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The Construction of Regional Ecological Security Pattern Based on a Multi-Factor Comprehensive Model and Circuit Theory

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ABSTRACT

Various ecological problems have become increasingly prominent due to the accelerated growth of urbanization. Ecological security and ecological conservation have become an important topics in the current scenario. This study took southern Anhui as an example, constructing comprehensive assessment models to conduct source identification from three perspectives, i.e. ecosystem services, ecological sensitivity and residents' ecological needs. Landscape resistance surface was built based on the reciprocal of habitat quality and night-time light data. According to the circuit theory, the ecological process in the heterogeneous landscape was simulated to identify ecological corridors, extract pinch points and divide barriers that need improvement, thereby to construct the southern Anhui ecological security pattern (ESP). The pattern comprised 20 ecological sources, 37 ecological corridors, 9 pinch points and 2 levels of improvement areas. Specifically, ecological sources were mainly distributed within the area of Huangshan city and Xuancheng city, mostly covered with trees; ecological corridors were mostly located in the northern part of the research area; pinch points were mainly farmland or beside construction land; the primary improvement area was mainly in Chaohu city and Maanshan city, while the secondary improvement area was distributed around the primary area. The study discussed the diversified improvement strategies of different barriers and introduced the optimization scheme "one centre, two wings, one belt", providing planning advice for decision-makers. The study expanded the construction of regional ESP, and partly guided the steady development of ESP of southern Anhui.

INTRODUCTION

The rapid development of urbanization has caused an increasingly intense contradiction between economic development and ecological conservation. Ecological systems like forests, waters, and wetlands have been destroyed, causing deterioration in the habitat quality and a decline in the biodiversity. On the other hand, people have higher needs for life thanks to the economic development, as well as new demands for ecosystem services. Ecological security pattern, the bridge between ecosystem services and societal development, is regarded as a crucial strategic tool to guarantee regional ecological security and increased well-being. The planning of ecological security pattern (ESP) has become a key for the Chinese governments at all levels to ensure the sustainable development of the regional economy, and coordinate the relationship between ecosystem and economic society. Also, it is regarded as a fundamental and a crucial method to realize regional ecological security, and one of the strategic modes for national land development and protection (Nathwani et al. 2019, Huang et al. 2020).

Currently, scholars in various fields at home and abroad have discussed the structure (He et al. 2020) and function (Song et al. 2020) of ESP, as well as its construction (Xun et al. 2018) and assessment (Yin et al. 2011, Schröter et al. 2020). In addition, scholars have conducted massive research concerning biodiversity conservation (Chen et al. 2017), nature reserve planning (Jia et al. 2005), remedy for ecosystem (Meng et al. 2012), etc. The research on ESP construction in China has formed a mainstream paradigm of "source identification—resistance surface construction—corridor construction". Generally speaking, the identification of sources should provide important ecological services and own nice landscape connectivity, greatly needed in regions. Traditional ecological source identification mostly comprises two methods: the first is to directly determine natural reserves, national parks, scenic spots, etc. as an ecological source. Though convenient to operate, it may lack the accuracy of patch assessment. Some scholars chose patches with a relatively stable type of eco-utilization in the long term as ecological sources, for example, woodland, grassland, farmland, etc. However, this method does not take land-use heterogeneity into account, as a land of the same type in different regions still differs to a certain degree. Another more scientific method is to construct a comprehensive indicator system to assess regional parcels, and then to determine ecological sources. The chosen indicators are determined by the functional importance of ecosystem services, ecological sensitivity, etc. (Peng et al. 2018). The weight and constitution of indicators in different areas are determined according to the local situation. Specifically speaking, indicators comprises important ecosystem services indicators like water conservation, biodiversity, carbon fixation ability, soil conservation, etc. (Gao et al. 2020), and ecological sensitivity indicators like elevation, slope, etc. However, scholars at home and abroad have not thoroughly considered the relationship between ecosystem services, ecological sensitivity and residents' needs for ecosystem services. The natural ecosystem cannot survive without "people", which means that a sustainable society needs a balanced development between ecological basic services and residents' ecological needs (Li et al. 2020). The construction of ESP is a multi-goal optimization process based on the coordinated "society-economy-ecology" development. In this regard, this study considered residents' needs for ecosystem services when selecting ecological sources.

The key to the ecological corridor selection is to simulate species migration and construct a resistance surface. Currently, scholars mainly apply circuit theory (Guo et al. 2020), minimum cumulative resistance (MCR) model (Li et al. 2007), and cellular automaton (Zhou et al. 2020) to simulate the movement of species migration. MCR model and ant colony optimization algorithms can only determine the position of the ecological source, as well as the position and direction of ecological corridor, unable to further identify patches and corridors that are more crucial. While circuit theory can be applied to study the movement pattern of ecological flow in a heterogeneous landscape, identify important patches and corridors by calculating isolation degree between patches, and then determine the range of corridor. For resistance surface construction, researchers often determine the resistance value of each patch based on their experience, leading to relatively large differences in the resistance value of different regions. The relatively more scientific method at present is to construct a resistance surface based on the reciprocal of habitat quality coupling with night-time light data (Wang et al. 2019).

This study chose southern Anhui as a research area and attempted to: (1) comprehensively consider the coordination between ecosystem services and residents' needs in the construction of ESP, determine ecological sources and verify their rationality; (2) based on the reciprocal of habitat quality, utilize the modification of night-time light data to construct regional landscape resistance surface; (3) based on circuit theory, select ecological corridor and its range, determine the pinch points that could influence the connectivity of ecological corridor and barrier, and study diversified strategies of ecological conservation, to provide advice for the planning of regional ecological conservation.

