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Heterogeneous Impacts of Human Activity Intensity on Regional Ecological Security Patterns: The Case of Southwest China

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Abstract: Intense human activities have significantly altered landscape structure, affected ecosystem services, and threatened ecological security. However, the spatial coupling relationship between regional ecological security patterns (ESPs) and human activity is still unclear. Taking southwest China as the study area, this study firstly assessed ecosystem service importance (ESI) and then identified ecological sources in conjunction with nature reserves. A minimum cumulative resistance model and circuit theory were used to extract ecological corridors and nodes to construct ESPs, and we further analyzed spatial relationships between ESPs and regional human activity intensity factors. Our results showed that ESI had obvious regional differences, and considering diversity and uniqueness of ecosystem functions, it is crucial for constructing ESPs. The ESPs—195 ecological sources, 490 ecological corridors, 212 ecological pinch points, and 17 barrier points—were important priority areas for ecological protection and restoration and will effectively guide differentiated ecosystem management. Intense human activities had significantly differentiated negative impacts on regional ESPs, and balancing regional ecological protection and economic development can achieve a win–win situation. Our research not only provides a new perspective for constructing ESPs but also provides important practical guidance for maintaining ecological security and landscape sustainability.

Keywords: circuit theory; ecological security patterns; spatial heterogeneity; ecosystem management; southwest China

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1. Introduction

The dual pressures of climate change and human interference result in numerous ecological and environmental challenges, including global warming [1], ecological degradation [2], biodiversity loss [3], and pollution [4]. These challenges increasingly hinder sustainable regional development. Especially in China, intense human activities, including rapid urbanization, tourist exploitation, and overstocking, are destroying ecosystem structures and affecting ecological processes [5,6] such that regional ecological security faces severe threats and challenges [7,8]. Ecological security refers to the integrity and health state of ecosystem structure, ecological process, and service function [9,10], and it is an important prerequisite for the sustainable development of a regional social economy [6]. Therefore, it has become an urgent need to effectively regulate and guarantee regional ecological security and coordinate regional ecological security maintenance and sustainable socioeconomic development [8,11,12].

Ecological security patterns (ESPs) derived from landscape ecology refer to specific landscape structure and landscape elements with important ecological significance, such as ecological sources, corridors, nodes, and networks [13,14]. Their spatial configuration plays a crucial role in maintaining regional landscape connectivity and sustainability [9]. ESPs are an important tool that helps implement rational allocation of ecosystem structure

and effective regulation of ecological processes [15,16]. ESPs in particular have become an important national strategy to balance regional ecological protection and socioeconomic development in China [8]. Hence, mapping regional ESPs is necessary for identifying priority protection areas and formulating differentiated management strategies for ecological protection. Generally speaking, the typical paradigm of ESP construction comprises three steps: determining ecological sources, constructing ecological resistance surface, and extracting ecological corridors and nodes [17].

Ecological sources are defined as priority areas or habitat patches that play decisive role in maintaining landscape ecological processes and providing ecosystem functions [18]. Some previous studies often simply selected ecological function zones or nature reserves as ecological sources, but they ignored specific ecological processes and landscape functions [19–21]. At present, more and more studies are attempting to determine ecological sources through assessing ecosystem services, ecological sensitivity, or ecological stability [4,8,16,22]. In particular, ecological importance assessment based on ecosystem services is widely applied. Nevertheless, these may miss some special ecological function zones, and face a challenge in determining the minimum area threshold and quantity for ecological sources. Therefore, this study first used quantitative (ecosystem service importance) and qualitative (nature reserve) analysis to determine important ecological patches, and combined this with threshold analysis to identify ecological sources to ensure their integrity and effectiveness.

The ecological resistance surface refers to the spatial resistance of species migration between ecological sources, and characterizes the difficulty of species migration through a certain spatial point [23]. It is commonly determined based on resistance assignment of land cover, but the uniform assignment cannot reflect the spatial heterogeneity of the same landscape. A modified resistance surface combined with different factors of topography, vegetation, economy, and landscape connectivity can more accurately reflect interior difference among different landscapes [13,24]. These will be more conducive to the accurate identification of ecological corridors and ecological nodes.

Ecological corridors refer to linear or ribbon-shaped landscape elements that connect different ecological sources or landscape patches to increase landscape connectivity [25], and they are responsible for connecting the flow of matter, energy, and information to increase landscape connectivity. Ecological corridors are often determined based on a minimum cumulative resistance model (MCR) [4] or circuit theory [8]. An MCR model is designed to calculate the cost of a species moving from source to destination [25]. It can effectively identify the optimal route, but it ignores specific range and width of corridors. Circuit theory, from McRae [26], can not only be used to identify linear corridors but can also accurately simulate and predict species movement patterns across complex landscapes based on current density, and has been widely applied in ecological analysis [27]. Ecological nodes refer to important sections that link ecological processes between landscape patches and affect species migration, including ecological pinch points and barrier points [28]. Ecological pinch points with high current density represent the areas with high frequency of species migration between landscape patches, while barrier points refer to the areas that seriously hinder species migration, and their presence or disappearance will seriously affect landscape connectivity [25].

Although constructing ESPs composed of ecological sources, corridors, and nodes is of great significance for coordinating ecosystem management and maintaining ecological security, it is also highly susceptible to environmental factors and human activities on temporal and spatial scales [27,29]. For instance, changes in precipitation, temperature, and soil properties can change landscape type and spatial configuration and further affect landscape connectivity [30]. Marginal climate effects and vegetation structure will affect the width and range of ecological corridors [31]. Human activities, such as increased population, urban expansion, tourism development, irrational grazing, and mineral exploitation, may lead to landscape fragmentation [32–35]. These will lead to significant changes in the number, area, and spatial pattern of ecological sources and corridors, and further affect the

connectivity and stability of ESPs. Therefore, it is necessary to pay more attention to the spatial relationship between ESPs and human activity intensity factors.

