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Linking ecosystem services and circuit theory to identify ecological security patterns

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Abstract: The rapid process of urbanization, accompanied by the sharp increase of urban population and expansion of artificial surface, has resulted in the loss of natural ecosystems and the degradation of ecosystem services. Identifying and protecting key places that have high importance for ecological sustainability are great challenges. Ecological security patterns are such an integrated approach to protecting regional ecological sustainability. In this study, taking Yunnan Province, China as a case study area, ecological sources were identified through ecosystem services, and circuit theory was used to model ecosystem processes in heterogeneous landscapes via calculating the 'resistance' or 'current', and thus to identify ecological corridors and key ecological nodes. The results showed that, ecological security pattern included 66 ecological sources, 186 ecological corridors, 24 pinch-points and 10 barriers. In details, the ecological sources were mainly distributed in the southwest and northwest of Yunnan Province, with the ecological corridors locating along the high mountains, and both ecological sources and corridors were mostly covered with forest land.

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Pinch-points covered by forest land and cultivated land, were distributed in the middle of Yunnan Province along the rivers. Approximately 75.9% nature reserves located in the identified ecological sources, and the remainings were mainly distributed in eastern Yunnan Province with small area, showing the effectiveness in identifying ecological security patterns. Among 81 projects of low–slope hill development carried out in Yunnan Province, 46.9% showed potential human stress on regional ecological security. Based on ecosystem services and circuit theory, this study provides a new approach to identifying the spatial range of ecological corridors and the specific location of key nodes for effective ecological conservation and restoration.

Keywords: ecological security patterns; ecosystem services; circuit theory; ecological corridors; pinch-points; Yunnan Province, China

1. Introduction

Along with the continuous urbanization in the last decades, human populations have been greatly concentrated in urban areas. However, disorderly expansion of urban construction land and significant loss of ecological land have restricted the sustainability of urban development (Peng et al., 2017a; Feist et al., 2017). As a result, hot to ensure the structural stability and functional security of natural ecosystems for sustainable urban development are global issues (Li et al., 2015; Cumming and Allen, 2017; Serra-Llobeet and Hermida, 2017). Especially in China, regional ecological security has faced a severe situation such as biodiversity loss (Zhang et al., 2016b; Peng et al., 2018), soil erosion and water resources scarcity (He et al., 2014; Qiu and Song, 2017; Li and Li, 2017).

The policy of ecological security patterns (ESP) has become one of important national strategies in China for coordinating the ecosystem protection and economic development, which were identified in a bottom-line approach to protecting priority areas (Peng et al., 2018). In general, ecological security patterns aim to achieve regional ecological sustainability through integrating landscape patterns with ecological processes, and comparing the importance of different landscape patches on specific ecological processes and ecosystem services. Therefore, in substance ESP construction is to identify the priority areas for regional ecological services, security, and sustainability. Similar to the concept of ’Secure Urbanism’ (Hodson and Marvin, 2009), ’Resilient Infrastructure’ (Sutton-Grier et al., 2015; Liu et al., 2016), and ’Spatial Conservation Prioritization’ (Hossain et al., 2017; Albanese and Haukos, 2016), ESP can be seen as the cognition and complement of the concept of ‘Planetary Boundary’ (Steffen et al., 2015), from the perspective of spatial patterns.

Under the background of global environmental change, the regulation and guarantee of regional ecological security has become an unavoidable problem. The new paradigm is an inevitable choice to move from isolated ecosystem control to integrateed ecological governance (Kukkala and Moilanen, 2017). Originating from landscape ecological planning, the construction of ecological security patterns provides a spatial solution to regional ecological security issues (Li et al., 2011; Li et al., 2013; Liu and Chang, 2015). Based on the understanding of the link between ecological processes and landscape patterns (Klar et al., 2012; Liu and Chang, 2015), specific positions in the landscape can be identified which are vital for improving landscape connectivity and controlling certain ecological processes. The spatial pattern of such positions corresponds to the patch-corridor-matrix paradigm of landscape patterns (Yin et al., 2015). At present, the construction of ecological security patterns has formed one research paradigm including the identification of ecological source, and ecological corridor.

The first step in ESP construction is to identify ecological source, which is mainly conducted through assessing ecological suitability, ecological risk, ecological importance, or ecological connectivity (Su et al., 2016; Teng et al., 2011; Zhang et al., 2016a). Among these techniques, ecological importance evaluation based on ecosystem services is the most common (Lin et al., 2016; Li et al., 2010; Liang et al., 2018). Ecosystem services are defined as the benefits human population gains directly or indirectly from natural ecosystems, such as food, clean water, flood control, climate regulation, erosion control, and recreation and tourism (Costanza et al., 1997). Human demanding for tangible biological resources and intangible ecological assets ultimately depends entirely on the supply and maintenance of ecosystem services. An ecological source can be regarded as the least ecological land to meet the needs of ecological security in urban development, and is the result of the trade-off between urban expansion and ecological protection. Generally speaking, it is prioritized to identify the areas with high ecosystem services as ecological source.

The next step is to identify ecological corridor through constructing the resistance surface (McRae, 2006), which is commonly based on the value assignment of land cover with such indicators as nighttime light intensity to revise the surface (Keeley et al., 2016). Additionally, the least cost analysis is often used to extract ecological corridors (Adriaensen et al., 2003; Chetkiewicz et al., 2006). Although the least cost analysis can quickly indicate the optimal route of ecological flow, it ignores the random walk of species and fails to clarify the specific range and key nodes of the corridor. In 2007, originating from physics, circuit theory was applied to the study of gene flow in heterogeneous landscapes (McRae and Beier, 2007). In circuit theory, the ecological flow can be analogized to the electric currents because they share the random walk property. Thus, it can be applied to predict the movement patterns across complex landscapes, to measure the isolation of habitat patches, and to identify important landscape patches. At present, circuit theory has been widely used in ecological protection analysis (Carroll et al., 2017; Dilts et al., 2016. Proctor et al., 2015), especially in identifying endangered animal protection priority areas (Koen et al., 2014; Breckheimer et al., 2014).