MATERIALS AND METHODS

Study Area and Data Sources

Southern Anhui, located in southern Anhui Province (29°31'-31°N, 116°31'-119°45'E) (Fig. 1), has an area of 31.2 thousand km^2. It has abundant forest resources and soils, with 20.5 thousand km^2 forest area, accounting for 45.7% of the total forest area in Anhui province. Southern Anhui is an important ecological source of the Yangtze River Delta, and also one of the most famous tourist spots in China. Long-term land development has caused severe

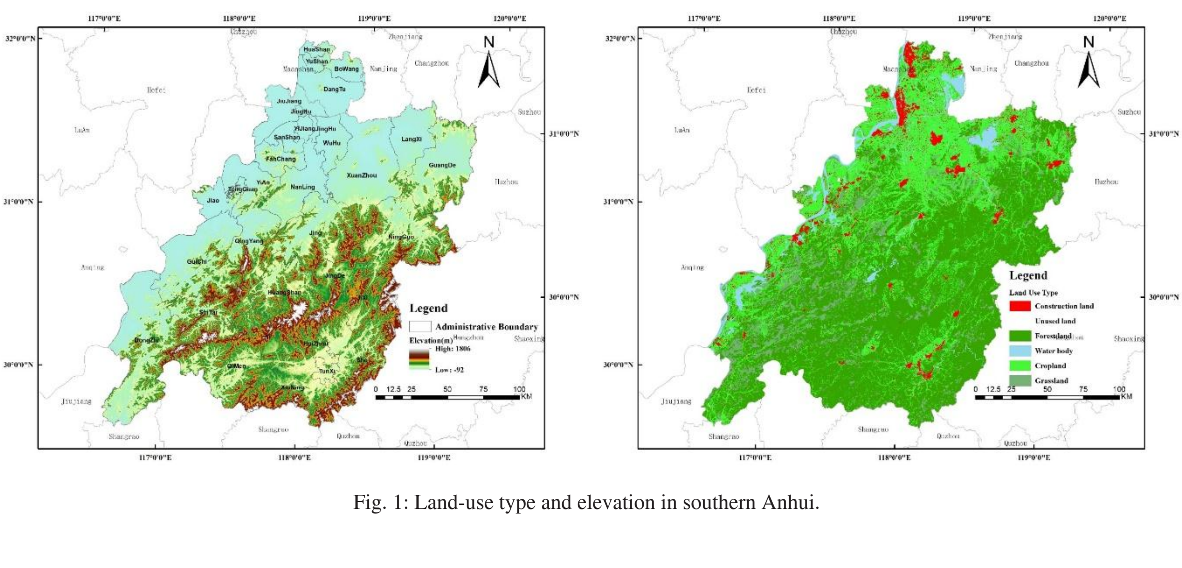

Fig. 1: Land-use type and elevation in southern Anhui.

influences on the ecosystem in southern Anhui, causing problems like habitat deterioration, biodiversity loss, deforestation, soil erosion, etc. Relatively large differences in environment exist within the region. Also, southern Anhui has not formed an interconnected ecological network.

The data sources used in this study were as follows: (1) the 2018 land use and NDVI database was provided by the Resource and Environment Data Cloud Platform; (2) digital elevation model (DEM) data was obtained from the Geospatial Data Cloud website at a spatial resolution of 90m; (3) meteorological data from National Tibetan Plateau Data; (4) soil data from Food and Agriculture Organization of the United Nations (FAO). (5) the 2018 NPP-Virrss was provided by the National Oceanic and Atmospheric Administration. We reclassified all data using the nearest-neighbour to ensure that the spatial resolution was 30m × 30m.

Research Framework and Methods

Identification of the ecological source: The ecological source refers to the area that, from the perspective of human services, plays a decisive role in maintaining regional ecological stability. It normally consists of ecological patches that have relatively important ecosystem services, high ecological sensitivity, and can satisfy residents' ecological needs (Dondina et al. 2016). The methodological framework is shown in Fig. 2, and each process has been described in detail thereafter.

This study applied relevant assessment models (InVEST model (Tallis et al. 2011), CASA model and water and soil conservation model (Zhang et al. 2019)) to quantitatively assess the ecosystem services in southern Anhui. According to the previous research and the local situation of the research area, the study gave four types of ecosystem services the weights of 0.2, 0.3, 0.2, and 0.3 respectively, and divided them into five levels based on natural breakpoint method. The assessment of ecosystem services in southern Anhui was then generated after overlaying the weights.

Ecological sensitivity reflects the complexity and probability of regional ecological problems. Its degree reflects the probability of ecological problems in the disturbance of unreasonable activities (Peng et al. 2018). To maintain regional ecological stability, it is supposed to protect areas with relatively high sensitivity. Southern Anhui is a hilly and mountainous region. According to relevant research (Zhang et al. 2011, Peng et al. 2018, Peng et al. 2017) and the actual situation of the research area, five types of indices, i.e. soil erosion intensity, vegetation coverage, land use type, elevation and slope were selected as assessment factors. The analytic hierarchy process was adopted to determine the weight of each indicator, and then the sensitivity of five