Southwest China is an ecologically sensitive and fragile area. Various high-intensity human activities and increased climate change have caused prominent regional eco-environmental problems, and these seriously threaten regional ecological security and sustainable development [7,36]. Therefore, taking southwest China as the study area, this study set three detailed objectives: (1) assess ecosystem service importance (ESI); (2) identify ecological sources based on ESI and nature reserves, and construct a source–corridor–node ESP paradigm based on circuit theory; and (3) analyze spatial relationships between ESPs and human activity intensity based on geographical weighted regression model. Our study aimed to (1) provide a new perspective for identifying ecological sources and constructing ESPs and (2) identify critical priority areas for ecological protection and restoration based on ESPs to provide practical guidance for differentiated ecosystem management and ecological security maintenance.

2. Materials and Methods

2.1. Study Area

Southwest China includes Chongqing Municipality, Sichuan Province, Yunnan Province, Guizhou Province, southwest Qinghai Province, and east Tibet Autonomous Region (85°30–112°30 E, 20°54–36°29 N), and covers 23.89% of China's land area (Figure 1). Southwest China has complex topography, the average altitude is 2869 m, and it spans tropical, subtropical and semi-arid regions with complex and diverse climate types. The spatiotemporal variation in average annual temperature (0–24 °C) and precipitation (600–2300 mm) is obvious in southwest China, and this increases from northwest to southeast [16]. Ecosystem types are dominated by forest and grasslands, accounting for about 42% and 35% of the study area, respectively. Superior climatic and abundant natural resources provide favorable conditions for the survival and reproduction of animals and plants, as well as various ecosystem services closely related to human well-being [7].

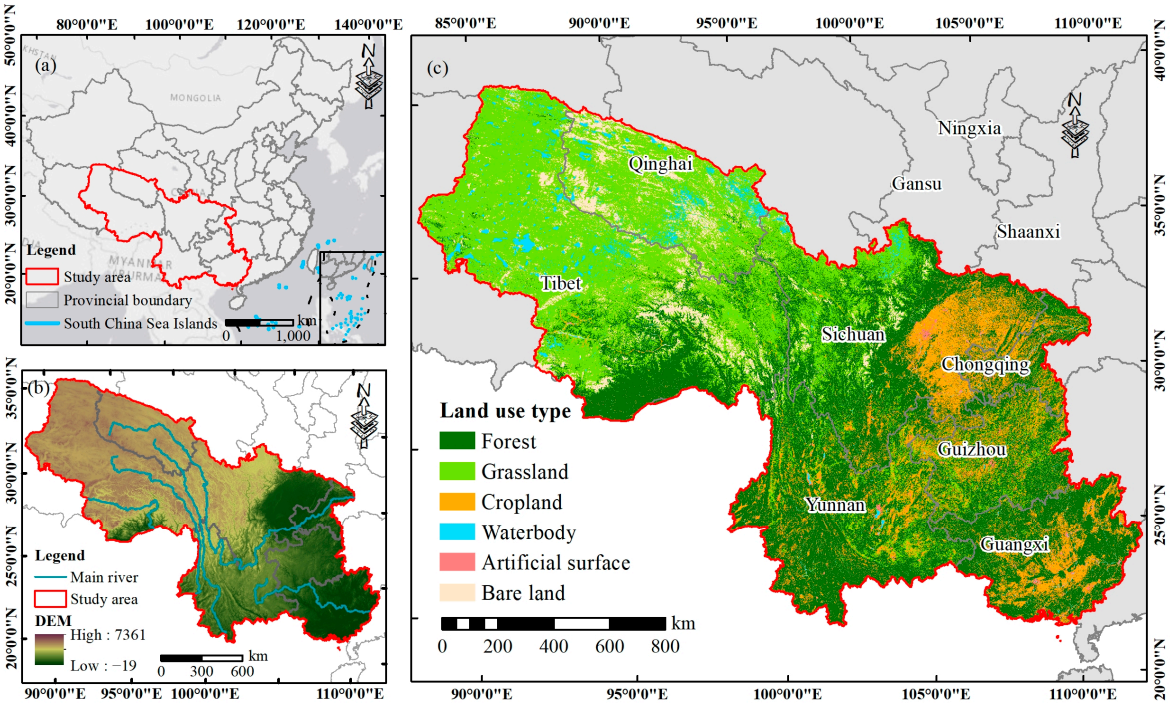


Figure 1. Overview of the study area. (**a**) Geographical location. (**b**) Elevation and main rivers. (**c**) Land use types.

2.2. Data Source

This study involved multiple data sources, including topographic, socioeconomic, climatic, vegetation, and other datasets. Details and sources of key data are shown in Table 1. In this study, all spatial raster data were resampled to 250 m resolution.

Table 1. Data sources.

Data Types	Format	Resolution	Data Source
Administrative boundaries	Shapefile		Resource and Environment Science and Data Center (http://www.resdc.cn/ (accessed on 18 January 2023))
Land use and land cover (LULC)	Raster	30 m	Resource and Environment Science and Data Center (http://www.resdc.cn/ (accessed on 18 January 2023))
Fractional vegetation cover (FVC)	Raster	1 km	Resource and Environment Science and Data Center (http://www.resdc.cn/ (accessed on 18 January 2023))
Net primary productivity (NPP)	Raster	1 km	Resource and Environment Science and Data Center (http://www.resdc.cn/ (accessed on 18 January 2023))
DEM	Raster	30 m	Resource and Environment Science and Data Center (http://www.resdc.cn/ (accessed on 18 January 2023))
Slope	Raster	30 m	Resource and Environment Science and Data Center (http://www.resdc.cn/ (accessed on 18 January 2023))
Precipitation	Raster	1 km	National Meteorological Information Centre (http://data.cma.cn (accessed on 25 February 2023))
Temperature	Raster	1 km	National Meteorological Information Centre(http://data.cma.cn (accessed on 25 February 2023))
Evapotranspiration	Raster	1 km	National Meteorological Information Centre(http://data.cma.cn (accessed on 25 February 2023))
Night light index	Raster	500 m	Resource and Environment Science and Data Center (http://www.resdc.cn/ (accessed on 18 January 2023))
Nature reserves	Shapefile		Resource and Environment Science and Data Center (http://www.resdc.cn/ (accessed on 18 January 2023))
Soil erosion sensitivity	Raster	1 km	Geographical Information Monitoring Cloud Platform (http://www.dsac.cn/ (accessed on 26 January 2023))
Landslide sensitivity	Raster	1 km	Geographical Information Monitoring Cloud Platform (http://www.dsac.cn/ (accessed on 26 January 2023))
Number of tourists	Excel		Statistical yearbooks
Urbanization rate	Excel		Statistical yearbooks

2.3. Methods

This study aimed to construct ESPs composed of sources, corridors, and nodes, and explore the spatial relationship between ESPs and regional development to provide decision-making references for regional differentiated ecosystem management and sustainable development. Figure 2 summarizes the overall research process and framework, including assessment of ESI, identification of ecological sources, construction of ecological resistance surface, extraction of ecological corridors, identification of ecological nodes, and analysis of spatial relationships between ESPs and regional development.

