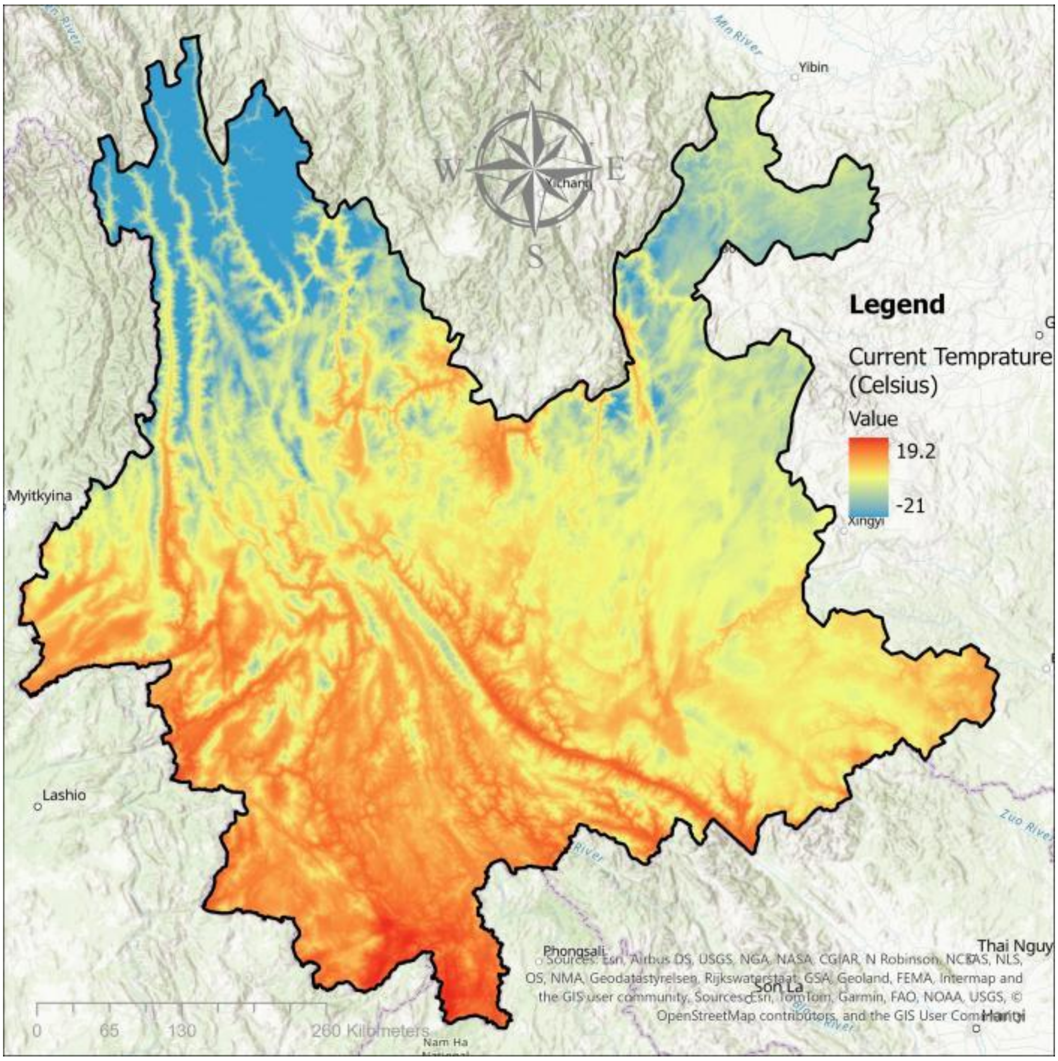


Figure 7. The average annual temperature of 2020. The current temperature trend shows an increase in the south and a decrease in the north.

In contrast to temperature, precipitation patterns across Yunnan Province in 2020 exhibit a distinct spatial distribution. Figure 8 showcases this trend, revealing that the southern areas receive notably higher levels of precipitation compared to the northern regions. Throughout the year, the southern part consistently records higher rainfall amounts, while the northern part experiences relatively lower precipitation rates. The range of precipitation spans from a minimum of 34 millimeters in the drier months to a maximum of 722 millimeters during the wettest periods. This disparity in rainfall distribution underscores the significant climatic variations within the province, influencing factors such as agriculture, water resource management, and ecosystem dynamics. Understanding these precipitation patterns is crucial for implementing effective strategies to mitigate the impacts of droughts, floods, and other hydrological events, thereby contributing to the sustainable development and resilience of Yunnan's communities and ecosystems.