Located in southwestern China, Yunnan Province is a crucial ecological security shelter in China, as well as Southeast Asia (Zhang et al., 2017). In 2015, the proportion of urban population in Yunnan Province was only 43%, which was less than the national average of 56% . In the current stage of accelerated urbanization, Yunnan Province is facing the conflicts between land development and ecological protection. Therefore, setting Yunnan Province as the study area, this study aimed to solve this conflict through constructing ecological security patterns. There were three detailed objectives: (1) to identify the ecological sources by quantifying three typical ecosystem services, i.e. carbon fixation, soil conservation and water conservation; (2) to extract critical ecological corridors based on circuit theory; and (3) to assess the effect of potential human disturbances on regional ecological security patterns.

2. Methodology

2.1. Study area and data sources

Yunnan Province is located in the southwest of China (21°08′–29°15′N, 97°31′–106°12′E) (Fig. 1). The province has an area of 39.41×10^4 km^2 and accounts for about 4% of China's total area. Mountains and plains account for 94% and 6% of the total area of Yunnan Province, respectively.

The province’s overall terrain decreases from the northwest to southeast. Yunnan Province is located in the low-latitude monsoon climate zone, a region most strongly affected by the southwest monsoon in China. Rich soil types and the complex environment characterize the study area, and as a result, it has the most abundant species in China and has been set as one of world biodiversity hotspots.

Yunnan Province belongs to the less developed area of China. By the end of 2015, the resident population was 47.15 million, of which 9.93% was living in poverty. To build a moderately prosperous society, the 13th Five-year Plan of Yunnan Province stated that by 2020, 55% of the population should be urbanized and economic growth should reach 8.5% per year, which would be much higher than the projected national growth rate of 6.5%. However, long-term human activities have significantly affected natural ecological processes, resulting in biodiversity loss, forest degradation, soil erosion and other ecological problems (Zhang et al., 2016b). Under the double pressure of rapid urbanization and natural ecological protection, there is an urgent need to identify and protect the key ecological patches that are important for regional ecological security, thereby providing a win-win solution for accelerating urbanization and protecting natural ecosystems.

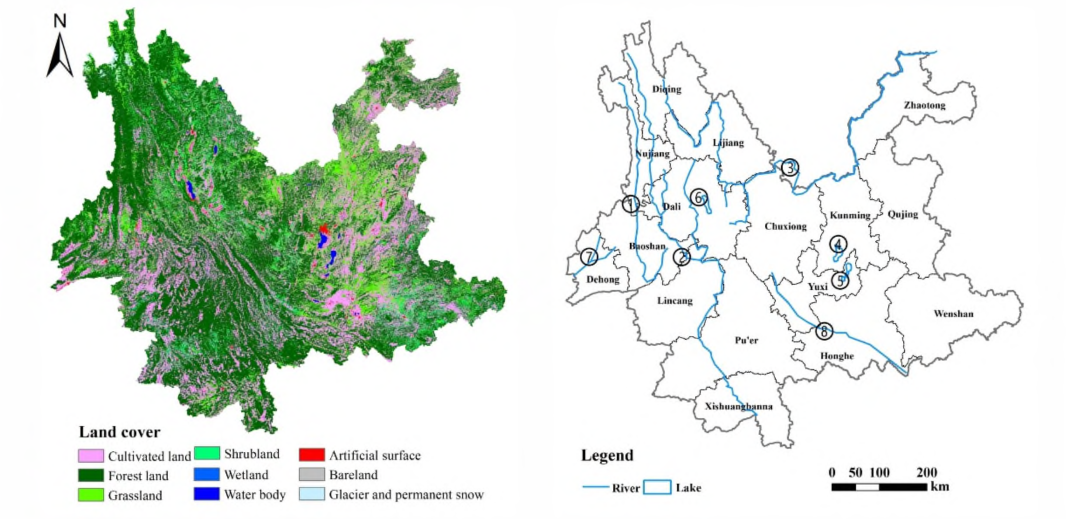

Fig. 1. Land cover and geographical location of Yunnan Province: (1) Nujiang River; (2) Lancang

River; (3) Jinsha River; (4) Dianchi Lake; (5) Fuxian Lake; (6) Erhai Lake; (7) Daying River; and (8) Red River.

Several datasets were used in this study. (1) The GlobeLand 30-2010 dataset with the resolution of 30m × 30m (http://www.globallandcover.com/GLC30Download/index.aspx) provided land cover information. (2) The Shuttle Radar Topography Mission dataset provided terrain data with 90m × 90m resolution (http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp). (3) Net primary production data (MOD17A3 NPP raster data products) with 1000m × 1000m resolution were obtained from the US government (https://lpdaac.usgs.gov/). (4) Soil-related data were obtained from the World Soil Database (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/) at the scale of 1: 4,000,000. (5) Vector data describing basic geographic information such as water body and roads at the scale of 1: 4,000,000 were obtained from the National Basic Geographic Information Center (http://www.ngcc.cn/). (6) Annual precipitation data for 1991 to 2010 were derived from the National Science & Technology Infrastructure dataset (http://www.cma.gov.cn/), which was interpolated using the Kriging method. All data was reclassified using the nearest neighbor method, and the grid of raster data was unified to be 1000 m × 1000 m.