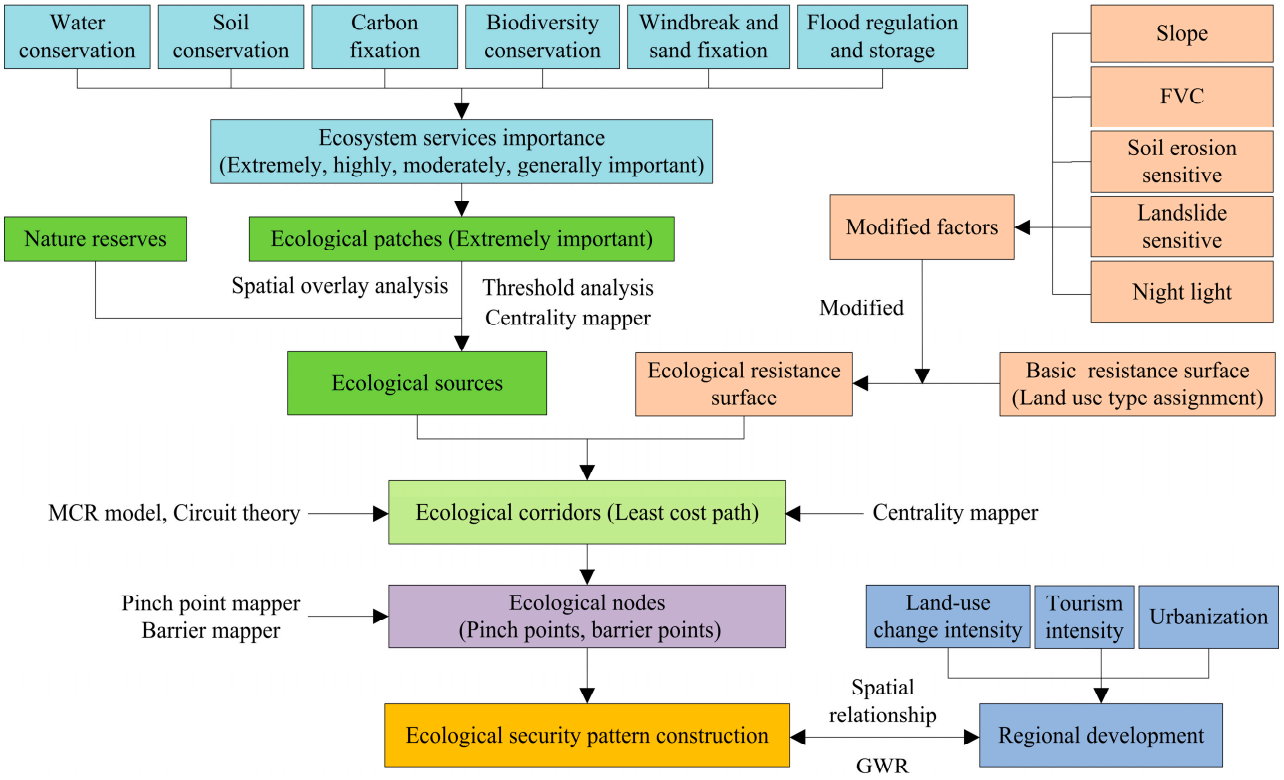


Figure 2. Overall research process and framework.

2.3.1. Ecosystem Service Importance Assessment

In this study, we selected multiple ecosystem services that are important in maintaining regional ecological security: water conservation (WC), soil conservation (SC), carbon sequestration (CS), wind prevention and sand fixation (WS), biodiversity conservation (BC), and flood regulation and storage (FS). The water balance equation was used to assess WC. SC was evaluated by calculating the amount of potential soil erosion and actual soil erosion. CS was calculated based on ecosystem biomass, and the modified soil wind erosion model was used to calculate WS. We selected a biological conservation planning model to assess BC, and specific calculation methods are shown in Table S1. Then, the comprehensive ecosystem service (CES) was calculated based on the equal-weight method. With reference to relevant literature [16,37], we ranked ecosystem services per unit area in descending order and calculated the cumulative ecosystem services. Then, we further classified ecosystem services into extremely important (0–25%), highly important (25–50%), moderately important (50–75%), and generally important (75–100%) based on the proportion of cumulative ecosystem services. Considering that each ecosystem service represents different function types, such as water, soil, carbon, and biodiversity, we extracted the highest importance value among different services for each cell to map the spatial pattern of *ESI*. The calculation formula used was:

$$ESI = \mathrm{Max}(S_1, S_2 \ldots\ldots S_i) \quad (1)$$

where *ESI* is ecological service importance and S_i etc. represent different *ESI*s.

2.3.2. Circuit Theory Model

The circuit theory model proposed by McRae can simulate gene flow in heterogeneous landscapes by current and predict the probability of migration and diffusion of organisms along a certain path [26]. In a circuit, electron migration is random, while the dispersal of

species or gene flows in a given landscape is also random. The circuit theory model combines random migration theory and species movement ecology to measure the connectivity of heterogeneous landscapes [27]. In the circuit theory model, heterogeneous landscapes are likened to circuits consisting of nodes and resistors. Each ecological source is treated as an electric circuit node, and individual species or gene flows are treated as electrons [8]. Then, landscapes with different resistance values are represented as conductive surfaces, and landscape components best promoting species flow are assigned low resistance values. The resistance distance directly maps the spatial distribution range of individual species or gene flows.