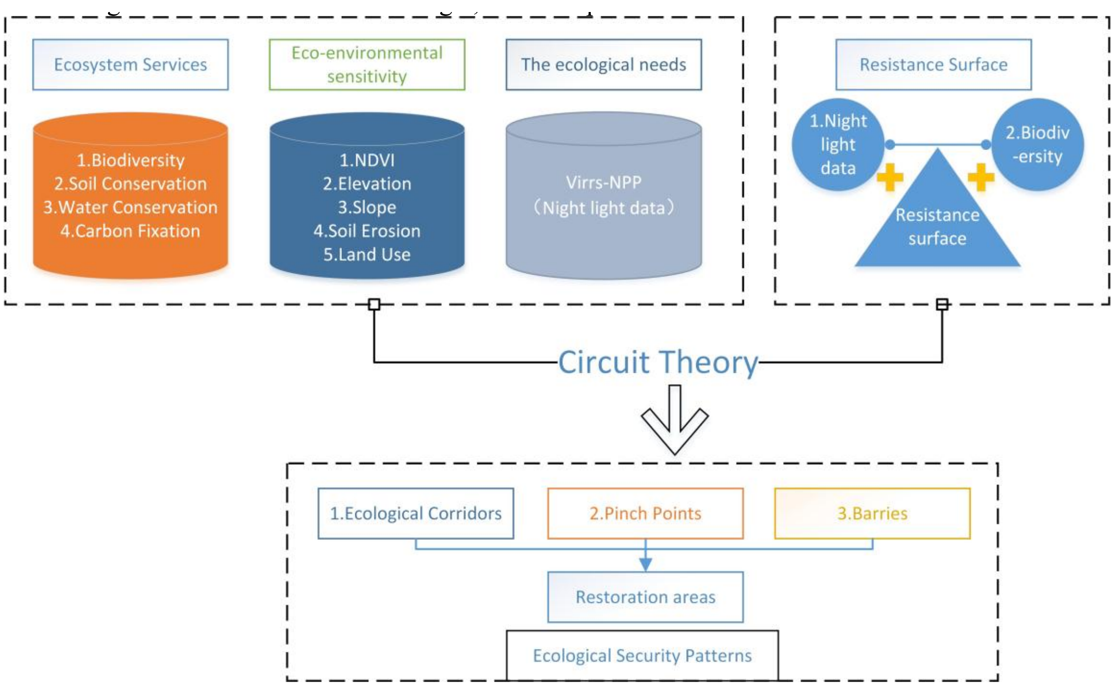

Fig. 2: Construction framework of ecological security pattern in southern Anhui.

Table 1: Classification and weighting of ecological sensitivity evaluation factors.

Evaluation factor/unit	Sensitivity assignment					Weights
	9	7	5	3	1	
NDVI		(0.65, 0.75]	(0.65, 0.75]	(0.35, 0.50]		0.20
Elevation (m)		(500, 800]	(800, 1100]	(1100, 1400]	1400	0.15
Slope		(5, 10]	(10, 15]	(15, 25]		0.15
Land-use type	Forest land or Waterbody	Grassland	Cropland	Construction land	Unuse land	0.20
Soil erosion intensity	Extremely strong erosion	Strong erosion	Moderate erosion	Mild erosion	Slight erosion	0.30

factors was valued and calculated according to their weight. According to the natural breakpoint method, five levels including no sensitivity, light sensitivity, medium sensitivity, high sensitivity and extreme sensitivity were divided to assess the ecological sensitivity. The specific valuation and weights are shown in Table 1.

Generally, land of ecological services with a closer distance towards human activities are applied by residents more often, accordingly with higher ecological importance. Therefore, further analysis based on population density distribution data is required to acquire the spatial distribution of ecological needs. As night-time light data based on VIIRS-NPP has proven to be accurate in reflecting the intensity and range of human activities, the nuclear density analysis was applied to calculate the aggregated intensity of ecological needs in different expanded radii. The radium of needs was set to be 10 km to calculate night-time aggregated intensity. The specific equations and explanations have been mentioned in some research (Peng et al. 2018, Peng et al. 2017).

At last, three assessment results, i.e. ecosystem services, ecological sensitivity and residents' ecological needs were valued respectively, based on the reference to associated statistics, at the weights of 0.5, 0.3 and 0.2, thereby generating the final result of the importance to protect the ecological sources. According to the natural breakpoint method, five levels were divided, and patches that were greater than level three were selected as an ecological source candidate. Considering that ecological source needs certain habitat area and is capable of providing important ecological services, some relatively small patches were eliminated according to the actual situation. In the meantime, patches that are relatively aggregated were combined with other patches, thereby generating the southern Anhui ecological source.

The construction of ecological resistance surface: The difficulty of species migrating to patches of different habitats can be reflected by the resistance surface. Resistance surface depicts the influence of landscape heterogeneity towards ecological process flow. The resistance value is related not only to the distance to the ecological source but also to the land use and human disturbance. For example, human activities will prevent material circulation and energy exchange between different landscape patches. Therefore, traditional resistance surfaces were mainly applied to simulate ecological resistance according to the land use of patches, and could not accurately simulate the distribution of resistance surface. Generally speaking, the higher of the habitat quality in the region, the more complex will be the biodiversity in the region, and easier will be the migration of species. Regarding relevant research (Zhou et al. 2020, Peng et al. 2017), the study considered the actual situation in southern Anhui and adopted the reciprocal of habitat quality to construct a resistance surface. In the meantime, night-time light data were applied as a calibration factor. Considering that the value can be zero, the study assigned the data at no-zero value, and it exerted no influence to the construction of the actual resistance surface.

$$R_Z = R_0 \times OLS$$

In the equation, R_Z represents the resistance value after the calibration of each grid, R_0 represents the original resistance value constructed based on land use type, *OLS* represents night-time light index.

Ecological corridor and security pattern: Circuit theory is generally required to identify sticking points and pinch points, and thereby to construct the complete regional ecological security pattern, as shown in Fig. 3 (Dondina et al. 2016). In the construction of an ecological corridor, the tool Linkage Mapper developed based on circuit theory can explicitly depict the exact positions of barriers and pinch points. Sticking points are the barriers to effective species migration and ecological process. Under the circumstances of high urbanization, it is of great significance to determine and ameliorate sticking points. Pinch points are the area of too frequent ecological processes, and also the key node of ESP construction, unable to eliminate or hamper. Circuit theory can identify the ecological corridors that suit real species migration routes, combined with the improvement of sticking points and the protection of nodes, and it helps scholars to have a clear understanding towards ESP construction and propose targeted advice for protection (Liu et al. 2018).

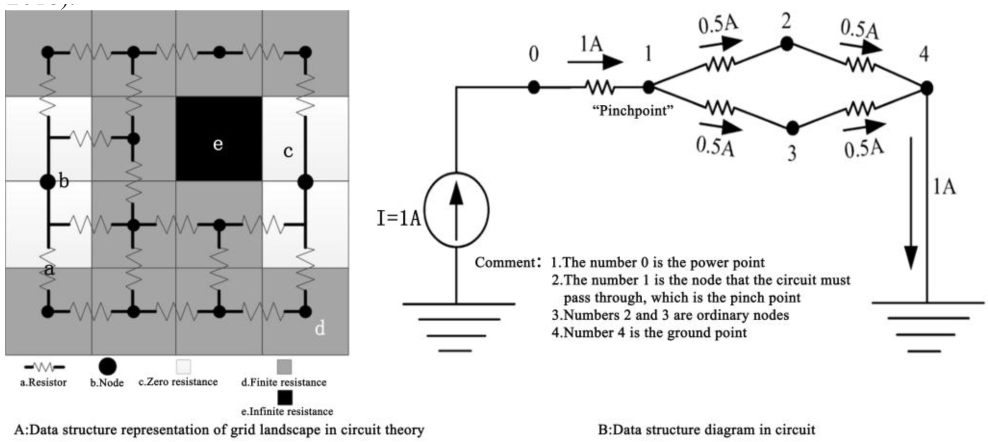

Fig. 3: Circuit theory grid circuit expression and resistance distribution diagram.

