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# Linking ecosystem services and circuit theory to identify ecological security patterns

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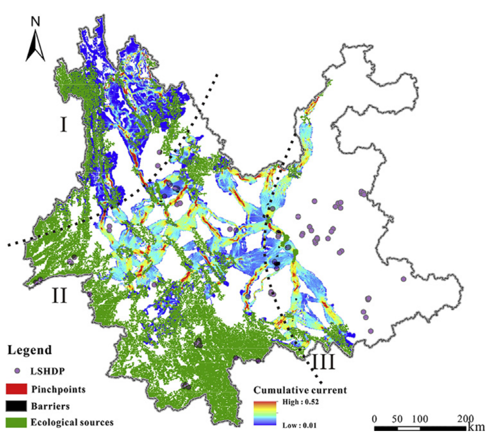
## HIGHLIGHTS

- Ecosystem services were used to identify ecological source.
- Ecological corridor, pinch point and barrier were identified using circuit theory.
- 38 development projects showed potential stress on ecological security patterns.

## GRAPHICAL ABSTRACT

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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 patterns 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. 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 were 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

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identifying the spatial range of ecological corridors and the specific location of key nodes for effective ecological conservation and restoration.



## 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, how 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-Llobet and Hermida, 2017). Especially in China, regional ecological security has faced a severe situation such as biodiversity loss (L. Zhang et al., 2016; Peng et al., 2018), soil erosion and water resources scarcity (He et al., 2014; Qiu et al., 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 integrated 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; R. Zhang et al., 2016). 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°8′–29°15′ N, 97°31′–106°11′E) (Fig. 1). The province has an area of 39.41 $\times 10^4$ 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 distributed 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 13$^{th}$ 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