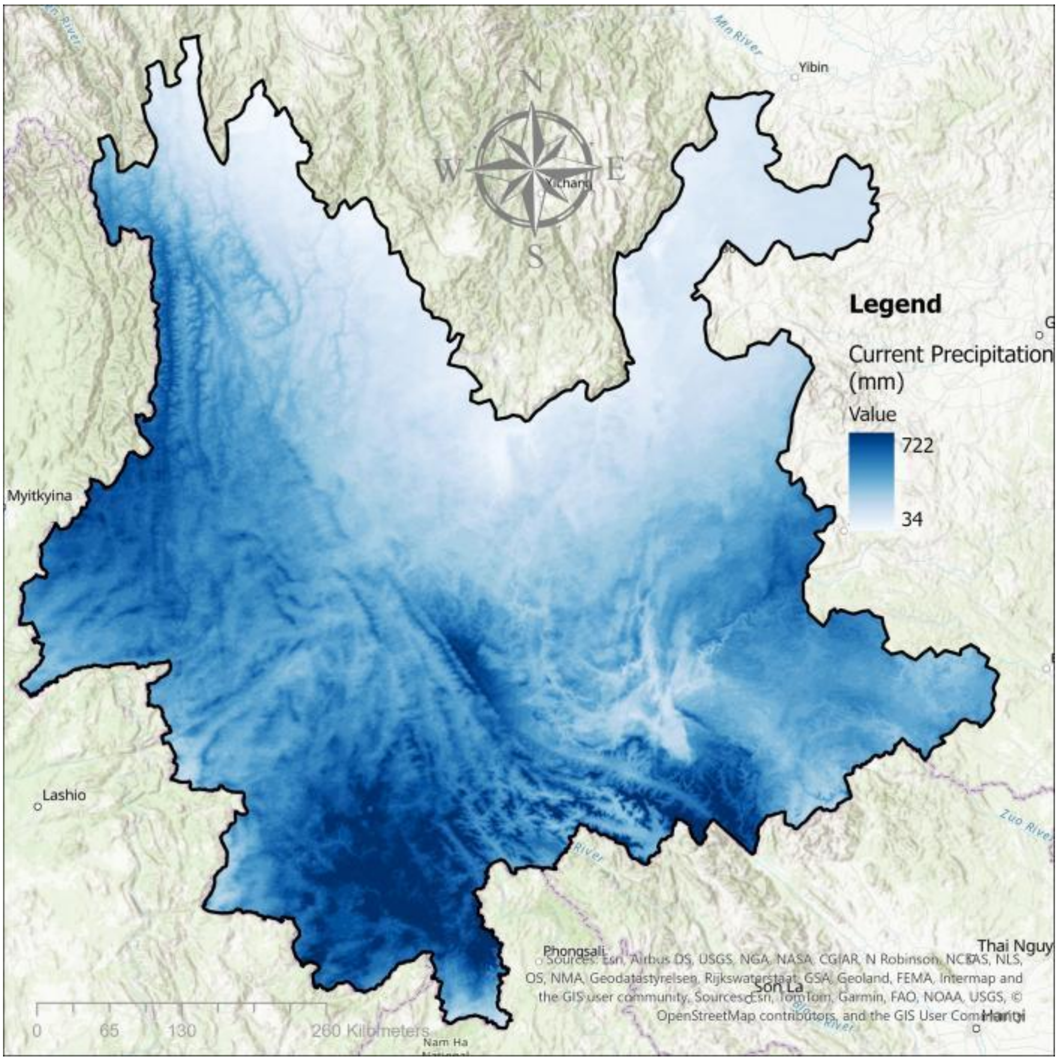


Figure 8. The average annual precipitation of 2020. Current precipitation levels in the southern regions are significantly higher than in the northern regions.

Looking ahead to the projected temperature trends for Yunnan Province in 2040, the climatic pattern is expected to resemble the current distribution, with some notable variations. Figure 9 shows the anticipated annual temperature fluctuations, indicating that the northern part will continue to experience relatively cooler conditions compared to the southern regions. However, due to ongoing climate change, an overall increase in temperatures across the province is likely.

The forecasted temperature range for 2040 (Figure 9) is expected to extend from a minimum of -6.2 degrees Celsius during the coldest months to a maximum of 23.5 degrees Celsius during the warmest periods. This projected shift suggests a potential rise in both average and extreme temperatures, with significant implications for sectors such as agriculture, public health, and infrastructure planning.

Understanding and preparing for these future temperature trends is crucial for Yunnan's policymakers, communities, and industries. Adapting to and mitigating the impacts of climate change will require the implementation of sustainable practices, resource management strategies, and infrastructure development plans. These measures are vital for enhancing resilience and ensuring the well-being of Yunnan's inhabitants as they face evolving climatic conditions.

