Journal of Geography and Cartography (2020) Volume 3 Issue 1: Special Issue - Man-land research by analyzing and mapping geographic phenomena using cartographic methods in China
doi:10.24294/jgc.v3i1.1304

ORIGINAL RESEARCH ARTICLE

Analysis of ecological security pattern of rare earth mining areas in South China based on MCR model

Hengkai Li[1*], Yuting Liu[1], Qin Li[1], Xiuli Wang[2]

[1] *School of Architecture and Surveying and Mapping Engineering, Jiangxi University of Science and Technology, Ganzhou 341000, Jiangxi Province, China. E-mail: Hen_ke_Li@126.com*

[2] *School of Economics and Management, Jiangxi University of Science and Technology, Ganzhou 341000, Jiangxi Province, China.*

ABSTRACT

The rare earth mining area in South China is the main production base of ionic rare earth in the world, which has brought inestimable economic value to the local area and even the whole nation. However, due to the lack of mining technology and excessive pursuit for economic profits, a series of environmental problems have arisen, which is a great threat to the ecosystem of the mining area. Taking Lingbei rare earth mining area in Ganzhou as an example, this paper discriminated and analyzed such aspects as the ecological source, ecological corridor and ecological nodes of the mining area based on the landscape ecological security pattern theory and the minimum cumulative resistance model (MCR) method, and constructed a landscape ecological security pattern of the mining area during the 2009, 2013 and 2018. The results show that: i) The patch area of the ecological source of rare earth mining area is small, mainly concentrated in the east and west sides of the mining area. ii) During the selected year, the ecological source area, ecological corridors, radiation channels and the number of ecological nodes in the rare earth mining area are increasing, indicating that the landscape ecological security of the rare earth mining area has been improved to some extent, but it remains necessary for relevant departments to make a optimized planning to further reconstruct the ecological security pattern of the rare earth mining area.

Keywords: Rare Earth Mining Area; MCR Model; Ecological Source; Ecological Corridor; Ecological Security Pattern

ARTICLE INFO

Received: 8 May 2020
Accepted: 29 June 2020
Available online: 5 July 2020

1. Introduction

Ecological security pattern refers to the arrangement, design, combination and layout of various natural and cultural elements in a region with specific technology based on the optimization of ecological, economic and social benefits, and formulate a multi-objective, multi-level and multi category spatial allocation scheme composed of points, lines, areas and networks. Due to the continuous development of various resources on the earth, there is a serious ecological imbalance, and various ecological security problems arise, such as resource shortage, sharp reduction of species and environmental pollution. People from all walks of life and scholars are paying more and more attention to ecological research, and further think and discuss the definition and derivation of its concept based on ecological security research. Therefore, a series of related studies are carried out around the theme of ecological security[1,2].

In the 21st century, rare earth, as an extremely important national strategic resource, plays an important role in high-tech and military fields such as military weapons and new material manufacturing[3]. Ion adsorption rare earth ores are scarce in many types of rare earth ores and have important mining value[4]. The main production area is located in the south of Jiangxi Province, China, and its reserves are as high as 80% of the world's total. However, due to its special mining process, the ionic rare earth mine in southern Jiangxi will bring direct damage to the surface vegetation and soil, resulting in a series of ecological and environmental problems, such as large-area vegetation degradation, farmland damage, soil erosion and desertification[5]. According to statistics, more than 100 km^2 of mountain forest land in Ganzhou City has been damaged due to rare earth mining[6]. The land that has been treated is very few, which puts great pressure on the ecology of the region. In recent years, the maturity of GIS and remote sensing technology has laid a technical foundation for the ecological monitoring of rare earth mining areas. As early as the end of the 20th century, Horvath, Luise, and Monjezi analyzed and comprehensively evaluated the impact of open-pit mining on ecological security, and formulated a series of ecological restoration and optimization measures, which opened a good beginning for later research[7–9]. Domestic scholars have also opened the road of ecological security in the mining area and achieved many results. Liu Xitao, Fan Xiaoshan and Yang Jianjun all tried to establish an ecological security evaluation index system for the mining area[10–12]. They put forward suggestions for ecological management of the mining area. As a result, some ecological problems were alleviated.

When exploring the ecological security pattern, MCR is a widely used model, which reflects the internal relationship of ecological security, integrates applicability and scalability, and plays an important role in technical methods and practical application[13]. Based on the MCR model, many scholars have constructed the ecological security pattern of land use from many aspects and put forward corresponding optimization schemes[13–16]. However, for the current research, the Minimum Cumulative Resistance Model (MCR) is mainly used to evaluate the ecological security pattern of urban land, and is rarely used in rare earth mining areas. Therefore, the present paper takes the Dingnan Lingbei rare earth mining area in Ganzhou as the research area to further explore the changes in landscape and patterns in this mining area by using QuickBird multi temporal high-resolution images and fully considering the landform of the rare earth mining area based on the manual vector map of the area. MCR model is used to analyze the landscape ecological security pattern of rare earth mining area, so as to further understand the change characteristics of landscape ecological security pattern of rare earth mining area and provide basic data and scientific decision-making for controlling the ecological environment of mining area.