2.2. Identifying ecological security patterns

The essence of constructing ecological security patterns is to develop a key pattern that contains an integrated network of ecological sources, corridors, and key nodes. By identifying and protecting the key pattern, regional ecosystem services and ecological processes can be well guanranteed. Three steps are included in identifying ecological security patterns in this study. The first was to identify ecological sources based on quantifying and mapping ecosystem services. The second was to construct resistance surface. The third was to extract ecological corridors and key nodes based on circuit theory. The specific framework was shown in Fig.2.

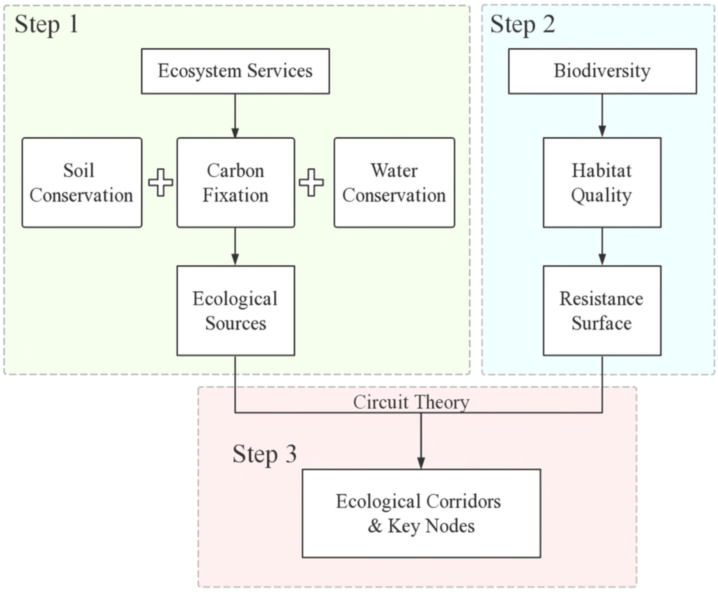

Fig. 2. Framework for identifying ecological security patterns.

2.2.1. Ecological sources

An ecological source is a key ecological patch that promotes ecological processes, sustains ecosystem integrity and provides ecosystem services with high quality or quantity. As a result, key ecological patches can be identified by evaluating the importance of ecosystem services. Due to the large area of mountains and hills, the vegetation coverage in the study area is high; however, the water loss and soil erosion is also very high due to the undulating topography. Therefore, three typical ecosystem services were selected for evaluation, i.e. soil conservation, carbon fixation and water conservation. These three ecosystem services were divided into five grades based on the method of natural breaks, and the patches with grades 4 and 5 for each kind of ecosystem services were chosen as ecological sources.

Specifically, soil conservation service was quantified using the Revised Universal Soil Loss Equation (Wischmeir, 1965; Okou et al., 2016).

$$A = R \times K \times LS \times (1 - C \times P) \quad (1)$$

where A is the average annual soil conservation (Peng, 2017b; Gaubi et al., 2017); R is the rainfall erosivity factor; K is the soil erodibility factor is based on the mass percentage of sand, silt, clay and organic carbon; LS is the terrain factor; C is the crop management factor; and P is the erosion control practice factor.

Carbon fixation is the conversion process of inorganic carbon to organic compounds by living organisms through photosynthesis. NPP can be calculated through the process-based CASA model, which assumes that plant productivity is correlated with the photosynthetically active radiation absorbed or intercepted by the green foliage (Jiang et al., 2016). Therefore, carbon fixation service can be approximately assessed by analyzing NPP.

In this study, NPP data were obtained from the NASA-USGS platform (https://lpdaac.usgs.gov/).

Water conservation refers to the service provided by vegetation's retention and interception of rainfall. Water conservation was estimated through water yield module in the InVEST model (https://www.naturalcapitalproject.org/invest/), which was as follows:

$$WC = (1 - TI) \times \mathrm{Min}(1, \frac{Ksat}{300}) \times \mathrm{Min}(1, \frac{TravTime}{25}) \times Y_{xj} \quad (2)$$

$$Y_{xj} = (1 - \frac{AET_{xj}}{P_x}) \times P_x \quad (3)$$

where WC is the average annual water conservation amount; TI is the terrain index, which is calculated according to digital elevation model; K_{sat} is soil saturated hydraulic conductivity;

TravTime is runoff time, which is determined using the slope length to divide the flow rate factor; Y_{xj} is the amount of water yield; AET_{xj} is the annual average evapotranspiration of pixel x of land use type j; P_x is the annual precipitation of pixel x; and the ratio AET_{xj}/P_x is calculated according to the drying index, crop coefficient, potential evapotranspiration, and the Zhang coefficient, etc. More details about these calculations can be found in the user guide of InVEST model (Sharp et al., 2016).

2.2.2. Resistance surface

The resistance surface describes the difficulty of species in moving through different habitat patches, and reflects the horizontal resistance to ecological process. The resistance surface characterizes the influence of landscape heterogeneity on the flow of ecological process (Beier et al., 2008; Spear et al., 2010; Adriaensen et al., 2003). The resistance value is not only related to the distance of ecological flow, but also is associated with land cover and human disturbance. For example, human activities will hinder material cycle and energy exchange among different landscape patches; consequently, most researches were based on expert experiences to assign resistance values corresponding to land use types (Gurrutxaga and Saura, 2011; Kong et al., 2010). Since this method is not able to describe the internal differences in the same land use type, an additional habitat quality assessment is required. However, the absence of detailed empirical data on animal movement probability is rather common (Chetkiewicz et al. 2006). In this approach, a resistance value was assigned based on the inverse of habitat quality because high habitat quality means high level of biodiversity, and refers to the low resistance to the species.