RESULTS AND DISCUSSION

Spatial Distribution Pattern of Factors

Every ecosystem service was divided into five levels according to the natural breakpoint method, and the significance from low to high was ranked from level one to five (Fig. 4). Results showed that ecosystem services presented a relatively significant spatial variation on overall quality which may result from the fact that the southern Anhui is higher than the northern. To analyze it in the context of the whole region, the biodiversity and water conservation of southern Anhui ranked the best, with the area greater than level three

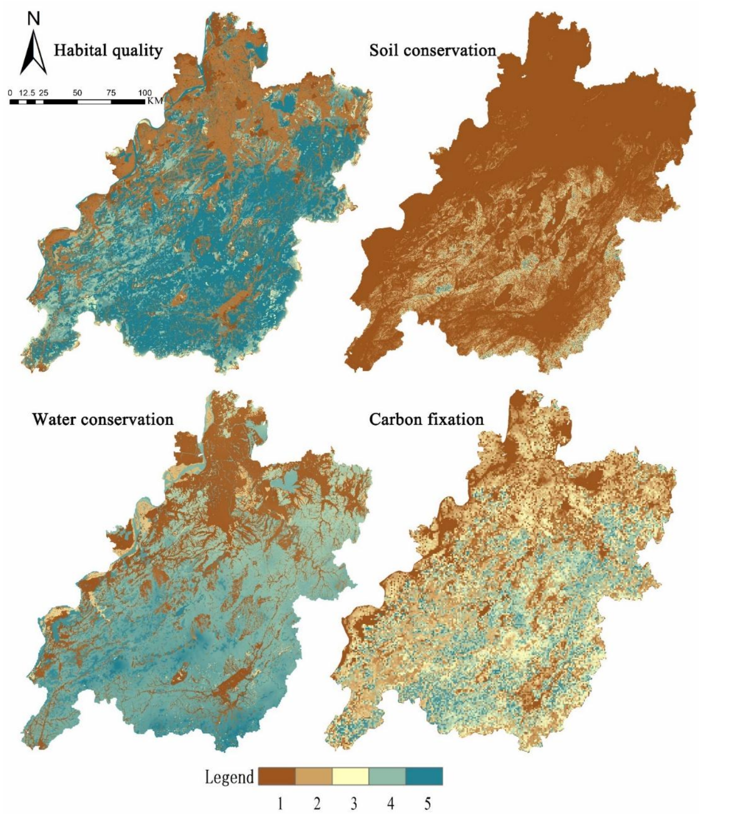

Fig. 4: Spatial distribution map of ecosystem service grades in southern Anhui.

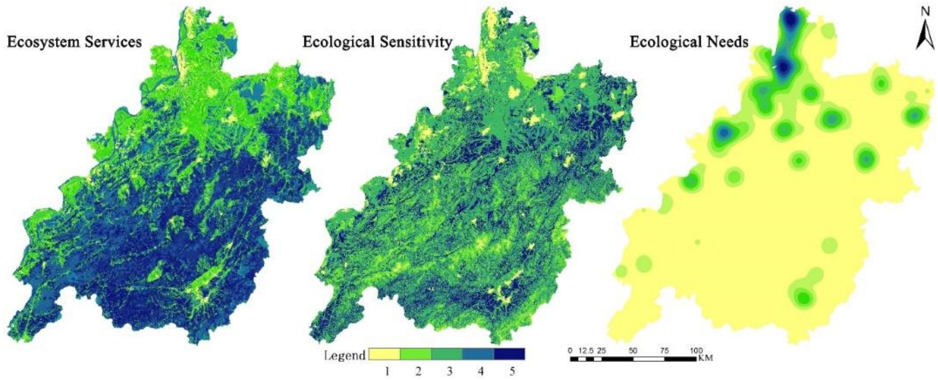

Fig. 5: The spatial distribution of factors for ecological source identification.

accounting for 62.7% and 48.5% of the total respectively, while the area of soil conservation and NPP that ranks greater than level three accounted for 1.17% and 34.6% of the total respectively. The soil conservation of southern Anhui is at serious risk, urging for certain protection strategies to renovate this function. Chaohu city and Maanshan city have high population density with rapid economic development, and face severely degenerated functions of biodiversity and water conservation and serious ecological problems, compared to Huangshan city and Xuancheng city.

Value water conservation, soil conservation, NPP and biodiversity at the weights of 0.2, 0.3, 0.2 and 0.3, and divide them respectively into five levels according to the natural breakpoint method. The assessment of ecosystem services in southern Anhui was then generated after overlaying the weights (Fig. 5). To understand the variations of ecosystem functions within the southern Anhui, the zonal statistics function in ArcGIS was applied to calculate the score of normalized ecosystem functions, as shown in Fig. 6. Qimen county ranked the highest in the assessment of ecosystem functions, while Jinghu district within Chaohu city ranked the lowest. The ecosystem functions presented an overall tendency of high in the south but low in the north. The overall ecosystem functions were related to elevation and population density.

The areas that rank greater than level three were mainly distributed in the south and the east, mostly consisting of woodland and grassland, accounting for 28.1% of the total area. The areas that have low sensitivity were mostly construction land, as well as the bare land at high elevation, located in the south of southern Anhui.