2.3.3. Construction of Ecological Security Patterns

(1) Identification of ecological sources. We selected extremely important areas for ESI and nature reserves as potential ecological sources and further determined the minimum patch area suitable for ecological sources based on threshold analysis. Then, we used the centrality mapper tool of the linkage mapper toolkit (http://www.circuitscape.org/linkagemapper (accessed on 5 April 2023)) in ArcGIS 10.6 to calculate the current flow centrality of each path on the linkage network, and each ecological source was assigned a final centrality score by adding up the current flow centrality of link paths across all core areas, which was used to evaluate the importance of ecological sources. Based on the natural breakpoint method, the ecological sources were divided into three levels—key, important, and secondary.

(2) Construction of ecological resistance surface. We determined the basic resistance surface based on the resistance assignment of land use types [8,13], and the resistance of forest, grassland, farmland, desert, wetland, and artificial land were 1, 5, 20, 30, 50, and 100, respectively. We further selected slope, fractional vegetation cover (FVC), soil erosion sensitivity (SE), night light index (NL), and landslide sensitivity (LS) to reflect regional ecological background, ecological risk, and ecological pressure to modify the basic resistance surface and determined ecological resistance surface. Generally speaking, high values of slope, SE, LS, and NL mean higher ecological resistance, while high FVC means less ecological resistance.

(3) Extraction of ecological corridors. We first simulated the least cost path between ecological sources as linear ecological corridors using the linkage pathways tool of the linkage mapper toolkit in ArcGIS 10.6. Then, the centrality mapper tool of the linkage mapper toolkit in ArcGIS 10.6 was used to calculate the current flow centrality of each path by analyzing the simulated linkage networks for the least cost path to reflect its importance for keeping the overall network connected. We used this to evaluate the importance of linear ecological corridors. Based on the natural breakpoint method, the ecological corridors were divided into three levels—key, important, and secondary. Moreover, we identified the current density corridors based on circuit theory [26] and analyzed spatial ranges and patterns of ecological corridors under different cumulative resistance thresholds of 1 km, 2 km, 3 km, 4 km, 5 km, 6 km, 7 km, 8 km, and 9 km. With reference to relevant literature [8], we further took into account the important ecological status and increasing ecological protection investment in southwest China and assumed that regional ecological protection investment can support about 60% of the whole study area to determine the optimal cumulative resistance threshold and ecological corridors.

(4) Identification of ecological nodes. We applied the pinch point mapper tool in ArcGIS 10.6 to extract ecological pinch points. It first accumulated currents between all pairs of ecological sources to generate a cumulative current map. Then, high-cumulative-current-density areas were extracted as ecological pinch points, and we further evaluated their importance according to the patch size of high-current-density areas. Then, we used the barrier mapper tool in ArcGIS 10.6 and moving window search method to identify the

barrier points. The central pixel value of search window was replaced by the minimum-cost distance between ecological sources, and the improvement score of unit minimum-cost distance was used to characterize the improvement in connectivity after the removal of barrier points. Based on the natural breakpoint method, the areas with high improvement scores were extracted as barrier points.

2.3.4. Geographical Weighted Regression Model

The geographically weighted regression (GWR) model explores the spatial relationship between different variables and related driving factors by establishing local regression equations at each point in the spatial range [38]. Hence, the GWR model in ArcGIS 10.6 was used to analyze spatial relationships between the area proportion of ESPs in each city and human activity intensity factors. In this study, we selected human activity intensity factors including land change intensity from low-quality habitats such as farmland, artificial surfaces, and unused land to high-quality habitat such as forest, grassland, and water bodies (LCI_1), and land change intensity from high-quality habitats to low-quality habitats (LCI_2), urbanization rate (UR), and tourists per unit area (TPA) (Figure S1). The calculation formula of the GWR model is:

$$y_i = \beta_0(\mu_i, v_i) + \sum_{k=1}^{m} \beta_k(\mu_i, v_i)x_{ik} + \varepsilon_i \quad (2)$$

where y_i is the area proportion of ESPs, i is the sampling point code, and μ_i and v_i represent coordinates of sampling point i. β_0 is the intercept of sample i, x_{ik} represents different human activity intensity factors, and k is the factor number. β_k represents the local regression coefficient, which reflects the interaction between ESPs and human activity intensity factors. When β_k is greater than 0, human activity intensity is beneficial to ESPs, while when β is less than 0, human activity intensity will affect the connectivity of ESPs. ε_i is the random error.

3. Results

3.1. Spatial Pattern of Ecosystem Service Importance

Extremely important areas for WC, SC, CS, and BC were mainly distributed in southeastern Tibet, southwestern Yunnan, northeastern Guangxi, and south–central Sichuan (Figure 3a–d): 5.45%, 3.13%, 5.24%, 16.70%, 0.93%, and 2.93% of the total area, respectively. Extremely important areas for WS and FS accounted for 0.93% and 2.93%, respectively, and they were mainly concentrated on the Qinghai–Tibet Plateau (Figure 3e–f). The extremely, highly, moderately, and generally important areas for CES accounted for 14.91%, 19.09%, 24.08%, and 41.92%, respectively, and there was obvious spatial heterogeneity (Figure 3g). The area of extremely important areas for ESI was about 64.77×10^4 km^2, and accounted for 28.22% of the total area. These were mainly concentrated in southeastern Tibet, western and southern Yunnan, southwestern and northeastern Guangxi, and central Sichuan (Figure 3h). The highly, moderately, and generally important areas accounted for 26.18%, 35.27%, and 10.34% of the total area, respectively (Figure 3i). The ESI in southwest China was generally at a high level.