In detail, the InVEST model (Version 3.4.2) was used to evaluate the habitat quality (Sharp et al., 2016), which was regarded as the proxy for biodiversity. The model considered the quality of natural habitat itselt, and degree of threats and the relative sensitivity of each habitat to different threats. That was to say, four factors were focused: each threat's relative impact, the relative sensitivity of each habitat type to each threat, the distance between habitats and threat sources, and the degree to which the habitat patch was legally protected. The evaluation result ranged from 0 to 1, representing the habitat quality from the worst to the best. In this study,parameters were set according to the InVEST user's guide and related studies. Natural habitat types included cultivated land, forest land, grassland, shrubland, wetland, and water body, and threat sources included city, railway, primary road, and secondary road.

2.2.3. Ecological corridors

The corridor is a narrow strip in the landscape that is significantly different from the two sides. In essence, corridors are the main channels for gene flow, meta-population dynamics, seed dispersal, infectious disease spread, and exotic invasion. That is to say, corridors are important in the maintenance or loss of biodiversity. Ecological corridors are usually set for improving ecological connectivity among ecological patches. There are some key nodes in ecological corridors, such as pinch points and barriers. A pinch point is a high-flow key node in the ecological process and a priority area for ecological protection because of its irreplaceability and importance in landscape connectivity. A barrier will impede the movement between ecologically important patches. Restoring the habitat of barriers can do the most to improve landscape connectivity.

In this study, circuit theory (McRae and Beier, 2007; McRae et al., 2008) was used to identify the ecological corridors in heterogeneous landscapes. In the circuit model, landscapes are represented as conductive surfaces, and low resistances were assigned to landscape components best promoting species flow, with high resistances for landscape components impeding species movement. Using an electrical analogy, effective resistances, current flow and voltages calculated across the landscape are related to ecological processes, such as movement of species and gene flow.

In physics, Ohm's law states that the current through a conductor between two points is directly proportional to the voltage between the two points.

$$I = V/R_{eff} \tag{4}$$

where I is the current through the conductor; V is the voltage measured across the conductor; and R_{eff} is the effective resistance of the conductor (or conductors). Moreover, R_{eff} is related to the way a circuit is constructed. In a parallel circuit with multiple branches and constant resistance in each branch, as the number of branches increases, R_{eff} decreases. In ecology, R_{eff} is considered to be an indicator that reflects the spatial isolation among the nodes. Likewise, I of a branch reflects the ecological flow and can be used to predict the probability of gene flow or species movement. Thus, an area with high current value can be identified as key components of ecological corridors.

To represent landscapes as circuits, each grid with finite resistance was represented as a node in two-dimensional space, connected to either its four first-order neighboring grids, or eight first-order or second-order neighboring grids. Grids with infinite resistance (i.e. zero conductance) were eliminated from further consideration. Grids of ecological sources were assigned zero resistance (infinite conductance). All the grids of one ecological source were collapsed into a single node. Once the landscape was represented as a network of electric circuit, Kirchhoff's circuit laws were used to calculate the current and voltage (Leonard et al., 2017).

The detailed identification process of an ecological corridor based on circuit theory was described as follows. Firstly, each ecological source was treated as an electric circuit node, and the cumulated resistance of each link between two nodes was calculated according to the least-cost path based on resistance surface. The cumulated resistance was assigned to be the electric resistance of the link. Secondly, for each pair of electric circuit nodes, one node was arbitrarily connected to a 1-amp current, while the other node was connected to ground. Effective resistances were calculated iteratively between all pairs of electric circuit nodes. For n nodes, there were $n(n - 1)/2$ times of calculation. The accumulated current value reflected the net migration amount of the random walkers to the destination node, and could be used to identify the importance of an ecological corridor. The larger was the accumulated current value, the more important was an area in the landscape. The areas with the highest current values were designated as pinch points. Thirdly, the barrier was identified as the key node that could greatly enhance the connectivity of ecological sources along with its ecological restoration. Along with ecological restoring of a certain area, the resistance of the area reduced; consequently, the cumulated resistance of the least-cost path connecting the nodes through the restoring area also reduced. Those restoring areas with the highest decreasing of cumulative resistance were identified as barriers.

Linkage Mapper software (http://www.circuitscape.org/linkagemapper), a geographical information system tool, was used to identify the ecological corridors. The range of the corridors was identified based on the threshold of cumulated resistance, and any area with cumulated resistance exceeding the threshold were excluded from ecological corridors.

3. Results

3.1. Spatial patterns of ecosystem services and ecological sources

Each ecosystem service were separated into five grades based on natural breaks, with the grade from 1 to 5 representing the importance level from low to high, respectively. The results showed that all the three ecosystem services exhibited spatial heterogeneity. The most important grade of water conservation covered 28,782 km^2, accounting for 7.30% of the total study area. This area was mainly distributed in Kunming Lake and Fuxian Lake because of their high conservation capability of water body, as well as in the western and southern parts due to abundant rainfall and high vegetation coverage (Fig. 3).

Yunnan Province experienced high capacity for carbon fixation service. The highest value of carbon fixation was located mainly in the southwest due to abundant precipitation, enrichment of vegetation and relative absence of human activities. Meanwhile, soil loss in Yunnan Province was serious due to the undulating terrain and complicated geology and geomorphology. The highest value of soil conservation service encompassed 23,280 km^2, accounting for 5.9% of the total study area. These areas were mainly distributed in the Gaoligong Mountain and southwestern Yunnan Province, both of which were at high elevation and covered with dense vegetation. Conversely, soil conservation service in the eastern part of Yunnan Province was poor.