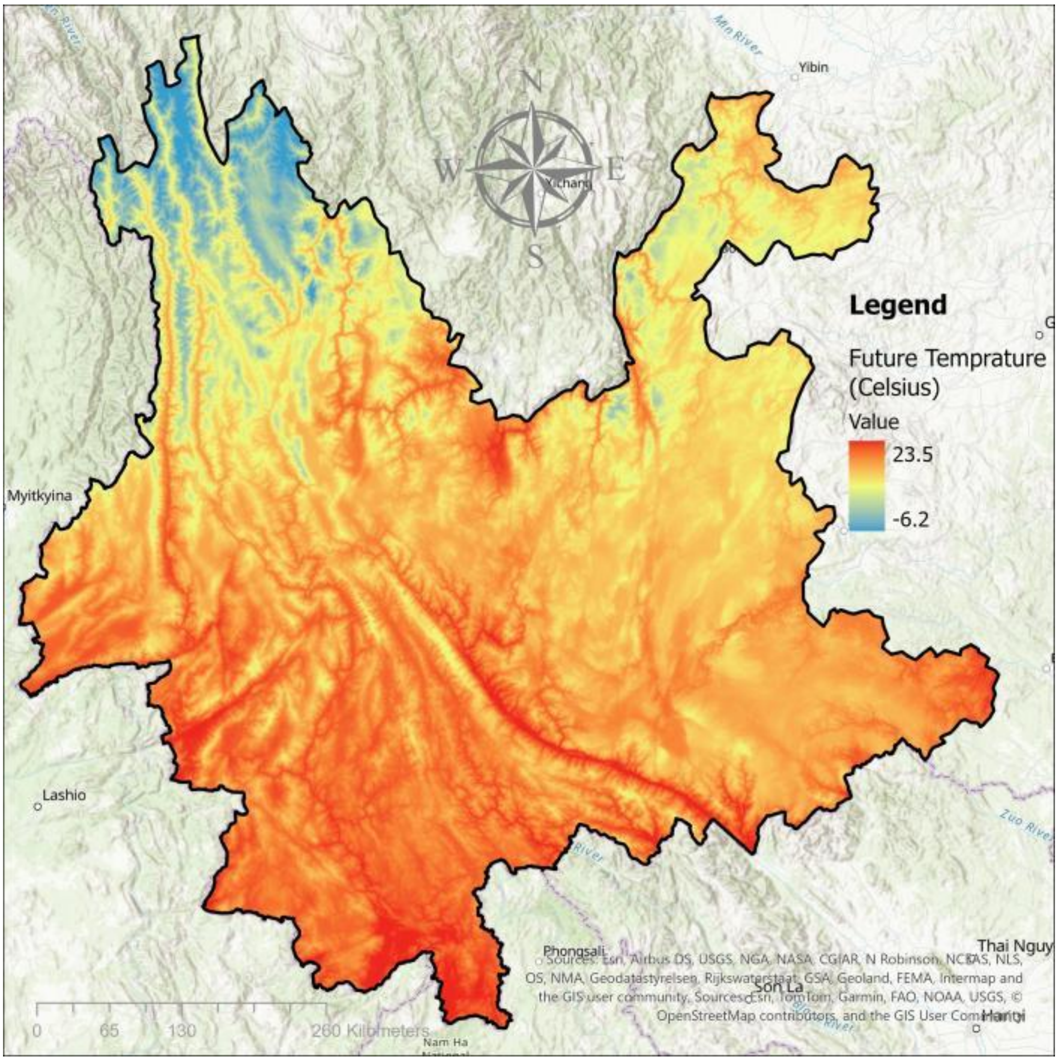


Figure9. Anticipated temperature range for 2040. In 2040, the annual temperature in the northern region is projected to remain relatively cooler compared to the southern region.

Looking ahead to the projected precipitation patterns for Yunnan Province in 2040, it is anticipated that the general spatial distribution of rainfall will resemble the current trend, albeit with notable shifts. Figure 10 illustrates the expected annual precipitation variations, indicating that southern areas will continue to receive higher levels of rainfall compared to their northern counterparts. However, due to the impacts of climate change, alterations in precipitation amounts are anticipated across the region.

The forecasted precipitation range for 2040 is expected to span from a minimum of 55.8 millimeters during the drier months to a maximum of 212.6 millimeters in the wettest periods. This projected variation underscores the potential for changes in both average and extreme precipitation events, with implications for water resource management, agriculture, and ecosystem dynamics.

As Yunnan prepares for these future precipitation trends, proactive measures such as water conservation strategies, land use planning, and disaster preparedness initiatives will be essential for enhancing resilience and mitigating the impacts of climate variability. By incorporating climate-smart practices into development plans, Yunnan can better adapt to evolving precipitation patterns and safeguard the well-being of its communities and ecosystems in the years to come.