2. Overview of the study area

Lingbei rare earth mining area is mainly located in the north of Dingnan County, Jiangxi Province, between 114°58′04″ E ~ 115°10′56″ E and 24°51′24″ N ~ 25°02′56″ N, including towns such as Jingnao and Huangxiang (**Figure 1**). It is a subtropical monsoon humid climate area, with an annual average temperature of 19 ℃, precipitation of 1774.3 mm, and uniform and sufficient light and heat throughout the year[17,18]. Among them, Lingbei mining area is composed of Laohukeng, Chenaoxia, Qingjingtang, Longchuankeng, Zuojaxing, Jiazibei, Aobeitang and other major ore occurrences. The mining area is rich in minerals and the rare earth grade is among the best in China. So far, it has a mining history of about 30 years. Taking 2001 as the watershed, the previous mining methods were more traditional, mainly pool leaching and heap leaching. This method will directly promote the vegetation, alleviate the damage degree of vegetation, and relatively reduce the ecological pressure. However, the ecology of some ore spots has not been improved, indicating that this method cannot fundamentally solve a series of environmental problems produced in the process of rare earth mining.

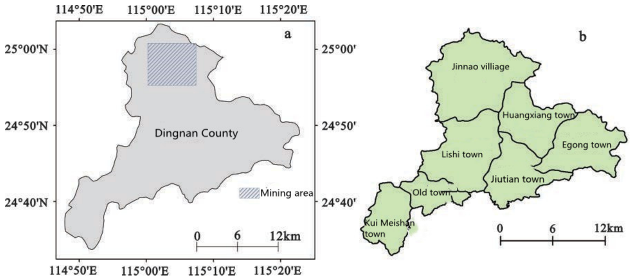

Figure 1. Location of the study area.

2. Data sources and research methods

2.1 Data sources

The land use classification data used in this paper mainly comes from QuickBird image data. The spatial resolution of the data is 2.44 m. The data comes from Google Earth. Combined with field investigation, the mining area is manually vectorized, which is mainly divided into water body, buildings, orchards, roads, tailings land (a large area of exposed area after mining) and sedimentation tank (including high pool), vegetation (mainly refers to natural forestland), reclaimed vegetation and farmland. DEM data has a spatial resolution of 30 m, mainly from geospatial data cloud platform (http://www. gscloud.cn). DEM is used to extract elevation and slope as resistance factors. The vector boundary is extracted from the national administrative division boundary map.

2.2 Research methods

2.2.1 Minimum cumulative resistance model (MCR model)

The minimum cumulative resistance model (MCR model) refers to the model of the total resistance that species need to overcome in the process from a "source" point to the target location[19]. Generally speaking, the resistance coefficient will be defined as a specific value, and the minimum resistance value is the source point, which is usually defined as 1. The determination of other impact factors is usually determined by comprehensively considering the actual situation of the mining area and the establishment path objectives of the study area. And the element resistance coefficient varies with different targets. The specific formula is expressed as follows:

$$MCR = f_{min} \sum_{j=n}^{i=m} (D_{ij} \times R_i) \tag{1}$$

where *MCR* is the minimum cumulative resistance of rare earth mining area, and *f* is the undetermined monotonic increasing function. D_{ij} represents the spatial distance from ecological land landscape units *i* to *j*. R_i is the resistance coefficient of landscape unit *i* to a certain movement; *m, n* represents the number of landscape units i and ecological sources j respectively.

2.2.2 Identification method of ecological source

Ecological source is the "source" of ecological land protection. It generally selects areas with strong ecological function and rich biodiversity. It is the habitat of existing species and the source of species exchange and diffusion. It is of great significance in meeting the ecological needs of rare earth mining areas and the integrity and healthy stability of landscape pattern[20–21]. The construction of ecological source shall at least meet the following three principles:

1) It is necessary to select the ecological source in the area with high habitat quality. Habitat quality refers to the living environment quality around species, which decreases with the increase of land use type intensity near the area[22]. Generally, it is defined as a large area of water and a large area of massive vegetation suitable for species habitat.

2) It is necessary to comprehensively consider the species diversity, land use type and environmental quality of the area in combination with the actual ecological status and land use of the mining area, so as to select the ecological source according to local conditions.

3) It is necessary to select the area with high ecological service function and can provide suitable habitat for species as the ecological source, which can make the ecological environment develop in a healthy direction and better serve the ecosystem.

3. Construction of comprehensive spatial resistance surface

The important influence on the construction of MCR model is the selection of its resistance factor[23]. The rare earth ore research area in this paper is located in the hilly area of southern China. According to the complex surface characteristics, the resistance factors such as slope, land use type and elevation that have a great impact on the mining environment are selected.