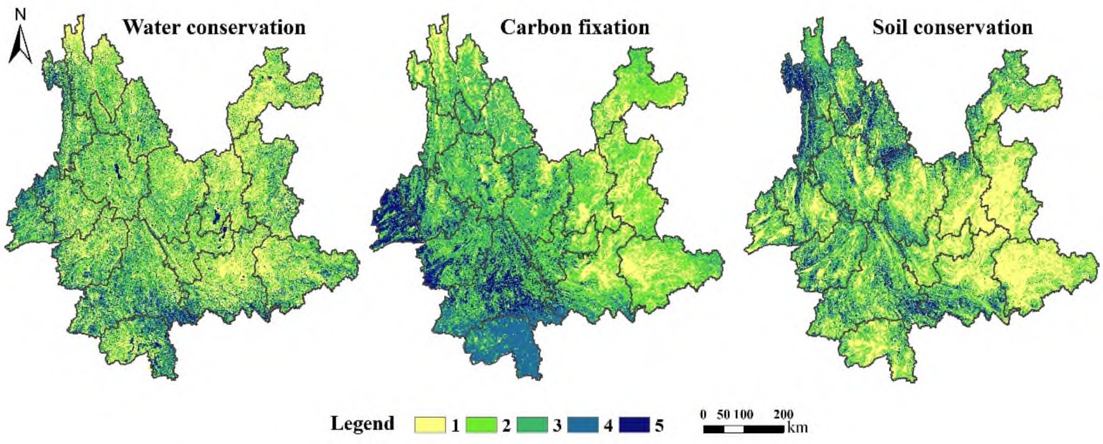

Fig. 3. Spatial distribution of ecosystem services grades in Yunnan Province (Grade 1 = lowest; Grade 5 = highest).

Ecological source is an important ESP component. When the grade of ecosystem services is larger than 3, it means the ecological quality of these zones are above the average level; therefore, zones with the grade of ecosystem service larger than 3 were designated as dominant areas for these services, and then were defined as the ecological sources (Fig. 4).

In general, ecological sources were located mainly in two regions of Yunnan Province. One was the southwestern edge of the province including the Nujiang River basin, the Lancang River basin and the upper reaches of the Jinsha River basin, and the other included the mountains and lakes in the central area of the province such as Dianchi Lake, Fuxian Lake, Erhai Lake and the Ailao Mountain. Encompassing 66 patches, ecological sources had an area of 94,946 km^2, accounting for 24.1% of the study area. The ecological sources consisted mainly of forest land, cultivated land, grassland and shrubland, and forest land was dominant, accounting for 71.4% of the total area of ecological sources. The distribution of ecological sources varied in different administrative regions of Yunnan Province. Among the cities, Pu'er accounted for the largest area proportion of ecological sources (25.6% of the whole ecological sources), followed by

Xishuangbanna (15.9%), and Qujing didn't have any ecological source area. The high distribution of ecological sources was due to the suitable climatic condition and few human disturbances in Pu'er and Xishuangbanna. In contrast, the climatic condition in Qujing was relatively poor, and the flat terrain had resulted in great human development and urban construction transforming natural ecosystems into artificial or semi-artificial ecosystems.

Comparing the distributions of ecological sources identified in this study with the nature reserves identified in the World Database on Protected Areas (https://protectedplanet.net/), 41 nature reserves (out of 54 identified in the study area) were included in the ecological sources. The 13 reserves that were not included in the range of ecological sources were mostly located in the eastern part of the province, with the area less than 100 km^2 and labelled as non-national nature reserves.

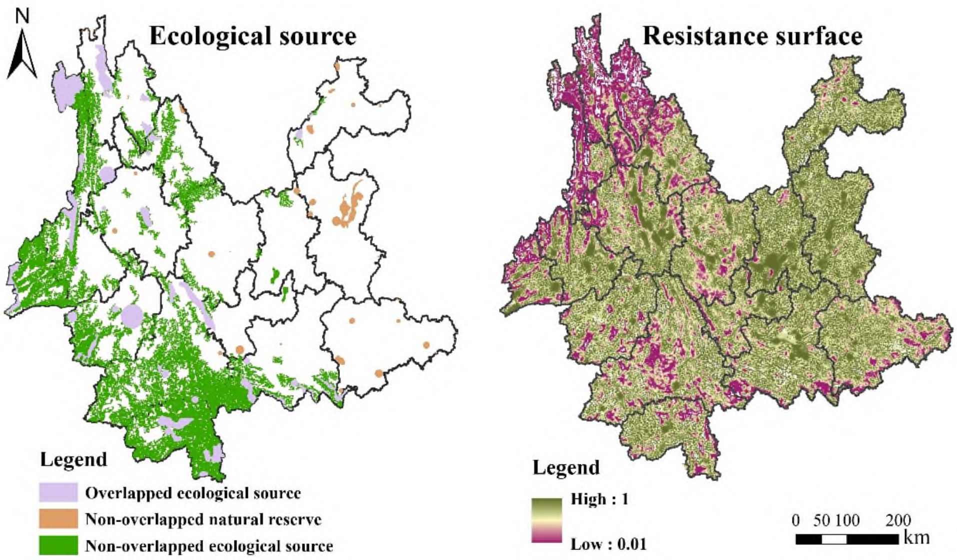

Fig. 4. Spatial distributions of ecological sources and resistance surface in Yunnan Province.