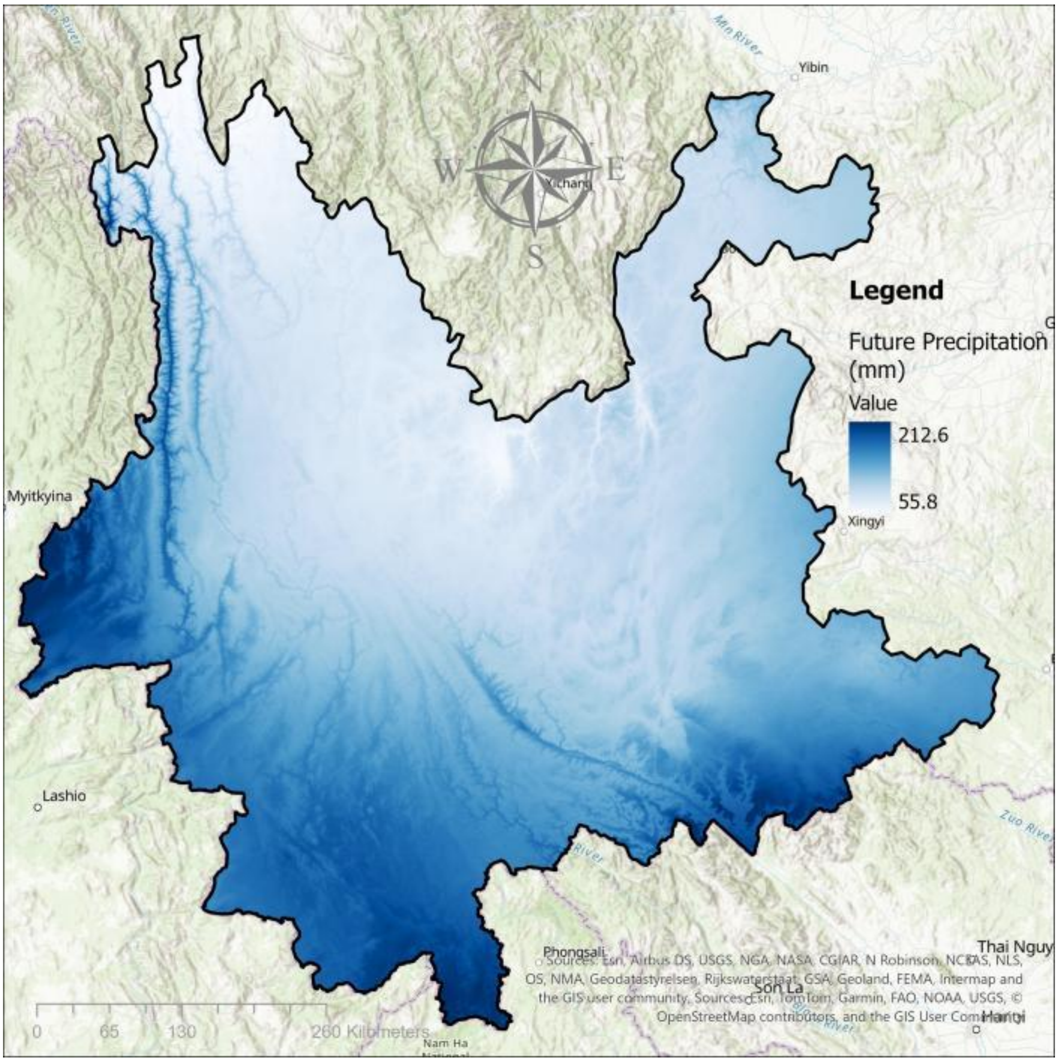


Figure 10.Anticipated precipitation range for 2040. By 2040, annual precipitation in the southern region will continue to exceed that of the northern region. However, due to the impacts of climate change, precipitation across the entire area is expected to change.

Figure 11 presents the calculated differences between the average temperatures in current conditions and projected future temperatures across various habitats within Yunnan Province. The analysis indicates a notable increase in temperatures across all habitats, with particularly pronounced changes expected in northern habitats.

In the northern habitats, the projected temperature rise surpasses 6 degrees Celsius compared to current conditions. This substantial increase underscores the heightened vulnerability of these regions to the impacts of climate change, including shifts in growing seasons, alterations in precipitation patterns, and potential disruptions to ecosystems and biodiversity.

Conversely, southern habitats are also anticipated to experience significant temperature increases, albeit to a slightly lesser extent, with an approximate rise of 4 degrees Celsius compared to current averages. Despite the comparatively lower magnitude of change, these temperature increases still pose significant challenges to local communities, agriculture, and ecosystems, emphasizing the need for adaptation and mitigation measures.