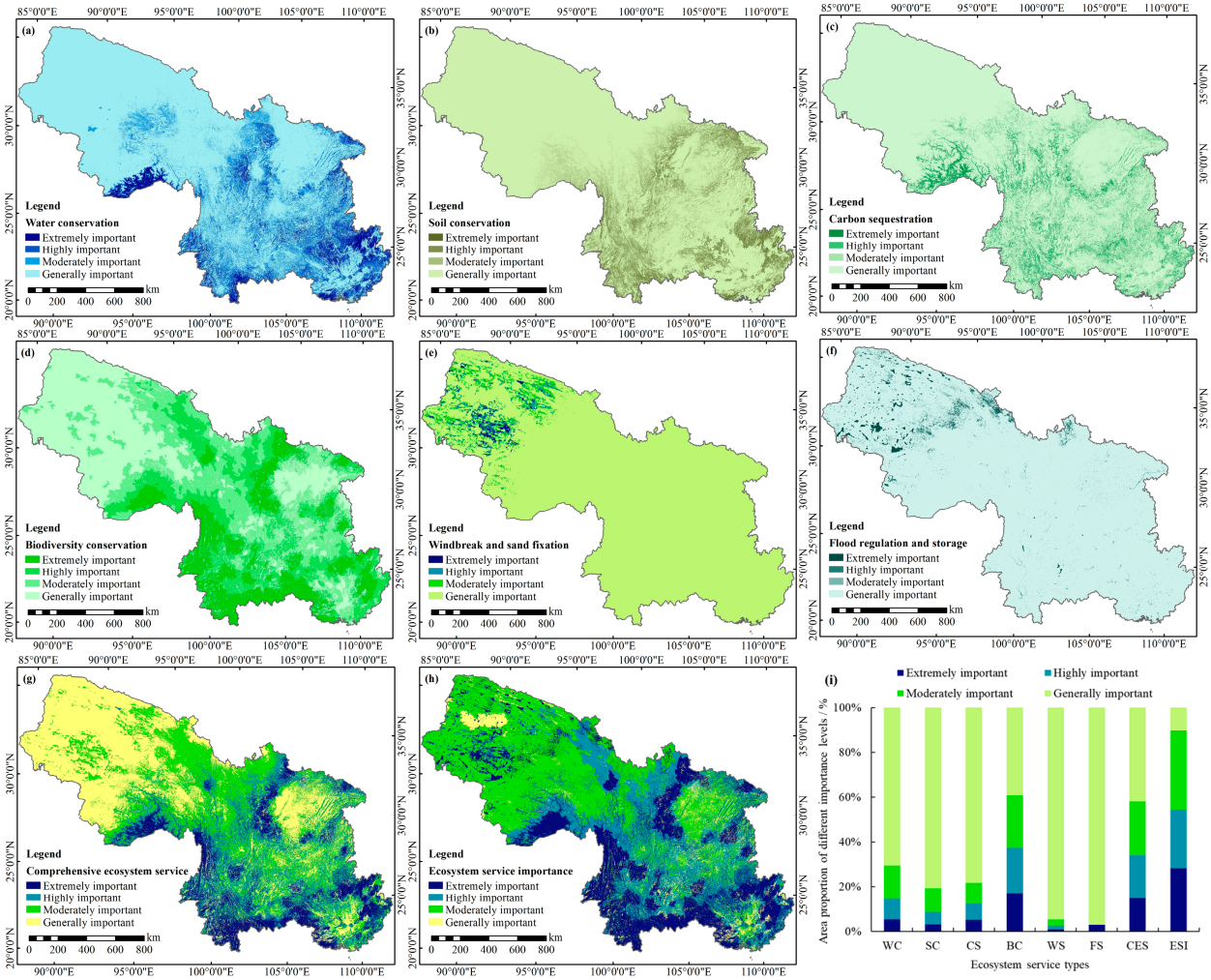


Figure 3. Spatial pattern and area proportion of ESI in southwest China. (**a**) Water conservation (WC). (**b**) Soil conservation (SC). (**c**) Carbon sequestration (CS). (**d**) Biodiversity conservation (BC). (**e**) Windbreak and sand fixation (WS). (**f**) Flood regulation and storage (FS). (**g**) Comprehensive ecosystem service (CES). (**h**) ESI. (**i**) The area proportion of different importance levels of ecosystem services.

3.2. Ecological Security Patterns

3.2.1. Ecological Sources

Potential ecological sources based on ESI were mainly concentrated in southeastern Tibet, central Sichuan, southwestern and northeastern Guangxi, and western and southern Yunnan (Figure 4a). Potential ecological sources based on 324 nature reserves were mainly distributed in western Sichuan, northwestern Tibet, and southwestern Qinghai (Figure 4b). They accounted for 21.76% of the study area, and had obvious spatial complementarity with the former. The threshold analysis results showed that both the number and area proportion of ecological sources decreased as the area threshold increased, and they gradually tended toward stability when the threshold was greater than 80 km^2. Therefore, this study selected patches larger than 80 km^2 as ecological sources (Figure 4c), and further identified 195 ecological sources: 12 key sources, 69 important sources, and 114 secondary sources (Figure 4d). These ecological sources accounted for 43.35% of the study area. Key sources were mainly concentrated in southern and western Yunnan, central Sichuan, northeastern Guangxi, southeast and northwest Tibet, and southwestern Qinghai, while these important sources were mainly concentrated in western Sichuan, eastern Yunnan, and central Tibet.

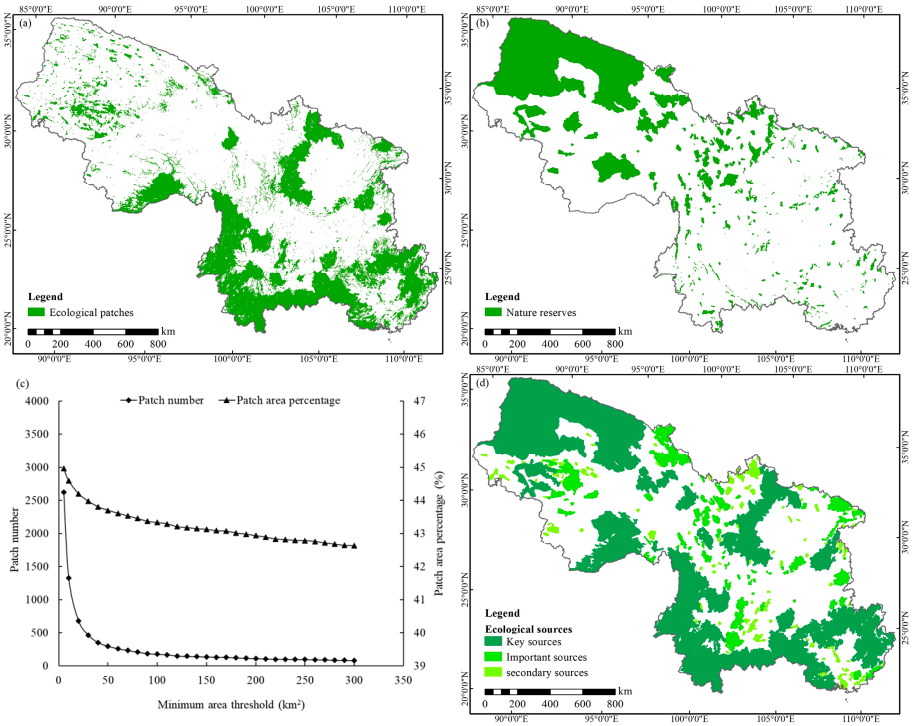


Figure 4. Identification of ecological sources in southwest China. (**a**) Spatial pattern of ecological patches based on extremely important areas. (**b**) Spatial pattern of nature reserves. (**c**) Variation characteristics of the number and area of potential ecological sources with different thresholds. (**d**) Spatial pattern of ecological sources with different importance levels.