1) Land use type. The closer the land use type is to the protection source type in the study area, the smaller its resistance to the exchange and diffusion between species and its resistance value will be. The tailings land caused by rare earth mining is the most important factor affecting the ecological security of the mining area. As a land use type, combined with the unique landscape of the rare earth mining area, the land use type factor is determined to be the most important of all factors, and its weight is given to 0.8[24].

Due to the particularity of each study area, the land use types are different. At present, the research on the resistance value of land use types is mostly aimed at cities or larger areas. Due to the particularity of Gannan rare earth mining area, the resistance coefficient should be given its own value in combination with the actual situation of the mining area. In this paper, combined with the actual situation of rare earth mining area, various ground objects are arranged in the order of resistance from small to large, as follows: vegetation < water body, reclaimed vegetation < orchard < farmland < road < building < sedimentation tank (including high-level tank) < tailings land. See Table 1 for details. It can be seen from the table that the vegetation with the lowest resistance coefficient in the mining area has the greatest service value to the ecosystem; The resistance of reclaimed vegetation is also small, because it is closely related to the source land; Water body has little influence on ecological security pattern, and its resistance coefficient is also small. However, the mined tailings land is easy to cause many ecological problems such as soil environmental damage and water and soil loss, which makes its ecological service value the smallest, so the resistance coefficient is the largest compared with other types[13,22,25].

Table 1. Resistance factor and drag coefficient of land use type in mining area

Resistance factors	Resistance coefficients
Vegetation	1
Reclaimed vegetation	2
Water body	2
Orchard	3
Farmland	4
Road	6
Building	8
Sedimentation tank	9
Tailing land	10

2) Slope. Rare earth mining area is located in typical hilly and mountainous areas, with significant soil and water loss. Slope is one of the influencing factors of land environmental problems such as landslide and soil erosion. In addition, it will also have a certain impact on species exchange and ecological flow diffusion in rare earth mining areas[26,27]. Therefore, when constructing the ecological pattern of rare earth mining area, the influence of slope should be considered. Based on the DEM data of rare earth mining area, this paper extracts the relative slope of rare earth mining area as one of the resistance factors. Since the mountain slope in the mining area is relatively gentle and the impact of slope is relatively small, this weight is given 0.1. According to the actual situation of rare earth mining area, the slope factors are classified. See **Table 2** for details of different grades and resistance coefficients[13,25].

Table 2. Slope resistance factor and resistance coefficient in the mining area

Resistance factors	Resistance coefficients
0°~5° flat slope	1
5°~15° gentle slope	3
15°~25° steep hill	5
25°~35° steep slope	7
>35° extremely steep slope	10

3) Altitude. Elevation will also have a certain impact on species migration and the diffusion of ecological flow. When species migrate in areas with similar elevation, it will be easier to pass, otherwise it will be more difficult. The elevation is regarded as one of the resistance factors in this paper, and its

weight is given to 0.1. Since the elevation of the rare earth mining area in this paper is between 290 ~ 800 m, it is classified into four resistance factors. The resistance coefficients of different grades are shown in **Table 3**[19].

Table 3. Height resistance factor and drag coefficient of mining area

Resistance factors (m)	Resistance coefficients
<300	1
300~400	3
400~600	5
600~800	8

According to different resistance factors and resistance coefficients, the cost-distance tool in ArcMap software platform is used to obtain the resistance surface data of land use type, elevation and slope after calculation. The resistance surfaces of the three resistance factors are superimposed according to the weight. The superimposed formula is: slope factor resistance surface × 0.1 + elevation factor resistance surface × 0.1 + resistance surface of land use type factor × 0.8, the minimum cumulative resistance surface models of the study area in 2009, 2013 and 2018 are obtained after calculation by superposition formula (**Figure 2**).

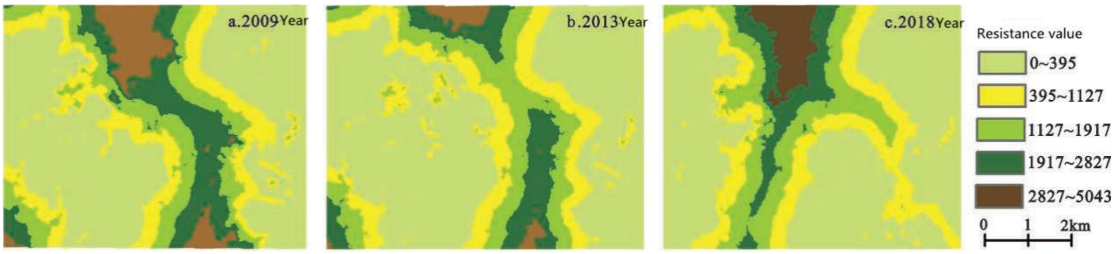

Figure 2. Schematic diagram of ecological sources in different years.