Residents' ecological needs were mainly distributed in the north and part of the east of southern Anhui, contrary to the distribution of ecosystem services and ecological

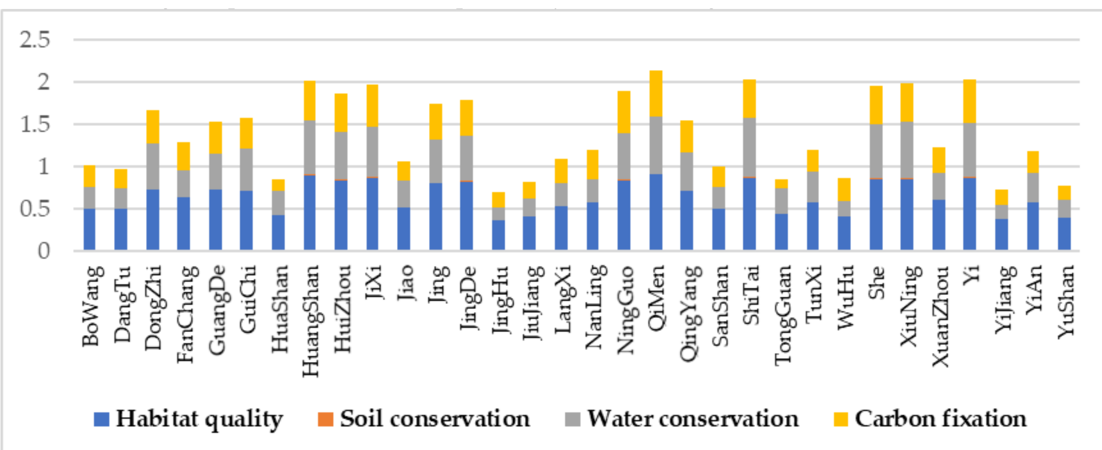

Fig. 6: The importance score of ecosystem services of counties.

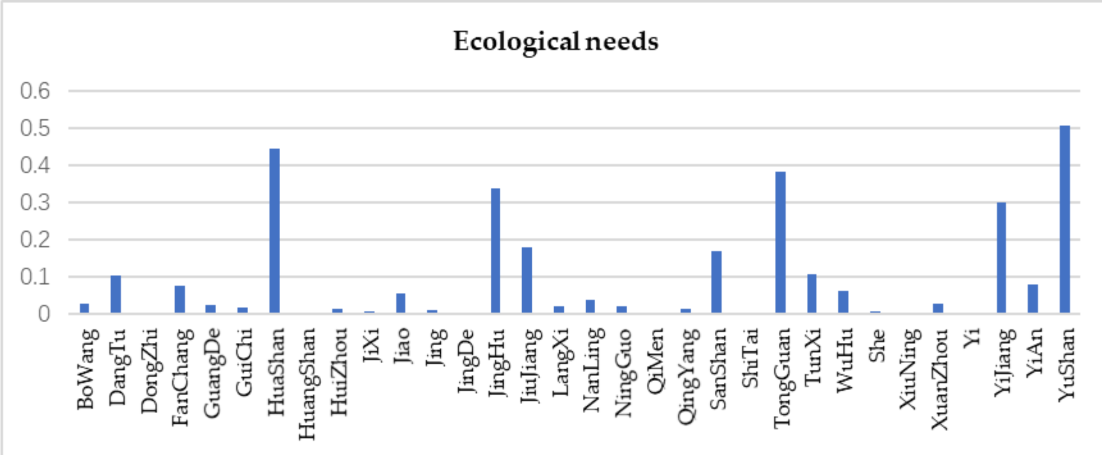

Fig. 7: The rank of residents' ecological needs in the counties and districts of southern Anhui.

sensitivity as shown in Fig. 7. For example, Jinghu district and Yunshan district are the economic centres of the region, and the ecological conditions within the region cannot satisfy the living needs of the majority; while the south and east of southern Anhui have sparse population, thereby they have relatively small residents' needs compared to the north. It means that apart from satisfying residents' needs, it is required to strengthen the connection between internal ecological lands within the region and construct a regional ecological network. It can help maintain regional ecological security and satisfy the coordinated development of "nature-society-ecology".

Ecological Source Extraction

Based on the assessment of ecosystem services, ecological sensitivity and residents' ecological needs in southern Anhui, patches that ranked greater than level three were extracted to identify the distribution of ecological sources, as shown in Fig. 8. The total area of ecological source in southern Anhui is 19269.54km^2, accounting for 51.3% of the total area. The areas are mainly distributed in the regions of Huangshan city, Xuancheng city and Chizhou city. These are the prime areas which can guarantee the ecological security of southern Anhui, as well as the ecological bottom line of urbanization