3.2. Spatial patterns of resistance surface and ecological corridors

The resistance value was defined as the inverse of habitat quality and was calculated to be in the range of 0-1 using the InVEST model (Fig. 4). Generally, the average ecological resistance of

Yunnan Province was 0.59. Among all the administrative regions, the resistance in Diqing and Nujiang was low (< 0.31 on average). In contrast, the cities of Kunming, Qujing and Zhaotong had the highest resistance, which was nearly 0.8.

Ecological corridor is also an important ESP component, which is usually composed of strip-like areas having specific width. Ecological corridors are important because of the role in connecting ecological sources. As shown in Fig. 5, the ecological corridors had the appearance of a 'spider web' that linked the southwestern, northern and central part of Yunnan Province in series. There were 186 clusters of ecological corridors with an average length of 41,803 m (ranging from 1,272 m to 250,552 m). The total area of the ecological corridors was 101,715 km^2, accounting for 25.8% of the study area. Ecological corridors were composed mainly of such three land use types as forest land, cultivated land and grassland. Ecological corridors had significantly different spatial distributions in the province: the northwest had more corridors and lower resistance, the midwest had fewer corridors and slightly higher resistance, and the east had the fewest corridors and highest resistance.

Overall, the ecological security pattern in Yunnan Province was composed of ecological sources mainly dominated by forest land connected by radial ecological corridors locating along the mountains and forest belts, including 66 ecological source patches, 186 clusters of ecological corridors, 24 pinch points and 10 barriers. The ESP mainly included ecological regions such as Cangshan Mountain, Erhai Lake, the Three Parallel Rivers, Ruili River, Daying River and Xishuangbanna (Fig. 5). Three main parts of ESP could be separated as follows: northern low resistance-abundant corridors area, southern medium resistance-multiple corridors area, and eastern high resistance-single corridor area, i.e. Northern ecological surplus area, Southern ecological balance area, and Eastern ecological fragile area.

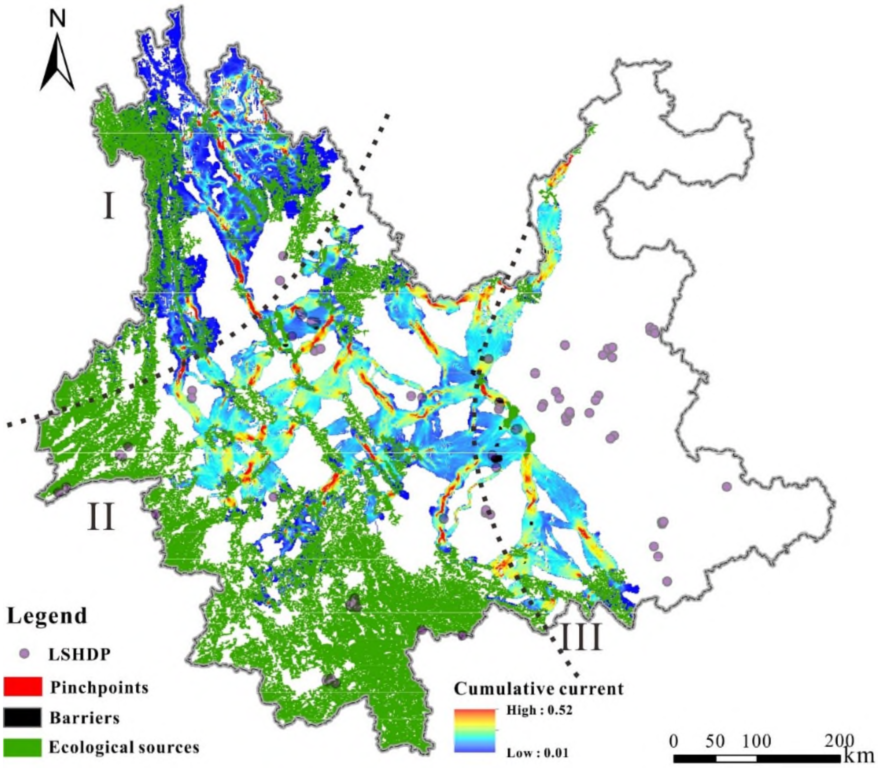

Fig. 5. Spatial distribution of ecological security patterns and low-slope hill development project (LSHDP) areas in Yunnan Province (I. Northern ecological surplus area; II. Southern ecological balance area; III. Eastern ecological fragile area).

I. The Northern ecological surplus area was almost entirely located in the longitudinal mountain-valley including the autonomous prefectures of Nujiang and Diqing, and Lijiang City. In this area, ecological corridors connected ecological sources in a pattern similar to pinnate leaves. The average current density of ecological corridors was low. As suggested by the relative absence of red areas in Fig. 5, there were few pinch points and no barriers. The low resistance to ecological flow mainly resulted from the abundant ecosystem types and biological species in the longitudinal mountain-valley area (Peng et al., 2012). The few pinch points identified in Lijiang, Shangri-La and

Lushui might be due to the threats from cultivated land exploitation and urban expansion that blocked the connection between this area and the center of Yunnan Province and increased the flowing difficulty of ecological processes in the north-south direction.