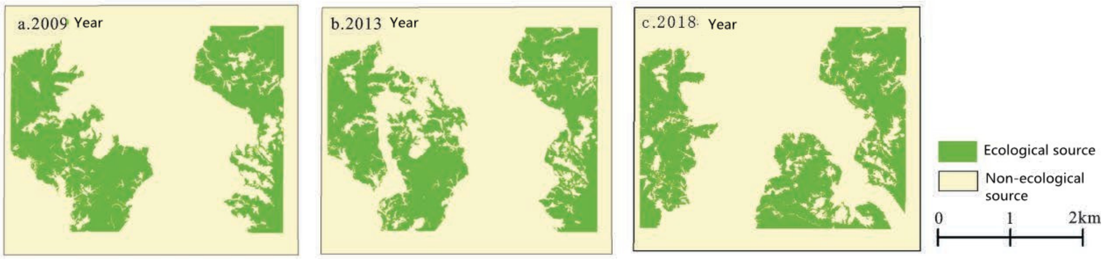

Figure 3. Model of minimum cumulative resistance surface in different years.

It can be seen from **Figure 2** that the overall resistance value of rare earth mining area was high in 2009. The main reason for this situation is that in the three years studied in this paper, the tailing land area of rare earth mining area was the largest in 2009, and the tailing land area gradually decreased after 2009. However, the tailing land is the largest resistance factor of the resistance factor of land use type, so it has a great impact on the overall ecological resistance value of rare earth mining areas.

4. Analysis on landscape ecological security pattern of rare earth mining area from 2009 to 2018

4.1 Spatial distribution of ecological source

According to the above source selection principles and landscape ecology knowledge, we know that high-quality ecological source areas have high ecological services and their value. Most scholars at home and abroad directly select ecological parks, large-area vegetation or water areas as the source of ecological security pattern[28]. However, according to the field investigation and the actual situation, the rare earth mining area in southern Jiangxi is located in the low mountain and hilly area in the south, and the vegetation is the main land use type. Therefore, the area with dense vegetation and of more than 10 km^2 is selected as the ecological source (**Figure 3**) [29]. Due to the long-term large-area rare earth mining in the middle of the area in 2009 and 2013, the vegetation in the middle of the mining area is seriously damaged, and the ecological source is mainly distributed on the east and west sides. However, after 2013, the environmental protection department has formulated and implemented some mining area reclamation measures, and the ecological environment of the mining area has been improved to a certain extent. By 2018, based on the distribution characteristics of the first two years, the ecological source has also increased to a certain area in the south of the mining area.

4.2 Construction of ecological security pattern

The construction of landscape ecological pattern can effectively guide people's production activities in the mining area, including the ecological restoration and planning of key vulnerable areas, as well as the balanced and sustainable development between economy and ecology, so as to provide a theoretical basis for the rational planning of mining land. To construct the landscape ecological pattern, besides the selection of ecological source, it is also necessary to distinguish, select and combine the ecological corridor, ecological node, radiation channel, patch and ecological matrix[30]. Based on the cost-distance analysis technology, through the construction of ecological resistance surface and the synthesis of minimum cumulative resistance surface for the selection of ecological sources, it is also necessary to extract ecological corridors, nodes and radiation channels, so as to form the ecological security pattern of rare earth mining areas.

1) Identification of ecological corridor. Ecological corridor refers to the most efficient path for the maintenance and diffusion of different species, that is, the low resistance valley line between the two sources[31]. This paper identifies the ecological corridor based on hydrological analysis, so as to connect the two adjacent source patches in the mining area.

2) Radiation channel is similar to ecological corridor[32]. It plays a channel role in species diffusion and maintenance, that is, it is a low resistance valley line for the outward diffusion of ecological source, which plays a key role in the protection of species diversity and the evolution and development among species.

3) The ecological node is the tangent point of the equal resistance line between the ecological sources according to the morphological characteristics of the minimum resistance model of the mining area, so it is regarded as the ecological node of the rare earth mining area[33,34].

According to the landscape ecological security pattern of rare earth mining area in 2009, 2013 and 2018 (**Figure 4**), the number of 3a ecological corridors is 1, 4 and 6 respectively. The number of radiation channels is 14, 16 and 19 respectively, and the number of ecological nodes is 1, 4 and 6 respectively.