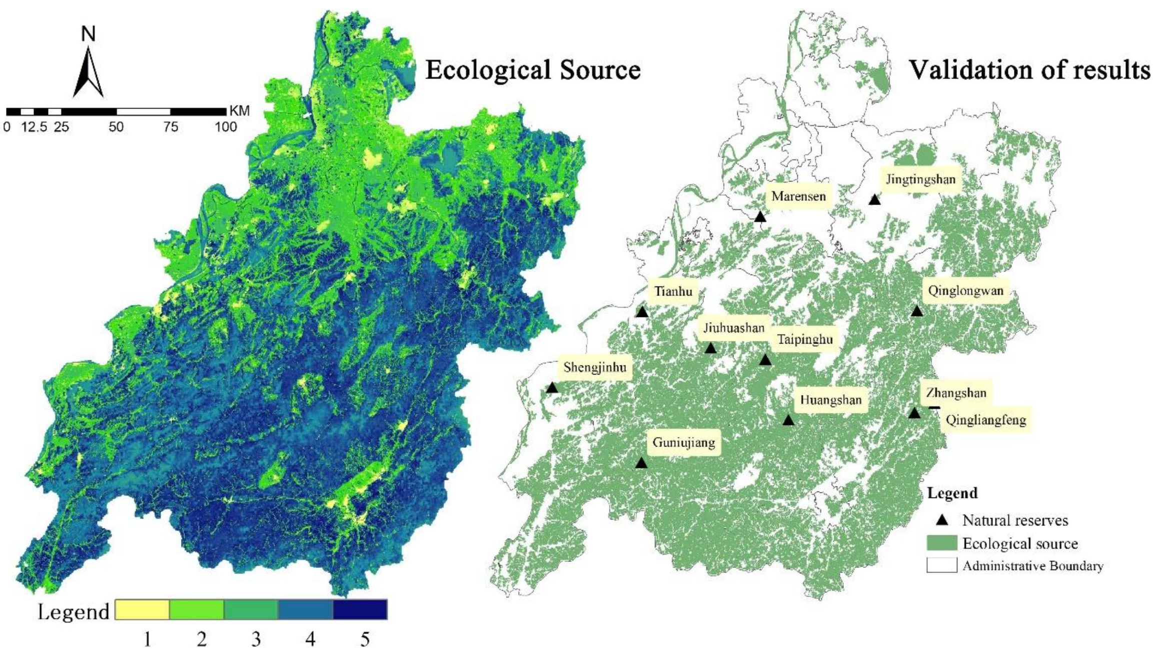

Fig. 8: Validation of results of ecological source extraction in southern Anhui.

Table 2:The area and the percentage of land-use in the ecological source region.

Land-use type	Area (km^2)	Proportion (%)
Cropland	432.34	2.2
Frost land	15369.49	79.7
Grassland	2557.99	13.3
Waterbody	896.53	4.7
Construction land	13.38	0.0995
Other land	0.1	0.0005

and environmental resource development. Exploitation and construction should be strictly prohibited in these areas. Among them, woodland was the most primary land use type, accounting for 79.7% of the total; grassland and waters accounted for 13.3% and 4.7% receptively; farmland accounted for 2.2%. It can be seen that certain ecological sources were exploited or constructed unreasonably. Besides, construction area and bare land accounted for less than 1% (Table 2).

To verify the effectiveness of the ecological source extraction based on a multi-factor comprehensive model, the study overlay the geographic position of ten national and provincial natural reserves and patches extracted from ecological sources. It can be found that natural reserves were basically within the extraction range of the ecological source, proving the validation of source extraction results.

The Construction of Minimum Accumulated Resistance Surface

The minimum accumulated resistance surface in an ecological source is shown in Fig. 9. Among them, the area along the Yangtze River, located in the north of research area, ranked the highest of the minimum accumulated resistance value, especially in the areas of Wuhu city and Maanshan city (Dangtu county, Jinghu District, Wuhu county and Fanchang county). The middle and south of the research area had complex surrounding landscape. As woodland and grassland limit human activities, thereby exerting a relatively small influence on the ecological environment, the minimum accumulated resistance surface is relatively small.

The ESP Construction of Southern Anhui

The spatial distribution of ecological corridors: The identification of the ecological corridor plays an important role in maintaining the ecological process. The ecological function of corridor closely relates to its spatial range such as the edge effect of corridor. The width of the ecological corridor based on circuit theory is determined according to the accumulated resistance and certain specific threshold. As shown in Fig.10, the range of ecological corridor was determined as the threshold of accumulated resistance increased from 1000 to 6000, and the ratio of the ESP area increased accordingly. The figure shows that as threshold increases, the area of ecological corridor increases accordingly, while there is slight or no change in the ecological corridor's spatial distribution.

Considering the urgent need for economic development, the limitation of financial investment in ecological conservation in southern Anhui, as well as the discussion of relevant research on ecological corridor, this study assumed that the investment in ecological conservation supported 10% of the whole research area, and applied threshold 3000 to determine the spatial range of ecological corridor. There were 37 ecological corridors determined, with a total length of 440.42

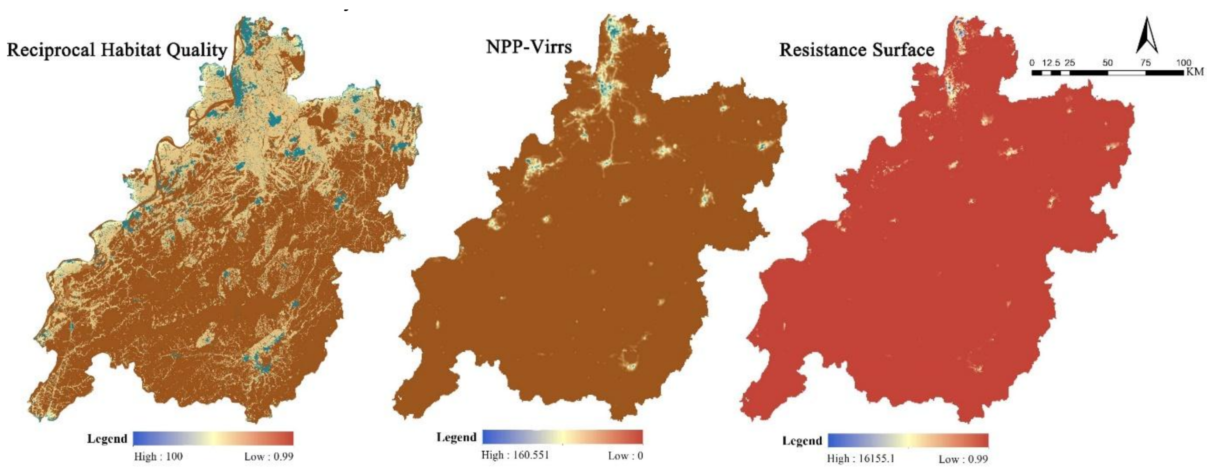

Fig. 9: Ecological resistance surface in southern Anhui.