Understanding the differential impacts of climate change across habitats is essential for devising targeted strategies to enhance resilience and sustainability. By incorporating ecosystem-based approaches, adaptive management practices, and community engagement initiatives, Yunnan can better prepare for and mitigate the adverse effects of rising temperatures, safeguarding the well-being of both human populations and the natural environment.

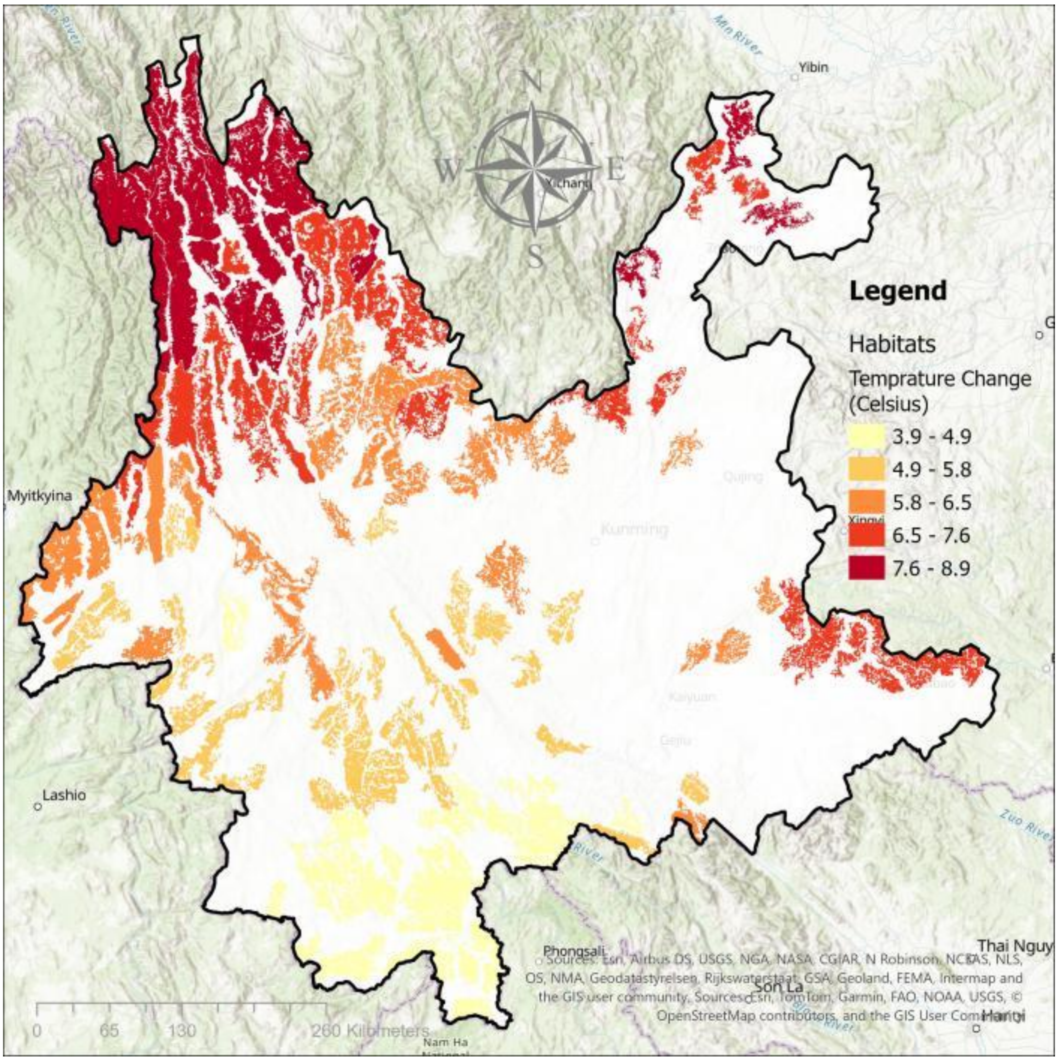


Figure 11.Differences between the average temperatures. The analysis indicates a significant temperature increase across all habitats, with a projected rise of over 6°C in northern habitats.

In Figure 12, we analyze the disparities in precipitation between current conditions and future projections across various habitats within Yunnan Province. The findings suggest a significant decrease in precipitation levels, particularly pronounced in southern habitats. Only some areas in the northern region will see a small increase..

Southern habitats are anticipated to experience a substantial reduction in precipitation, with an estimated decrease exceeding 279 millimeters compared to current averages. This decline raises concerns regarding water availability, agricultural productivity, and ecosystem resilience in these regions, necessitating adaptive measures to mitigate potential impacts.