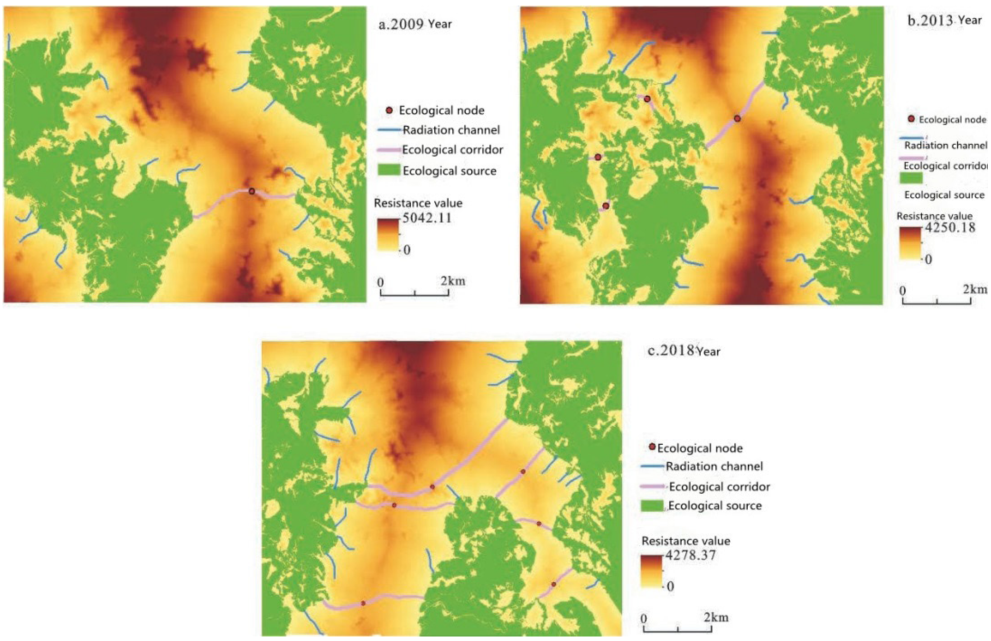

Figure 4. Integrated ecological security pattern of rare earth mining areas in 2009, 2013 and 2018.

Compared with 2009, the ecological source area, ecological corridors, radiation channels and the number of ecological nodes in the rare earth mining area increased in 2013, and the maximum resistance value decreased. In 2009, due to excessive mining in the middle of the mining area, a large amount of tailings was accumulated and the resistance value was high. The ecological source areas were mainly distributed in the east and west. There was only one ecological corridor and a small number of radiation channels, which greatly hindered the circulation of species between the east and the west. Combined with the images and field investigation, it can be seen that in 2013, due to the introduction of a series of environmental protection measures, such as the wide application of in-situ leaching technology, tailings land reclamation, returning farmland to forest, mining standardization, etc., the vegetation in the mining area has been protected to a certain extent. The area began to grow, and the ecosystem began to repair itself or man-made. It can be seen from Table 4 that the total area of source patch in the mining area in 2009 was 34.833 km^2, mainly concentrated in the vegetation position. The total source area in 2013 was 37.286 km^2, an increase of 2.452 km^2 compared with 2009. The source of the mining area tends to shift to the west, and the source areas in the middle and west have increased (**Figure 5**).

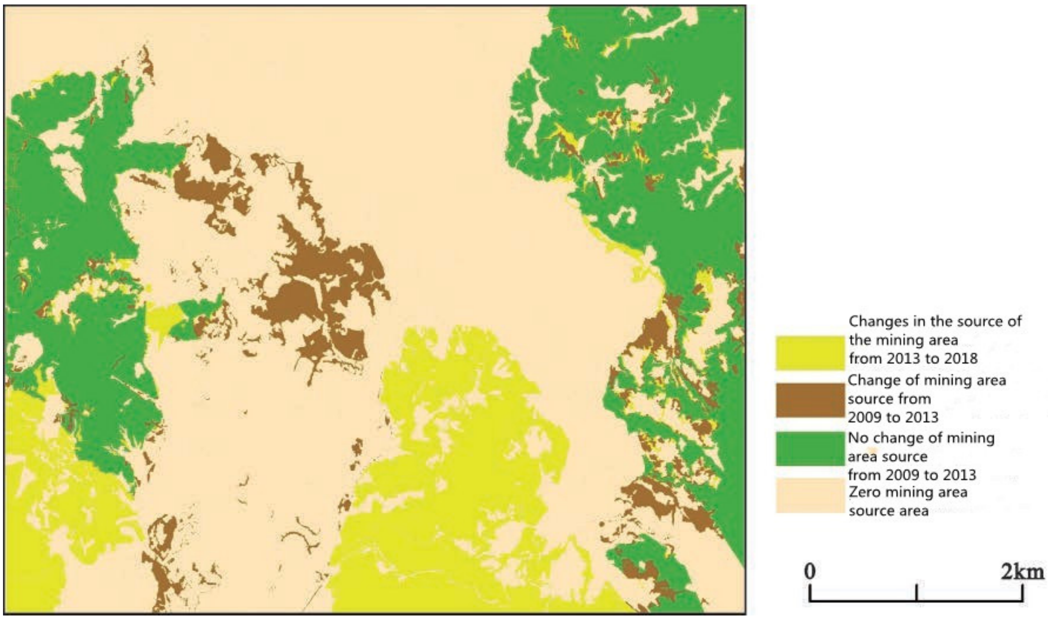

Figure 5. Spatial change of ecological source of rare earth mining areas in 2009−2018.