II. The Southern ecological balance area is located mainly in the mid-mountain and wide-valley, including the autonomous prefectures of Dali, Dehong, Chuxiong and Xishuangbanna, and the cities of Baoshan, Lincang and Pu'er. The average current density in this region was higher than that in the longitudinal mountain-valley area in northwestern Yunnan Province. Furthermore, the ecological corridors in this area were numerous, short, wide and divergent from one ecological source to another, forming a dense network. Some parts of the ecological corridors contained small pinch points and barriers, which were priority areas for future ecological restoration actions. This area was distributed across the south subtropical zone and north tropical zone, with good heat conditions, virgin forest, rich wildlife resources and abundant water resources. The northern part of the region located in the West Yunnan Urban Agglomeration including Dali, Ruili and Longyang, famous leisure travel destinations. The southern part of the region was covered in the Southwest Yunnan Urban Agglomeration centered around the cities of Jinghong and Pu'er, which was economically characterized as biological industry, hydropower industry and forest industry. Regional development in both urban agglomerations would inevitably lead to slight degradation of local ecosystems. Therefore, in the development process in the mid-mountain and wide-valley area, it was necessary to strengthen the ecological protection in the Lancang River Basin and Erhai Lake Basin, esecially for the conservation of biodiversity and tropical rainforest.

III. The Eastern ecological fragile area can be found in the eastern developed zone of Yunnan Province including the cities of Kunming, Yuxi, Qujing and Zhaotong, and the autonomous prefectures of Honghe and Wenshan. In this area, the average resistance value was high, and the number of ecological corridors was very smal. However, the typical length of ecological corridors was longer than that in the other two areas of the province. In the south of this area, especially near the Red River, there were many pinch points because of the poor ecological conditions, increasing population, and over-exploitation of cultivated land and construction land. As a result, ecological restoration should be taken seriously on the west of Ailao Mountain, where most ESP in this area located.

4. Discussion

4.1. Conflicts between land development and ecological protection

To relieve the conflicts between human demandings for cultivated land and construction land, Yunnan Province had promulgated a development strategy to encourage urban construction in the region of low-slope hill. Till 2017, there were 81 pilot projects for the integrated development of low-slope hill, which were distributed in 15 cities or autonomous prefectures excluding only Nujiang. These projects were effective in preserving cultivated land in the flat areas, and providing construction space for urban or industrial development. That was to say, these projects realized the win-win between cultivated land preserving and urban development. However, low-slope hill was usually ecological fragile, and high level of human activities associated with land development might result in great ecological risk and then ecosystem degradation. Thus, it was necessary to measure the potential conflicts between low-slope hilly land development and ecological security protection.

Using ArcGIS 10.2 software (ESRI, Inc., Redlands, CA, USA) to overlay spatial distribution of low-slope hill development project (LSHDP) areas on the identified ecological security patterns (Fig. 5), it could be found that, 21 projects (25.9% of the total number) locating in ESP range might intensify the ecological resistance, decrease the ecological connectivity, and thus result in high potential ecological risks. If the original ecological connectivity and sustainable supply of ecosystem services were planned to be maintained, more social capital should be invested to protect the ecological sources, corridors, and pinch points around spatial distribution of the projects. The more projects meant more human interference, and more ecological protection investment. In detials, 10 projects located in ecological sources in Pu'er, Dehong and Xishuangbanna, and the other 11 projects were distributed in ecological corridors in Kunming, Yuxi, Chuxiong and Dali. Among them, one projects in Kunming City was distributed in barriers, with none in pinch points. Furthermore, there were 16 projects locating within the 2-km buffer zone surrounding ecological corridors, and 22 projects were distributed within the 2-km buffer zone surrounding ecological sources. These projects were conducted for tourism and trading port development, and the former were mainly distributed in Kunming, Dali and Yuxi, with the latter in Dehong, Pu'er and Xishuangbanna. In all, there were 38 projects (46.9% of the total number) with potential human disturbance to regional ecological security.

All the LSHDPs were conducted according to engineering suitability of urban or industry construction of low-slope hilly regions and local environmental impact, with more focus on economic costs and benefits rather than regional ecological security and sustainability; not surprisingly, human disturbances caused by the projects had leaded to potential while significant ecological risks. To minimize such problems in the future projects, it was necessary to transform the projects' strategic impact assessment from local environmental impact to provincial ecological security impact.

4.2. Impact of resistance threshold on ecological corridors identification

Corridors play an important role in the maintenance of ecological processes. The ecological function of corridors is closely related to their spatial range such as the edge effect of corridors . In this study, the range of ecological corridors was identified based on the cummulated resistance with a specific threshold. As shown in Fig. 6, along with the changing thresholds of cummulated resistance from 1000 to10,000 in an increment of 1000 to determine the range of ecological corridors, the corresponding area proportion of ecological security patterns accounted for 34.1%, 42.6%, 46.7%, 49.9%, 54.1%, 56.5%, 60.9%, 61.9%, 64.3% and 68.3%, respectively, of the total area of Yunnan Province. It could be found that along with increasing thresholds, the area of ecological corridors increased accordingly, but the spatial distribution of ecological corridors remained almost unchanged.

In addition, the maximum cumulative current value of pinch points was gradually reduced as the threshold increased, because the wider corridors effectively increased the circuit connection path, resulting in the current shunt. Nevertheless, despite the decreased cumulative current value of pinch points, the position of the pinch points did not change significantly, which indicated that protecting natural ecosystems in key locations in the landscape was effective for ensuring the regional ecological security. In this study, considering the urgent need for economic development and the limited financial input for ecological protection in Yunnan Province, it was assumed that ecological protection investments could only support to manage 50% of the whole study area. Therefore, the threshold of 4000 was selected to identify the spatial range of the ecological corridors.