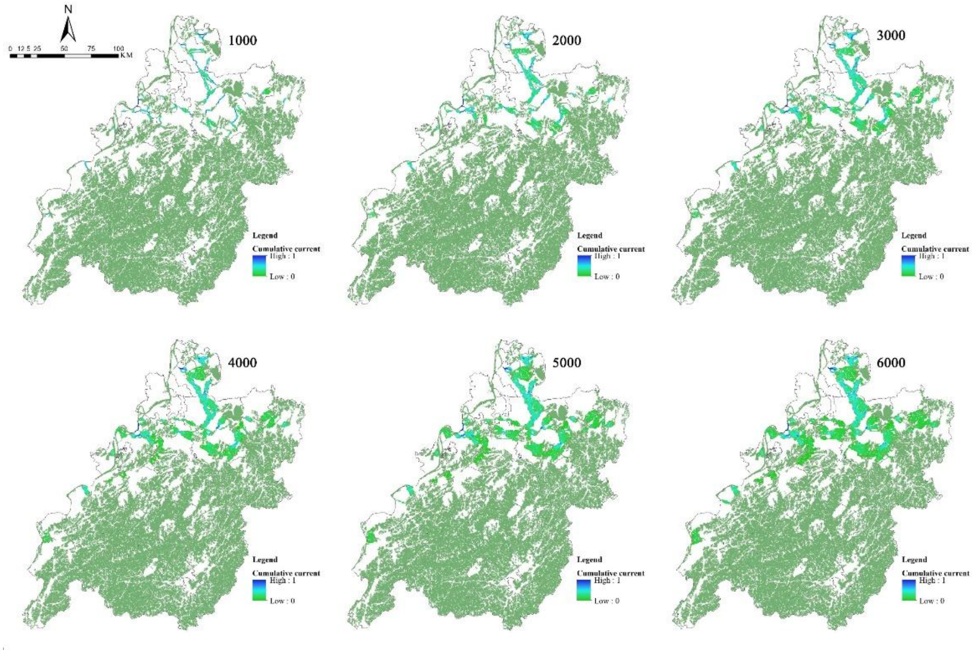

Fig. 10: Spatial distributions of ecological corridors for thresholds from 1000 to 6000.

km, mostly consisting of farmland. The ecological corridors in the south had high current density and presented a shape of cobweb, while the southwest and east had relatively small current density and presented a clustered distribution. The longest ecological corridor in the region was 59 km; the shortest 1.2 km.

The spatial distribution of barriers and pinch points: Linkage Mapper tool developed based on circuit theory was applied to determine the barriers that could influence the connection quality of ecological corridors, divide improvement areas in ecological corridors, and identify pinch points based on current corridors. The method is applied to give priority to the areas that are important to the connectivity of the research area, as shown in Fig. 11.

The ecological corridor barriers in southern Anhui were divided into primary and secondary improvement areas. The

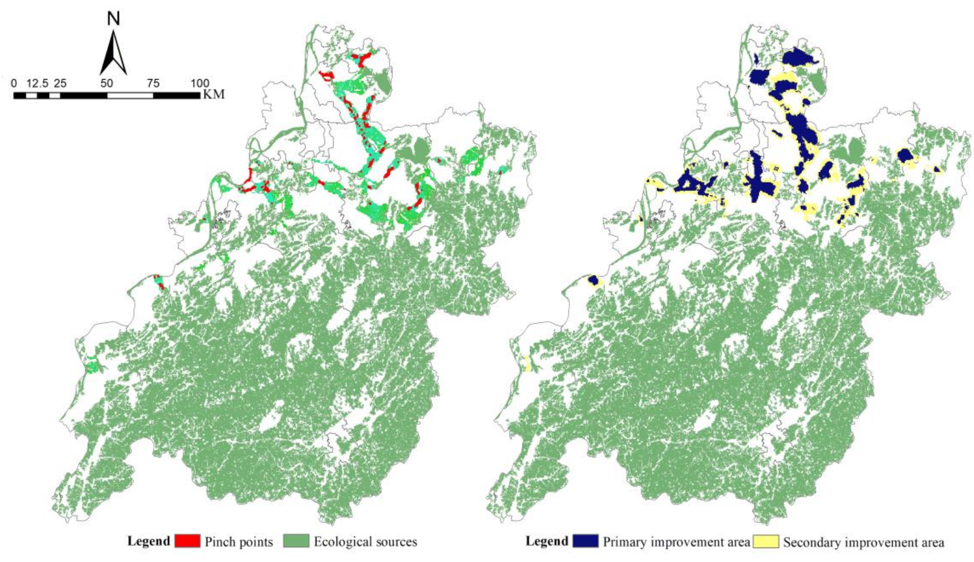

Fig. 11: Spatial distribution of pinch points and improvement areas.

area of the primary area was 1144.42 km^2, mostly distributed between sources or in the fringe area of sources; the area of the secondary area was 969.18km^2, mainly distributed around the primary improvement area. The range of secondary area depended on the number of connective sources and the distance between sources, influenced by both construction land and farmland.

According to the natural breakpoint method, the area with the highest ecological corridor density of the three levels was regarded as a pinch point area, with a total area of 119.24 km^2. The pinch points were mainly distributed close to the fringe area of the northern research area, with many cornerstones–small ecological sources within. The pinch points of the southwest were mainly distributed between the Yangtze River and ancient forests in southern Anhui, with a complete ecological conservation system and good landscape connectivity. According to the distribution of pinch points, 9 important pinch points were extracted for ecological conservation and improvement.

The Construction and Planning Strategies for ESP in Southern Anhui

The construction of ESP in southern Anhui is based on the comprehensive consideration of the ecological corridor, improvement area and the pinch point. There were 20 ecological sources, 37 ecological corridors, 9 important pinch points and 2 levels of improvement areas. The ecological corridors, pinch points and improvement areas were mainly distributed in the north, relating to the actual situation of southern Anhui. Southern Anhui, the important area with ecological functions of the Yangtze River Delta, has a major district of woodland and grassland, mostly distributed within Huangshan city, Chizhou city and Xuancheng city. Maanshan city and Wuhu city in the region are the bridge between southern Anhui and the external area. The rapid economic development causes significant ecological degradation in the area. To maintain the ecological connection of southern Anhui to the outside world and perform its important ecological function of serving residents, the ESP of southern Anhui is designed accordingly (Fig. 12).