Table 4. Changes in ecological source area of rare earth mining areas in 2009−2018 (km^2)

Year	Total area of ecological source	Area change
2009	34.833	−
2013	37.286	Increased 2.452
2018	36.465	Decreased 0.82

Note: − means no data was available.

Compared with 2013, the area with high resistance value in rare earth mining area decreased, and the part with high resistance value moved eastward in 2018. Besides, the number of ecological corridors increased by 2, and the number of radiation channels increased by 3. Combined with **Figure 5** and Table 4, it can be seen that the ecological source area is distributed in the east-west south, and some source areas are transferred to the south. The total source area is 36.465 km^2, which has decreased by 0.820 km^2 compared with 2013, and the source area has become more concentrated, mainly because the source growth location was originally the tailings land of the mining area, and the land has been seriously damaged.

After 2013, benefiting from the instructions of Several Opinions of the State Council on Supporting the Revitalization and Development of Gannan and Other Former Central Soviet areas (http://www.gov.cn/zhengce/content/2012-07/02/content_4618.htm), the ecological environment in southern Jiangxi has been highly concerned by the party and the state.

Since then, the environmental protection department has issued a series of policies for the treatment of environmental problems in rare earth mining areas, and invested a lot in the treatment of ecological and environmental problems in rare earth mining areas. In these five years, the ecological security of the mining area has been further improved.

The ecological corridors in rare earth mining areas are mainly connected to two large source patches in the East and West. However, due to the accumulation of a large number of rare earth ore points in the middle of the mining area and the exploitation of rare earth ore points, there are a large number of rare earth tailings and sedimentation tanks in the middle of the mining area, so the resistance value in the middle of the mining area is high and there is poor connectivity between the eastern and western parts of the mining area. For only one ecological corridor connecting the eastern and western ecological source patches, and the two ecological corridors intersect with multiple roads and rare earth tailings, there are multiple vulnerable parts with insufficient stability. Once any problem occurs, it may lead to the fracture of the overall ecological structure of the mining area. The ecological nodes located in the mining points and construction areas are relatively dense, and its construction goal is to build a secondary source for the maintenance of ecological functions in the mining area. In this case, this type of ecological nodes are also most vulnerable to human interference and destruction, so the construction and protection of this type of ecological nodes should be strengthened. Due to the large number of sedimentation tanks and tailings in the central area of the mining area, affected by rare earth mining activities, it will also interfere with the ecological corridor and ecological nodes, which reduces the stability of the ecological security pattern of the mining area.

There is little difference in the size of patches in the ecological source areas of rare earth mining areas, and the distribution is relatively concentrated. The number of ecological corridors is small. The ecological nodes are mostly distributed near rare earth tailings and buildings. The connectivity and stability between the east and west parts are low, but the overall ecosystem stability is constantly improving in these 9 years, so relevant departments also need to further plan the ecological security space of rare earth mining areas.

5. Optimization measures of ecological security in rare earth mining areas

As the core area of the landscape ecological security pattern of the mining area, the ecological source is an insurmountable red line for rare earth mining and residents' life. The overall goal of the optimization of the ecological source of the rare earth mining area is to protect the existing ecological source and continuously expand the area of the ecological source. During the nine years, the ecological source areas on the east and west sides of the rare earth mining area are relatively stable and are the object of key protection and construction. Protective measures such as building buffer zones around them can be taken to protect the original vegetation and make it better play its role of ecological service; with the goal of restoring the original condition, the reclamation is accelerated at the junction of the original vegetation and the mining area. For the small patch sources increased in the later stage, artificial interference should be reduced to prevent damage, and construction and human activities of any nature should be prohibited to make them develop in the natural direction; For the area where the reclaimed vegetation becomes the source, because the vegetation coverage of the area is low and belongs to the ecologically weak area, measures such as supplementary planting and fertilization should be taken to accelerate the growth.

To increase the construction of ecological corridors in the East-West source areas, in the process of construction, the primary vegetation in the mining area should be selected, and a reasonable corridor width should be formulated according to the land use type, slope and elevation of the mining area, and the resistance value should be reduced to build the best ecological corridor in the mining area, reduce the flow obstruction between species in the East-West ecological source areas, and strengthen the connectivity between the East and the West. The ecological corridor in the central area is increasing year by year, which is the concentration area of mining points. When the ecological corridor passes through artificial landscapes such as buildings, sedimentation tanks and roads, appropriate isolation zones should be established around the environment, buffer zones should be established by strengthening the construction and protection of artificial green spaces, and more ecological corridors and radiation channels should be built around the ecological source and it shall strengthen connectivity between sources. In previous years, farmland and orchards were mainly concentrated in the east, but in recent years, the construction of ecological corridors in this area has become better and better, and the number has gradually increased. When the corridors intersect with farmland or orchards, the natural components of the ecological corridor area or the land use types similar to the natural components should be preserved, so as to improve the ecological stability and prevent the fracture of the overall ecological corridor.