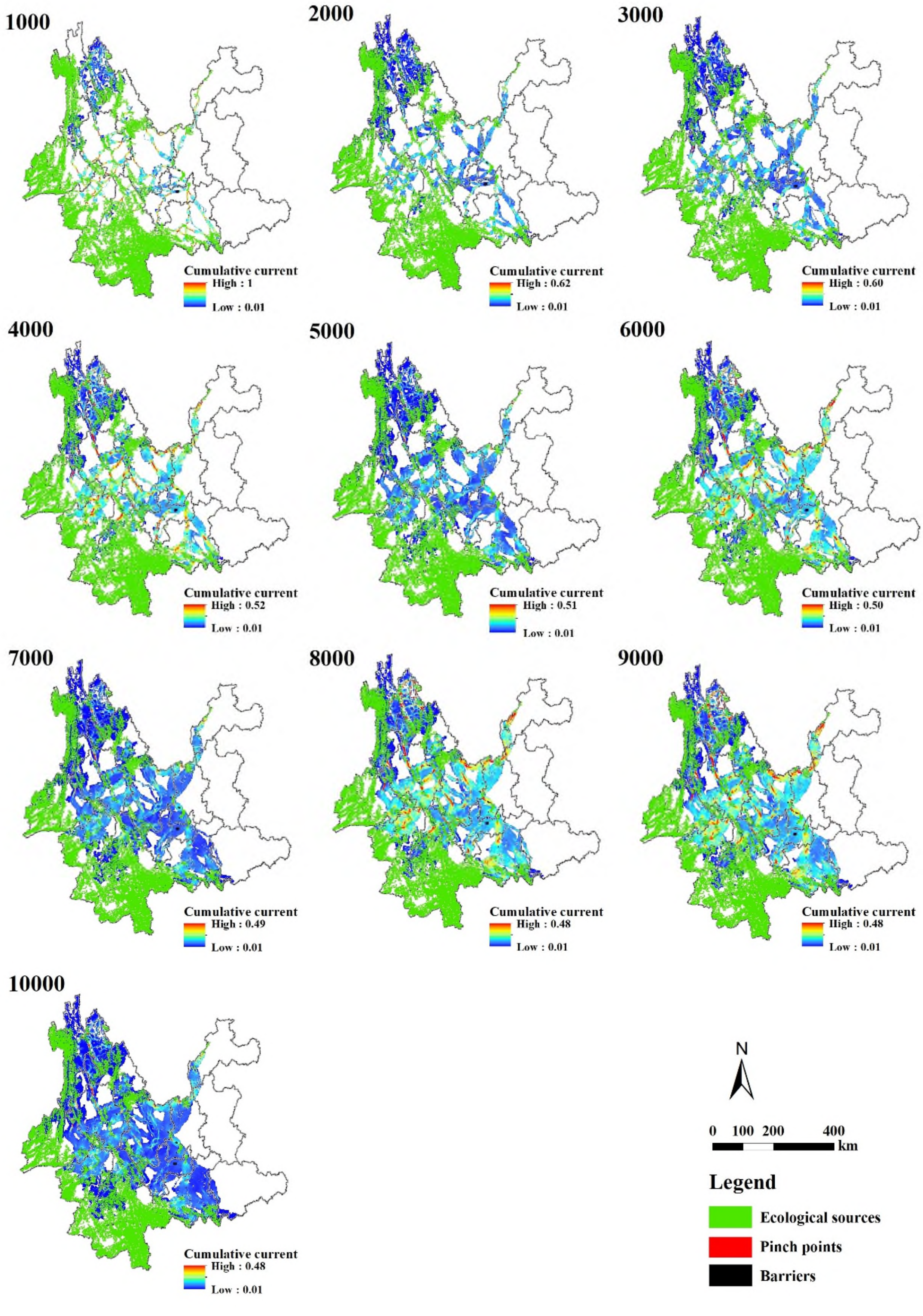

Fig. 6. Ranges of ecological corridors and cumulative current values under the thresholds from 1000 to 10,000.

5. Conclusions

Spatial conservation prioritization in developed countries often emphasizes the uniqueness and vulnerability of natural ecosystems due to the high level of urbanization, low population density and abundant natural resources. Conversely, in developing countries such as China, where natural habitats are under the pressure of high intensity human interference in the process of rapid urbanization, only ecological bottom-line thinking can achieve a win-win solution that balances ecological protection and economic development. Although previous studies have identified ecological security patterns at the scale of watersheds or counties, what traditional methods identified was only the direction of ecological corridors and lacked specific range identification. This study provided a new approach to the construction of ecological security patterns with identifying a spatial range of ecological corridors as well as the location of key nodes in the corridors, based on ecosystem services and circuit theory.

The results showed that the ecological security patterns in Yunnan Province was composed of ecological sources mainly dominated by forest land, and radial ecological corridors distributed along mountains and forest belts. ESP in Yunnan Province included 66 ecological source patches, 186 clusters of corridors, 24 pinch points and 10 barriers, mainly distributed in ecological regions such as Cangshan Mountain, Erhai Lake, the Three Parallel Rivers, Ruili River, Daying River and Xishuangbanna. Based on spatial overlay analysis, 75.9% of the existing nature reserves were included in the identified ecological sources. Furthermore, some projects of low-slope hill development were shown to exert significant human stress on regional ecological security. Thus, the rationality of LSHDP should be re-assessed. In addition, the area of pinch points and barriers should be given more priority for implementation of ecological restoration and reconstruction practices.

However, some key issues related to ecological security patterns are still difficult to answer. For example, how large should the area of the ecological source are be in proportion to the total study area? Besides circuit model, are there any other suitable methods that can be used to identify ecological corridors? And how to assess the accuracy or uncertainty related to the identifications of these ecological landscape units? Moreover, since ecological security is characterized differently across different scales; another important question is how to integrate ecological security patterns across these various scale levels?

Hence, much more further research, considering multiple case studies across different scales, is needed in order to resolve all of these scientific questions.

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