3.2.2. Ecological Corridors and Nodes

Ecosystem types in southwest China were dominated by forests and grasslands, and the basic ecological resistance was relatively low (Figure 5). The revised ecological resistance value ranged from 0.07 to 99.97, and had obvious spatial heterogeneity. Then, we extracted 490 least cost paths as linear ecological corridors: 18 key corridors, 242 important corridors, and 230 secondary corridors. The key and important corridors were mainly distributed in northern Yunnan, western Sichuan, and central Tibet. The secondary corridors were mainly in Guizhou, eastern Sichuan, and northeastern Yunnan (Figure 6a). The cumulative resistance threshold analysis results showed that with thresholds increasing from 1 km to 9 km, the area proportion of ecological sources and ecological corridors increased gradually. However, when the threshold was greater than 4 km, the spatial pattern of ecological corridors was basically stable, and the area proportion growth slowed significantly (Figure S2). Therefore, this study selected the 4 km threshold to map ecological corridors with spatial width and scope (Figure 6b), and the area ratio of 63.18% is basically consistent with our assumption of 60%. The ecological corridors in Tibet and southeastern Sichuan were relatively narrow.

This study identified 212 ecological pinch points based on ecological corridors with a width threshold of 4000 m: 68 key pinch points, 78 important pinch points, and 66 secondary pinch points. Key and important pinch points were concentrated in western Sichuan and eastern Tibet (Figure 6c), while secondary pinch points were mainly concentrated in eastern Sichuan, central Tibet, and northeastern Yunnan. This study also identified 17 barrier points, which were mainly distributed in northwestern Tibet (Figure 6d). Strengthening these barriers will significantly increase the connectivity of ESPs.

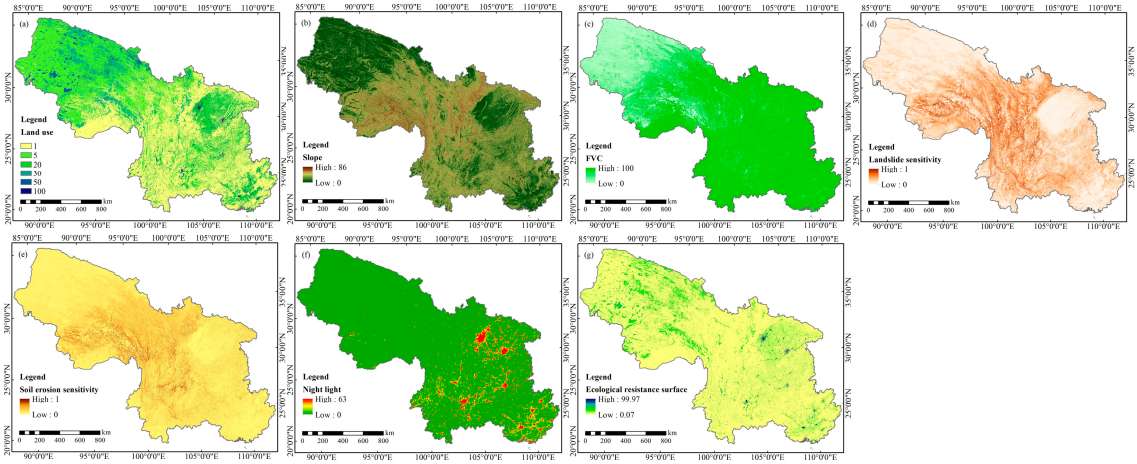


Figure 5. Construction of ecological resistance surface in southwest China. Construction of ecological resistance surface in southwest China. (**a**) Land use types. (**b**) Slope. (**c**) Fractional vegetation cover. (**d**) Landslide sensitivity. (**e**) Soil erosion sensitivity. (**f**) Night light index. (**g**) Spatial pattern of ecological resistance surface.

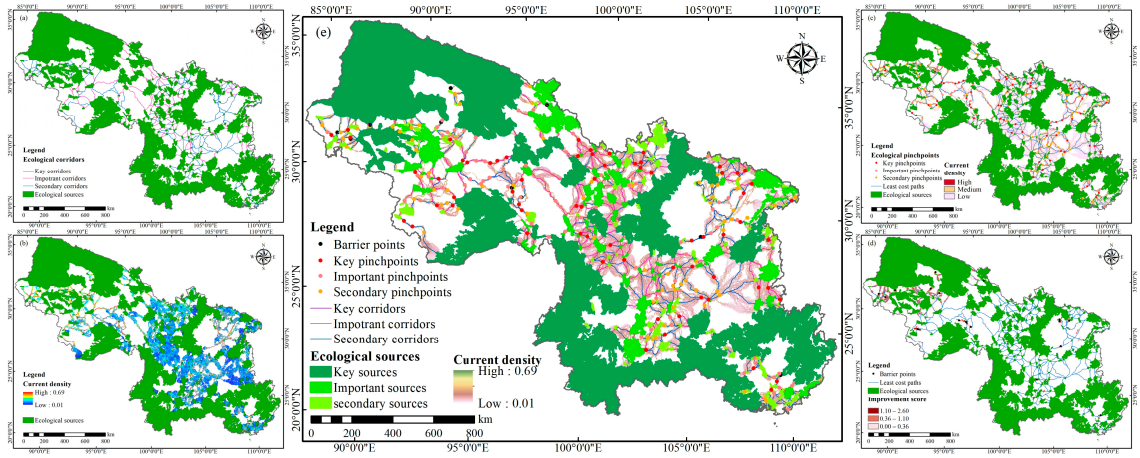


Figure 6. ESPs in southwest China. (**a**) Potential ecological corridors based on least cost path. (**b**) Ecological corridors based on current density. (**c**) Different levels of ecological pinch points. (**d**) Barrier points. (**e**) ESPs.