From the landscape ecological security pattern of the constructed rare earth mining area for 3 years, it can be analyzed that more ecological nodes are located near the tailings land of the mining area, which is also the weak part of biological exchange in the mining area. Especially in the part with high resistance value in the middle, the land use types are mostly tailings land and sedimentation tank. The reclamation measures for this location should be accelerated. The main land use types should be planting vegetation or building other land use types with low resistance coefficient. It is strictly prohibited to carry out rare earth mining, production and construction in the area of ecological nodes, so as to reduce the interference of human activities.

6. Conclusion and discussion

In this paper, patches with important ecological significance are extracted as the ecological source, and three factors as land use type, slope and elevation, which have a great impact on the ecological environment of the mining area, are selected to construct the ecological resistance surface based on the MCR model. On this basis, the best ecological corridor between adjacent ecological sources and the radiation channel connecting with the outside are identified, the ecological nodes with important ecological significance are determined, and the security pattern for protecting species diversity is constructed. The conclusions are as follows:

1) From 2009 to 2013, the area with high resistance value in the mining area decreased year by year, the location of ecological source continued to shift to the direction of high resistance value, and the source area also increased, which was concentrated in the east and west sides. The original land use types on the east and west sides were mostly tailings land and farmland, the area of reclaimed vegetation also increased, and the ecological pattern of the mining area became more and more reasonable. Land damage caused by mining has improved.

2) In the three years studied, the number of ecological corridors, radiation channels and ecological nodes in the mining area has increased, but the concentration area of mineral points in the middle is still the place with the highest resistance value, and the ecological security status of this area is the worst in the region. Moreover, the ecological corridors mostly intersect with roads, rare earth tailings and farmland, forming an ecological fragile area in the corridor. In order to maintain the stability of the ecological pattern and the connectivity of the ecological corridor, we should strengthen ecological regulation, focus on protecting the ecological land around the mining sites and timely reclamation, and advocate returning farmland to forest and primitive land use types, so as to ensure the circulation among species.

Considering the landscape connectivity of the mining area, the protection of biodiversity and the stability of the regional ecosystem, this paper comprehensively constructs the landscape ecological security pattern of the rare earth mining area, obtains the corresponding optimization measures for the landscape ecological security of the mining area and establishes the ecological corridor construction of the rare earth mining area, and makes the ecological security pattern of the mining area more systematic and complete. However, there remain some limitations. It is one-sided to only select vegetation as the source patch identification while ignoring other land use types that may have little impact on the whole area but are of great importance to the local area, which should be further explored in the future researches.

Conflict of interest

The authors declare that they have no conflict of interest.

References

1. Zhang X, Yu W, Cai H. Summary of research on regional ecological environment vulnerability assessment methods. Acta Ecologica Sinica 2018; 38(16): 5970–5981.
2. Liu J, Zhang K, Ma W. Study on ecological security evaluation of mining area based on high-resolution satellite remote sensing image: Taking Jingjing mining area as an example. Geography and Geography Information 2015; 31(5): 121–126.
3. Li H, Lei J, Yang L. Vegetation coverage extraction and landscape pattern analysis of ionic rare earth ore based on Landsat imagery. Transactions of the Chinese Society of Agricultural Engineering 2016; 32(10): 267–276.
4. Wang C, Liu Y, Zhao L, *et al.* Present situation and development trend of rare earth materials and green preparation technology in China. Progress in Chinese Materials, 2018, 37(11): 1–5.
5. Li H, Lei J, Wu J. Analysis of land damage and recovery process in rare earth mining area based on multi- source time series NDVI. Transactions of the Chinese Society of Agricultural Engineering 2018; 34(1): 232–240.
6. Li H, Wu L, Liu X. Multi-temporal remote sensing monitoring of surface environment changes in rare earth mining areas: Taking Lingbei rare earth mining area as an example. Journal of China University of Mining and Technology 2014; 43(6): 1087–1094.
7. Horvath B, Gruiz K. Impact of metalliferous ore mining activity on the environment in Gyongyosoroszi, Hungary. Science of the Total Environment 1996; 184(3): 215–227.
8. Schroeter L, Gläβer C. Analyses and monitoring of lignite mining lakes in Eastern Germany with spectral signatures of Landsat TM satellite data. International Journal of Coal Geology 2011; 86(1): 27–39.
9. Monjezi M, Shahriar K, Dehghani H, *et al.* Environmental impact assessment of open pit mining in Iran. Environmental Geology 2009; 58(1): 205–216.
10. Liu X, Bao Y, Hu Z, *et al.* Ecological safety evaluation of land reclamation in mining area after closure. Transactions of the Chinese Society of Agricultural Engineering 2007; 23(8): 102–106.
11. Fan X, Han Y. Ecological safety assessment of Ningdong Mining Area. China Soil and Water Conservation 2011; 11: 56–59.
12. Yang J, Zhang Y, Zhou Y, *et al.* Research on ecological security evaluation of Xinjiang Zhundong Openpit Coal Mine. China Mining Industry 2015; 24(10): 76–82.
13. Pan J, Liu X. Ecological safety assessment and pattern optimization of inland river landscape based on spatial principal component and minimum cumulative resistance model: Taking Ganzhou District of Zhangye City as an example. Chinese Journal of Applied Ecology 2015; 26(10): 3126–3136.
14. Zhang J, Qiao Q, Liu C, *et al.* Study on the planning of ecological land use in Beijing based on the model of minimum cumulative drag. Acta Ecologica Sinica 2017; 37(19): 6313–6321.
15. Meng J, Wang Y, Wang X, *et al.* Construction of landscape ecological security pattern in Guiyang City based on minimum cumulative resistance model. Resources and Environment in the Yangtze Basin 2016; 25(7): 1052–1061.
16. Tan H, Zhao Y, Sun Z, *et al.* Micro-scale ecological safety assessment and optimization system for abandoned site restoration. China Environmental Science 2016; 36(7): 2169–2177.
17. Li H, Yang L, Lei J. Comparison of Landsat-8 thermal infrared data for retrieving surface temperature of rare earth mines. Journal of the Chinese Rare Earth Society 2017; 35(5): 657–666.
18. Wang S, Song Q. Risk assessment of debris flow in Jiangxi Dingnan rare earth mining area supported by spatial information. Remote Sensing Information 2012; (1): 59–63.