Conversely, northern habitats are expected to witness a comparatively modest decrease in precipitation, estimated to be around 50 millimeters. While this reduction is less severe than in southern areas, it still poses challenges for water resource management and ecosystem stability, particularly in regions already vulnerable to water stress.

Recognizing the differential impacts of changing precipitation patterns across habitats is crucial for informed decision-making and adaptation planning. Implementing measures such as water conservation practices, integrated land use planning, and climate-resilient infrastructure can help mitigate the adverse effects of declining precipitation, promoting sustainable development and resilience across Yunnan's diverse ecosystems and communities.

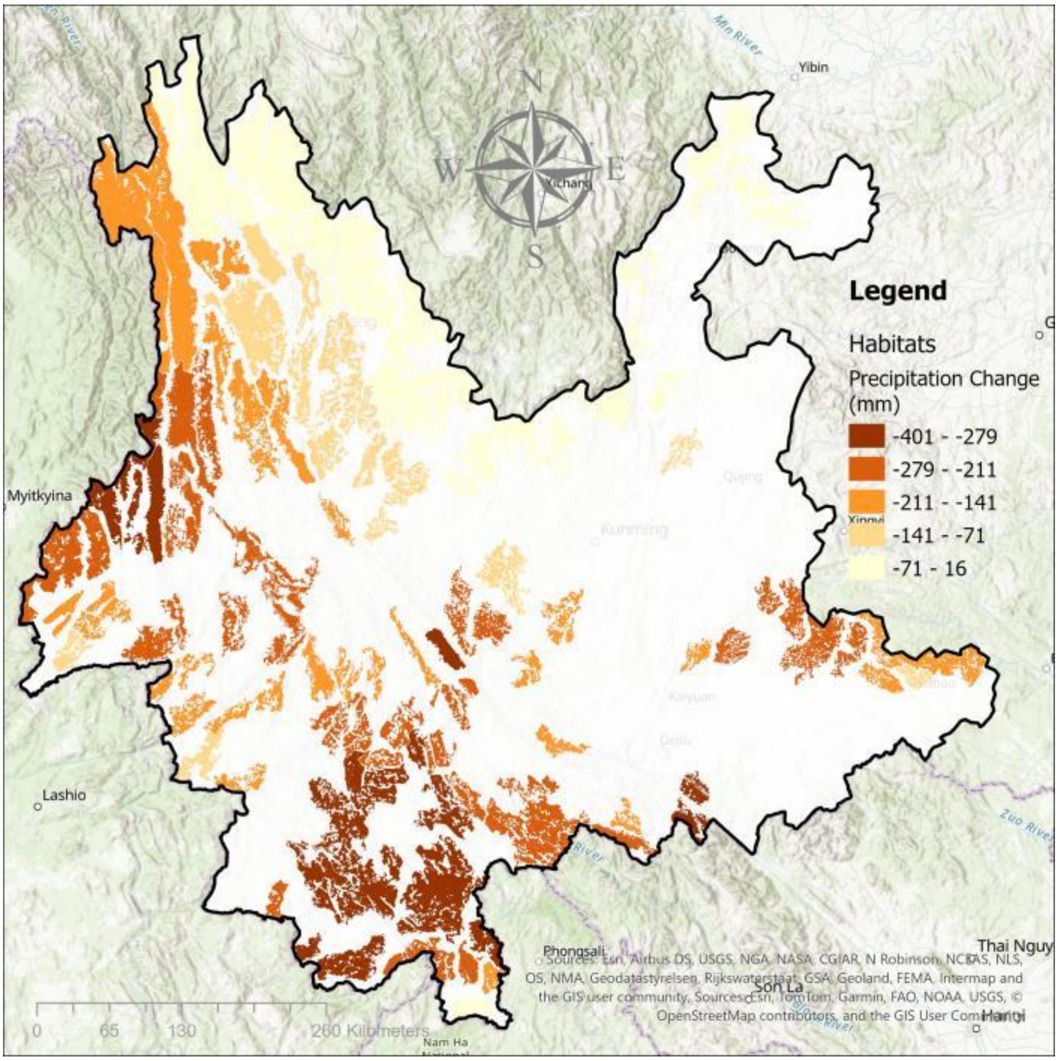


Figure 12. Differences between the average precipitation. Precipitation will decrease significantly, especially in southern habitats, with over 279 mm less than current averages, while only parts of the northern region may see a slight increase.