Currently, scholars believe that barrier improvement, ecological pinch point protection and buffering zone construction are effective methods to optimize regional ESP under the circumstances of urbanization. In this study, the improvement area in southern Anhui mainly consisted of farmland and construction land. The improvement area was

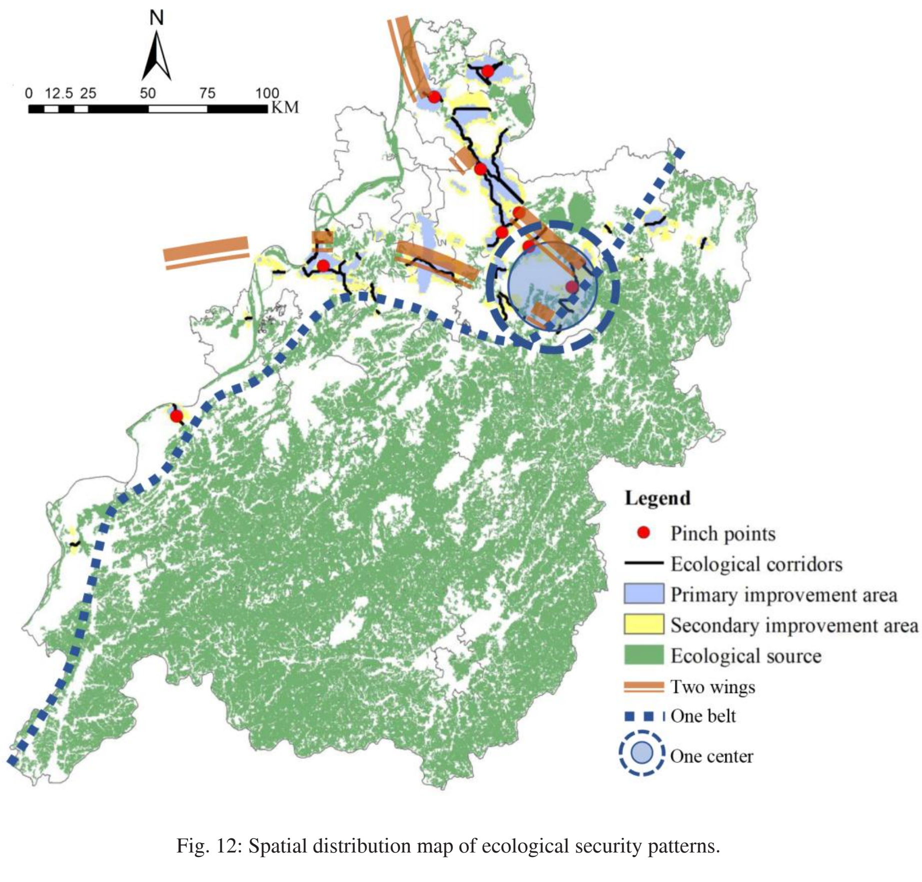

Fig. 12: Spatial distribution map of ecological security patterns.

located in the construction area, mainly around the urban area of Maanshan city of Wuhu city. The urban areas are the center for economic and population growth. Therefore, it is inappropriate to eliminate barriers in practical improvement strategies. Generally speaking, setting urban green belts in an economically developed area is a proper method to deal with the problem. Barriers besides farmland or sources should be eliminated in place, to enhance corridor connectivity. For pinch points that are important to the connection to the ecological source, the development-prohibited area should be set. In the meantime, unified planning at the provincial, city and county level should be conducted to ensure the connectivity of the ecological corridor. In this regard, a comprehensive spatial pattern of "one centre, two wings, one belt" should be generated at the regional level. "One centre" refers to the intersection of Chaohu city, Maanshan city and the southern mountainous area, regarded as an important node allowing species to accept ones from other sources; "two wings" refers to the ecological corridors from the southern mountainous area to Chaohu city and Maanshan city. Due to the overlength of the corridor, policymakers should adopt effective methods to ensure the connectivity of corridor and safeguard species to successfully migrate to the intersection of the southern mountainous area; "one belt" refers to the biological buffering zone that should be set between the southern mountainous area and northern plain area, to prevent the land expansion or population increase in the plain area and thereby avoiding the ecological degradation in the southern mountainous area.

Currently, there is no unified agreement about the method and indices of source extraction at home and abroad. Therefore, it is necessary to conduct validation after indices construction. The study overlaid the geographic positions of national and provincial natural reserves on source identification results, partly verifying the reasonability of the indices extracted from ecological sources. However, limited by manpower and material resources, the study did not construct a quantitative assessment standard of long-term dynamic monitoring. It is required to conduct more in-depth research to verify the reasonability of extracted indices.

Besides, southern Anhui is a region that has a close connection to its surrounding cities, and it surely could be influenced by the outside material and energy flow. Therefore, further research should consider breaking the boundaries of administrative divisions, as well as the influence of surrounding ecological factors on the ecological pattern of the research area.

CONCLUSION

The study constructed identification indices of "people-oriented" ecological source based on ecosystem services, ecological sensitivity and residents' needs and applied the reciprocal of habitat quality and night-time light data to construct landscape resistance surface. At last, based on circuit theory, ESP of southern Anhui was constructed, and then the optimization scheme was generated accordingly.

The main conclusion comprises: (1) the multi-factor comprehensive assessment model based on ecosystem services, ecological sensitivity and residents' needs was applied to identify 20 ecological sources in southern Anhui that suited "nature-ecology-society". Compared with the geographic positions of national and provincial nature reserves, the feasibility and rationality of the model were verified. The area of ecological source accounted for 51.3% of the total, mainly consisting of woodland and grassland; (2) the regional landscape resistance surface in the study was built according to the reciprocal of habitat quality and night-time light data. Compared with the valuation that only considers the land-use type, this valuation considered the important influence of human activities on the ecological process. Therefore, this construction of resistance surface is more reasonable; (3) the range and direction of 37 ecological corridors in southern Anhui were identified according to circuit theory, and then two levels of improvement areas and 9 important pinch points were divided accordingly. The area of the primary improvement area was 1144.42km^2, mainly distributed in the north of southern Anhui; the area of the secondary area was 969.18km^2, mostly consisting of farmland and construction land.

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