19. Greenberg JA, Rueda C, Hestir EL, *et al.* Least cost distance analysis for spatial interpolation. Computers and Geosciences 2011; 37: 272–276.
20. Du Y, Hu Y, Yang Y, *et al.* Building ecological security patterns in southwestern mountainous areas based on ecological importance and ecological sensitivity: A case study of Dali Bai Autonomous Prefecture, Yunan Province. Acta Ecologica Sinica 2017; 37(24): 8241–8253.
21. Li Q, Zhang Z, Wan L, *et al.* Landscape pattern optimization of the Ningjiang River Basin based on landscape ecological risk assessment. Acta Geographica Sinica 2019; 74(7): 1420–1437.
22. Wu J, Zhang L, Peng J, *et al.* Comprehensive identification of landscape ecological security patterns in Shenzhen. Acta Ecologica Sinica 2013; 33(13): 4125–4133.
23. Wei C, Zhang J, Cheng M, *et al.* Study on landscape safety pattern of Wu'an City based on Minimum Resistance Model. Resource Development and Market 2017; 33(12): 1417–1421, 1408.
24. Huang C, Yin X, Huang G, *et al.* The construction of ecological security pattern in Tong'an District of Xiamen City. Tropical Geography 2018; 38(6): 874–883.
25. Wang X, Yang L, Li H. Ecological safety evaluation of rare earth mining area based on PSRAHP Model. Journal of the Chinese Rare Earth Society 2018; 36(4): 504–512.
26. Pan J, Su Y, Huang Y, *et al.* Land use and landscape pattern change and its driving force in Yumen City in the past 30 years. Geographical Research 2012; 31(9): 1631–1639.
27. Huang Z, Fu B, Chen L. Differentiation of soil and water loss in different slopes, land use types and precipitation changes in Loess Hilly Region. China Soil and Water Conservation Science 2005; 4: 11–18, 26.
28. Li Y. County ecological land use identification and safety pattern construction based on MCR model. Chongqing: Southwest University; 2017.
29. Meng J, Wang X, Zhou Z. Comprehensive optimization of landscape pattern in arid regions: a case of the middle reaches of Heihe River. Journal of Peking University (Natural Science Edition) 2017; 53(3): 451–461.
30. Zhao Y, Tan W, Yi Q, *et al.* Construction of ecological security pattern in typical plateau lake basin: Taking the Penghu Basin as an example. China Environmental Science 2019; 39(2): 768–777.
31. Li H, Yi N, Yao W, *et al.* Ecological land use planning in Shangri-La County based on landscape safety pattern. Acta Ecologica Sinica 2011; 31(20): 5928–5936.
32. Liu J, Lü X, Yang Q, *et al.* Wetland Ecological Security Pattern Design in the Northeast of Sanjiang Plain. Acta Ecologica Sinica 2009; 29(3): 1083–1090.
33. Yu K. Sur face ecology strategic point identification method and surface model of theoretical geography. Acta Geographica Sinica 1998; 65(S1): 11–18.
34. Wu W, Lu P. Identification of key locations of land ecosystem: A case study of Huimin County in the Yellow River Delta. Hebei Agricultural Sciences 2011; 15(4): 68–72.