Discussion

Habitat quality and fragmentation

In this comprehensive study, we applied the InVEST habitat quality model across Yunnan Province, rigorously assessing the factors influencing habitat quality and fragmentation. Previous studies identified land-use types such as croplands and built-up areas as primary determinants of habitat quality. However, our findings reveal that infrastructure developments, particularly roads and railroads, also play a substantial role in habitat degradation and fragmentation in this region (Jaarsma & Willems, 2002; Laforge et al., 2022; Zhuo et al., 2022). By calculating habitat quality across Yunnan and employing advanced statistical measures, including standard deviation and Morphological Spatial Pattern Analysis (MSPA), we identified core habitat zones and assessed their susceptibility to fragmentation. In eastern Yunnan, habitat quality has declined dramatically, driven by rapid urban expansion around major cities like Kunming, Qujing, and Yuxi. The development of these urban centers, combined with the spread of surrounding croplands, has fragmented habitats into smaller, isolated patches. These fragmented patches emphasize the pressing need for connectivity solutions, as small, disconnected habitats may fail to sustain viable populations of many species. Establishing ecological corridors to reconnect these patches could be crucial for preventing further biodiversity loss and maintaining ecosystem stability in these highly impacted regions.

Climate Change

The analysis conducted in this thesis elucidates the anticipated impacts of climate change on temperature and precipitation patterns across Yunnan Province. It reveals a consistent trend of increasing temperatures, with significant variations observed among different geographical regions. The projections indicate a consistent trend of rising temperatures, with stark variations among regions. In particular, northern Yunnan is expected to experience a substantial temperature increase, surpassing 6°C above current averages. This unprecedented rise poses severe risks for the province, intensifying threats such as heat stress, water scarcity, and habitat degradation, which could undermine local agriculture, threaten species survival, and strain communities already grappling with environmental challenges.

Projected changes in precipitation patterns could have equally significant ramifications. The analysis reveals that southern habitats may experience a substantial reduction in rainfall, with decreases exceeding 279 mm from current levels. Such a drastic decline could strain water resources, disrupt agricultural productivity, and reduce ecosystem resilience, making southern Yunnan increasingly vulnerable to droughts and water scarcity. This highlights an urgent need for adaptive strategies to safeguard water availability, particularly for regions dependent on agriculture and vulnerable to climate-induced stress.

While northern areas are also anticipated to see reductions in rainfall, the projected decrease is less severe (around 50 mm). Nonetheless, even this moderate decline presents challenges for water resource management, particularly in regions that are already sensitive to water stress.

Given these projections, our findings underscore the necessity of proactive climate resilience planning that integrates climate-smart agriculture, robust water management infrastructure, and ecosystem-based adaptation strategies. Such measures will be essential for minimizing the adverse impacts of climate change on food security, water resources, and biodiversity.

In addition to infrastructural investments, enhancing community resilience through capacity-building programs, early warning systems, and social safety nets can empower vulnerable populations to adapt to shifting climate conditions. Additionally, fostering regional cooperation and policy alignment is critical, as many climate-related challenges, such as water management and disaster response, transcend local boundaries. By adopting a comprehensive approach to climate change mitigation and adaptation, Yunnan Province can serve as a model for climate resilience, paving the way for sustainable development and improved well-being for current and future generations.

Policy implication

Based on this research, we identified priority ecological corridors critical to reconnecting fragmented habitats across Yunnan Province. We recommend that relevant authorities initially focus on establishing shorter, high-priority corridors, as these areas offer the greatest immediate impact with minimal investment. Our study underscores the importance of constructing and preserving these essential pathways, especially for connecting high-value conservation areas that support endangered species like the Asian Elephant (Elephas maximus) and Yunnan Snub-nosed Monkey (Rhinopithecus bieti). Concentrating on shorter corridors provides a practical, effective strategy for quickly reducing habitat fragmentation and strengthening ecological connectivity, which is crucial for sustaining these sensitive species.

For corridors exceeding 10 km in length, however, further research is essential due to the greater potential for unintended ecological consequences. Extended corridors may introduce unforeseen impacts on species dynamics, agricultural land use, and local economies, necessitating a cautious approach. Detailed studies on the specific species occupying these core habitats, along with evaluations of agricultural and economic impacts, will help ensure that corridor design promotes beneficial connections without disrupting established movement patterns or introducing invasive species.

By prioritizing short but significant corridors and carrying out targeted research on longer corridors, relevant authorities can develop a strategic, sustainable approach to habitat connectivity. This approach not only supports biodiversity but also aligns with regional policy goals for ecosystem health and resilience. Future research should also consider the potential for community involvement in corridor conservation, as local engagement is often key to the success of regional connectivity projects. Incorporating insights from community-led conservation and regional policy alignment can strengthen Yunnan’s position as a leader in habitat restoration, benefiting both biodiversity and local livelihoods.