3.2.3. Ecological Security Patterns

The ESPs in southwest China consisted of 195 ecological sources, 490 ecological corridors, 212 ecological pinch points, and 17 barrier points. They covered 145.00 × 10^4 km^2, and accounted for 63.18% of the total area (Figure 6e). Key sources were evenly distributed in space, with high integrity and connectivity. Key corridors and important corridors were alternately distributed, and provided convenient passages for biological migration. Ecological sources, corridors, and nodes were interconnected and jointly constructed the ESPs, which play an important role in maintaining regional biodiversity and ensuring regional ecological security.

3.3. Spatial Relationship Between ESPs and Human Activity Intensity

High-value areas of the ESP area ratio in different prefecture-level cities were mainly concentrated in western Sichuan and western and southern Yunnan, while low-value areas were mainly concentrated in the Sichuan Basin (Figure 7a,b). Statistical analysis results showed that the ESP area ratio was significantly positively correlated with LCI_1 (R = 0.417, $p < 0.01$) and significantly negatively correlated with LCI_2 (R = −0.492, $p < 0.01$), UR

(R = −0.400, $p < 0.01$), and TPA (R = −0.517, $p < 0.01$). Moreover, geographically weighted regression results showed that LCI_1 in Sichuan, Chongqing, and Tibet had a significant positive impact on the ESPs (Figure 7c). LCI_2 showed a significant negative impact on the ESPs, and the degree of influence gradually increased from north to south (Figure 7d). The UR had a significant negative impact on the ESPs in Sichuan, Chongqing, Yunnan, Guizhou, and Guangxi (Figure 7e), while TPA had a significant negative impact on the ESPs in Sichuan, Yunnan, Guizhou, Chongqing, and eastern Tibet (Figure 7f). It can be seen that the effect of human activities on the regional ESPs had obvious spatial heterogeneity.

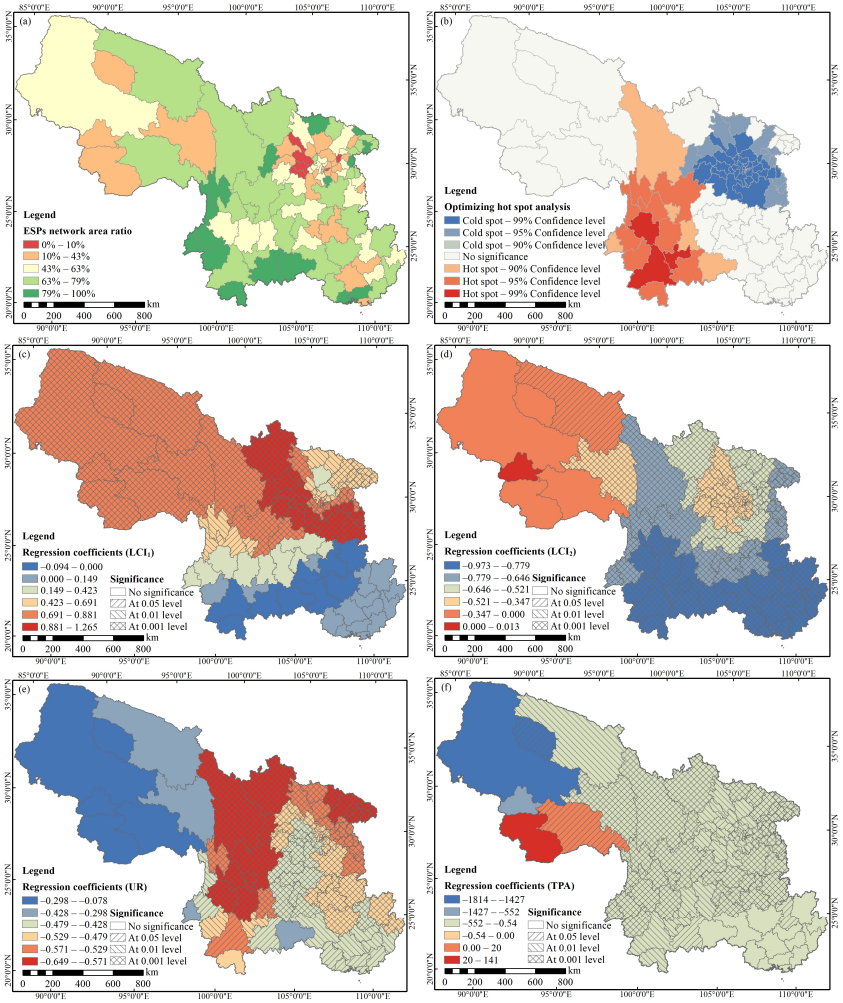


Figure 7. Spatial relationship between ESPs and human activity intensity factors in southwest China. (**a**) Spatial pattern of ESP area proportion in different prefecture-level cities. (**b**) Spatial clustering characteristics of ESP area ratio. (**c**) LCI_1. (**d**) LCI_2. (**e**) UR. (**f**) TPA.

4. Discussion

4.1. Methodological Advantages

Constructing ESPs based on a source–corridor–node paradigm has been widely recognized [39], but these research methods still need to be further improved. Instead of just selecting ecological functional space or ecological assessment [19–21], this study combined quantitative (ESI) and qualitative (nature reserves) analysis to identify and determine ecological sources. Our method not only considered the important ecosystem services in the southeastern part of study area but also considered the key conservation areas for special species in the northwest. This will better ensure the integrity and effectiveness of ecological sources. Overall, this approach adds new insights into the methodology of ecological source identification.

Moreover, constructing ecological resistance surfaces is the key to extracting ecological corridors and ecological nodes [40]. This study selected five spatial indicators related to ecological background, ecological risk, and ecological stress as a correction index to construct the ecological resistance surface, which can more realistically simulate the impediments to migration for species under the interaction of natural factors and human activity [41]. Linear ecological corridors ignore the spatial scope, width, and importance of real corridors, and hardly reflect the real situation of ecological corridors [42–44]. Our study identified the key corridors, important corridors, and secondary corridors as well as their spatial widths based on circuit theory, and further determined ecological pinch points regarded as stepping stones for species migration, barrier points, and their influence sphere. These advantageous methods better ensure the integrity and effectiveness of ESPs.

4.2. Effect of Threshold Setting on ESPs

Ecological sources depend on ecological function, patch area, patch quantity, and spatial pattern, and marked differences among these will affect ecological corridors and nodes, further changing regional ESPs [45,46]. In particular, the setting of minimum area threshold will directly affect the quantity and spatial pattern of ecological sources [47]. In this study, combining ESI and nature reserves to identify ecological sources was more suitable for the important ecological status of southwest China, and this ensured the accuracy and effectiveness of ecological source identification. Moreover, our study selected 80 km^2 as the optimal patch area of ecological sources based on threshold analysis and determined the number and pattern of ecological sources. These ecological sources were highly coincident with ecological red lines and key ecological functional areas. The appropriate ecological sources lay the foundation for the construction of ESPs.

The primary function of ecological corridors is connecting different ecological sources to maintain ecological processes [48], and the width, length, quantity, function, and surrounding matrix of corridors will affect spatial configuration and connectivity [8,25]. In particular, the setting of corridor width will directly affect the ecological function of corridors [48,49]. Wide ecological corridors can significantly reduce the spatial resistance of species migration and movement and further affect the distribution of ecological nodes [8]. This study not only extracted least cost paths of different levels but also analyzed the pattern and range of ecological corridors under different width thresholds of corridors (Figure S2). The results showed that along with the increasing thresholds of accumulated resistance from 1 km to 9 km, the area of ESPs accounted for 50.28%, 55.57%, 59.77%, 63.18%, 66.10%, 68.71%, 70.98%, 73.09%, and 74.00%, respectively. Although the width and area of ecological corridors increased, their spatial pattern remained basically unchanged. When the cumulative resistance threshold was greater than 4 km, the increase in the spatial width and area of the ecological corridor became significantly slower. Limited by the trade-off between rapid economic development and ecological protection investment, increasing investment in conservation can only support limited ecosystem management [8]. Therefore, this study selected 4000 m as the spatial range of ecological corridors, and the area ratio of 63.18% is basically consistent with our assumption of 60%. It can be seen that the infinite increase in the width of the corridor may also increase its redundancy and inefficiency. Only reasonable ecological corridors can better ensure the authenticity and effectiveness of ESPs.

4.3. Application of ESPs to Guide Differentiated Ecosystem Management

Constructing ESPs can accurately identify key landscape elements and ecological processes [42,48]. These will help guide regional ecological protection and restoration, effectively control construction land expansion, and optimize ecological land patterns [50]. Nevertheless, climate change, human activities, and management policy cause obvious spatial heterogeneity in landscape ecological processes and ecological function change [51–54]. Therefore, formulating precisely differentiated ecosystem management strategies for different administrative regions, different functional zones, and different landscape elements is very important [55]. In this study, key and important ecological sources, corridors, and

pinch points in eastern Tibet, northwestern Yunnan, and western Sichuan must strictly control large-scale and high-intensity human activities and implement priority protection to prevent ecosystem degradation. In particular, it is vital that nature reserve management committees, rangers, and local residents work together to monitor ecological damage. In addition, these obvious ecological protection gaps in southeast Tibet, northern Yunnan, and Guizhou need to reasonably build, expand, or integrate nature reserves to better protect and improve ecological environments. Ecological blind areas, barrier points, and narrow ecological corridors in western Tibet, northeastern Yunnan, and northwestern Guizhou should be implemented in more ecological projects to improve ecosystem services and increase connectivity.

Moreover, balancing regional ecological protection with socioeconomic development is vital. Our results showed that LCI_1 in Sichuan, Chongqing, and Tibet had a significant positive impact on the ESPs, where desertification control, grazing management, and ecological engineering have significantly improved ecosystem services and optimized the ESPs. LCI_2, urbanization, and tourism intensity had significant negative impacts on the regional ESPs in western Sichuan, northwest Yunnan and northeast Chongqing, and these areas need to properly control human activities such as urban expansion and tourism development to prevent encroachment on ecological land and damage to landscape connectivity. For the largest key ecological sources in Yunnan and Guangxi in particular, high-intensity human activity must be prohibited, and ecological agriculture and ecological tourism should be actively advocated to achieve win–win results in ecological protection and economic development.

5. Conclusions

Constructing ESPs is an effective approach to identity the priority areas for ecological protection and maintain regional ecological security under intensified climate change and human activities. Our research showed that ecosystem services are extremely important in southwest China, and their diversity and dominance determined the spatial heterogeneity of ESI. Combining ESI and nature reserves to identify ecological sources can ensure their integrity and effectiveness. Taking ESPs composed of ecological sources, corridors, pinch points, and barrier points as the priority conservation and restoration areas in southwest China, the implementation of differentiated ecosystem management can effectively avoid ineffective ecological protection. Intense human activities will seriously threaten or destroy ESPs, and accurately balancing ecological protection and socioeconomic development will achieve a win–win situation. Our study provides an effective decision-making reference for regional ecosystem management. However, this study still lacked some comparative research on the spatial and temporal scale effects, including future multi-scenario simulation and the validity verification of ESPs. Influence mechanisms of different natural and human factors on ESPs still need to be explored in depth. These issues will be the focus of attention in future work.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13122172/s1, Figure S1: Spatial pattern of land use change and human activity intensity factors in Southwest China. (a) Spatial of land change intensity from low-quality habitat such as farmland, artificial surface and unused land to high-quality habitats such as forest, grassland and water body (LCI_1). (b) Spatial of land change intensity from high-quality habitat to low-quality habitats (LCI_2). (c) Spatial of urbanization rate in different cities (UR). (d) Spatial of tourists per unit area in different cities (TPA); Figure S2: Spatial pattern of ecological corridor with different width thresholds: (a) 1 km, (b) 2 km, (c) 3 km, (d) 4 km, (e) 5 km, (f) 6 km, (g) 7 km, (h) 8 km, (i) 9 km; Table S1: Methodology for ecosystem services assessment.

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