While these strategies are tailored to Yunnan, they offer valuable insights for other countries facing habitat fragmentation challenges. Nations with rich biodiversity, such as Brazil, Indonesia, and India, can adapt this approach to their unique ecological and socio-economic contexts. For example, prioritizing shorter corridors in regions with high biodiversity hotspots, such as the Amazon rainforest or Western Ghats, can facilitate cost-effective conservation and reduce initial barriers to implementation. Moreover, integrating community engagement practices can significantly enhance corridor management, as demonstrated in Kenya's successful wildlife migration corridor initiatives.

The Kimana Wildlife Corridor in Kenya provides a noteworthy example. This corridor connects Amboseli National Park to the Chyulu Hills and Tsavo ecosystems, enabling the movement of species such as elephants. Local Maasai landowners lease their land for conservation through a Payment for Ecosystem Services (PES) model, compensating them financially. This arrangement not only ensures the protection of critical habitats but also fosters local support by aligning conservation with economic incentives. Similarly, the Marsabit-Meru Corridor, managed by the Northern Rangelands Trust, secures essential migration routes between Marsabit and Meru National Parks. This initiative empowers communities by establishing locally managed conservancies and providing economic opportunities while promoting coexistence between humans and wildlife.

These examples highlight the importance of combining ecological priorities with community-led approaches to conservation. By adopting similar strategies, countries with rich biodiversity can reduce habitat fragmentation, foster local support, and address challenges such as human-wildlife conflict. Such integrated approaches ensure the sustainability of conservation efforts while aligning with regional and global policy goals.

Future Climate Adaptation Strategies and Community Engagement

Yunnan Province must implement forward-looking adaptation strategies to strengthen climate resilience that address both ecosystem and community needs. Climate-smart agricultural practices—such as drought-resistant crop varieties, rainwater harvesting, and improved irrigation techniques—are essential to sustain agricultural productivity in the face of shifting climate patterns. Ecosystem-based adaptation, including reforestation and wetland restoration, can enhance carbon sequestration and help stabilize local climates.

Community engagement is equally important. By actively involving local communities in adaptation planning, the province can ensure that policies are tailored to local needs and more widely accepted. Programs such as capacity-building workshops and knowledge-sharing initiatives can empower communities to participate in adaptive management. Additionally, early warning systems and social safety nets can support vulnerable populations, enabling them to better cope with the impacts of extreme weather events. Regional cooperation, both within Yunnan and with neighboring areas, is also vital for addressing shared challenges such as water scarcity and disaster risk reduction. These strategies will ensure that climate adaptation efforts are sustainable, inclusive, and effective, contributing to the well-being of both ecosystems and communities in Yunnan Province.

Conclusion

Biodiversity is globally recognized as essential for ecosystem health and human well-being, but is threatened by habitat fragmentation caused by human activities. To address this issue, we developed a framework that extends the traditional concept of connectivity by integrating ecological suitability. The framework was subsequently applied to a regional connectivity study in Yunnan Province, China. The framework introduces the concept of regional connectivity by identifying more corridors that connect habitats and have similar characteristics, thus maximizing the potential for reconnecting the most fragmented habitats. In addition, the framework enables planners to focus on corridors that maximize species interactions by connecting areas of high-value habitat. This study contributes to a deeper theoretical understanding of ecological corridor design and provides a broadly applicable framework that has the potential to significantly improve the effectiveness of global biodiversity conservation efforts.

While the Yunnan Province study provides valuable insights, recognizing its limitations is critical for nuanced interpretation. The construction of resistance surfaces is critical for identifying suitable biodiversity conservation areas in Yunnan. At the same time, changes in temperature and precipitation patterns due to climate change need to be taken into account to ensure the long-term effectiveness of corridors and the fitness of conditions for species within the habitat. The study's commendable focus on habitat fragmentation should be complemented by addressing other environmental issues, such as the urban heat island effect, to create multi-functional corridors. Furthermore, future research must delve into the analysis of corridor widths, essential for preventing ecological deterioration and maximizing resource allocation. Acknowledging these limitations and incorporating them into future research agendas will contribute to a more comprehensive understanding of optimizing ecological corridors in Yunnan Province and beyond.

Acknowledgments

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Appendix A

AHP method for factors with respect to resistance surface.

Table S1. The comparative matrix with respect to the comprehensive resistance surface.

		1	2	3	4	Priority
LUSE	1	1	3	5	8	58.20%
NDVI	2	0.33	1	2	5	23.50%
NTL	3	0.2	0.5	1	3	12.90%
SLOPE	4	0.12	0.2	0.33	1	5.30%

Inconsistency: 0.02 (<0.1)