Assessment of Ecological Security in Rare Earth Mining Area Based on PSR Model

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Abstract

Rare earth (RE) mining activities have caused the vegetation destruction, soil erosion, soil desertification and other ecological problems. To quantitatively evaluate the eco-security of the RE mining area, we took Lingbei RE mining area in Dingnan County as study area and used the PSR (Pressure-State-Response) model and AHP (Analytic Hierarchy Process) method to construct its eco-security assessment system which was made up of 3 criterion levels and 10 factors. The results showed that the forest land had the most contribution to the eco-security in the RE mining area, and the tailings produced by RE mining had less; the average value of the eco-security in the mining area increased from 6.99 in 2008 to 7.00 in 2014. The natural growth and reclamation of the vegetation in the mining area could improve the eco-security. Vegetation destruction and exploiting RE would worsen it; mining RE would directly lead to the deterioration of the eco-security.

Key Words: RE Mining Area, Eco-security Assessment, PSR Model, AHP

1. Introduction

RE is widely used in all areas of national economic production, which is extremely important strategic resource [1,2]. However, RE mines are mostly located in remote mountainous areas with high-dense covering of forests. Their distribution are scattered and numerous, which resulted in high cost and difficulty to supervise. The disorderly and extensive mode of RE resource exploitation not only caused waste of resources, but brought a series of ecological problems such as large area land damage, vegetation destruction and soil erosion, which severely damage and threat to the eco-security of RE mining area [3]. With the continuous RE exploitation, the ecological environment problems are becoming more and more serious. And the ecological environment of RE mining area has become an important research content of eco-security.

PSR framework theory is proposed by the world economic cooperation organization (OCED), which could take different categories such as social economy, natural environment and human activities into consideration [4]. And it is a more comprehensive guidance evaluation model that is widely used in eco-security evaluation in mining area. For example, Ke X L used the PSR model and the fuzzy comprehensive evaluation method to assess the Zhengzhou coal mine eco-security [5]. Liu Y H constructed the ecological evaluation index system and made eco-security assessment of Yanzhou mining area, combined with mathematical statistics, GIS technology and PSR model [6]. Yang J J applied principal component analysis and PSR model to study eco-security of the Xinjiang Opencast Coal [7]. The special exploitation methods of RE mining area and its influence on the eco-security of mining area are different from those of other mining areas. Currently, the eco-security assessment of RE mining area is less. Therefore, selecting 2 remote
sensing images as the basic data in this research, according to the ecological conditions in the mining area, we constructs a set of eco-security evaluation system for RE mining area combined with the analysis of PSR model and AHP method, which could provide theoretical basis and technical support for the evaluation and management of the ecological environment of RE mining area.

2. Data Acquisition and Processing

2.1 Study Area

Lingbei RE Mining area is located about 20 kilometers north of Dingnan County, Jiangxi Province of China, whose longitude is from 114°58’04”E to 115°10’56”E, and its latitude is from 24°51’24”N to 25°02’56”N, by covering the area of 200 km², as shown in Figure 1. Undergoing more than 20 years of mining activities in this mining area, it led to large areas of vegetation destruction and RE tailings production.

2.2 Data Sources and Preprocessing

The data used in this study mainly include remote sensing (RS) image data, rainfall data, topographic data, soil data, land use data, and population data as shown in Table 1.

The RS imagery data has 2 scenes Landsat image with cloudless in the study area when the satellites were transiting. Their acquisition time and related information are shown in Table 2. USGS pointed out that TIRS band 11 of Landsat-8 satellite has calibration uncertainty, and TIRS band 10 is located in lower atmospheric absorption region, and its atmospheric transmittance is higher than TIRS band 11, which is more suitable for surface temperature inversion [8]. Therefore, we use TIRS band 10 to inverse surface temperature with single band.

Taking the 2008 Landsat TM image as the reference, the 2014 Landsat OLI image was registered, and geometrically corrected with quadratic polynomial method. To obtain the study area, the 2 scenes image were cut and covered with mining boundaries. The relevant DEM data was first embedded, then, it was masked to obtain the DEM data of mining area.

3. Methodologies

Based on the characteristics of RE mining area and the influence of natural factors, socioeconomic factors on the ecological environment of mining area, the factors of eco-security evaluation index in RE mining area were selected and the weight of its each index factor was determined by AHP method. The eco-security evaluation system in RE mining area was constructed by PSR model. In accordance with this system, the eco-security of RE mining area in 2008 and 2014 could be calculated and analyzed.

3.1 Construction of Eco-security Evaluation Index in RE Mining Area

The establishment of a scientific index is the basis for the evaluation of eco-security. The following table shows the data parameter of satellite in the study area.

Table 2. The data parameter of satellite in the study area

<table>
<thead>
<tr>
<th>Data Name</th>
<th>Sensor</th>
<th>Path/row</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008-12-10</td>
<td>Landsat-5 TM</td>
<td>121/43</td>
</tr>
<tr>
<td>2014-10-8</td>
<td>Landsat-8 OLI</td>
<td>121/43</td>
</tr>
</tbody>
</table>

Table 1. The data used in the study area

<table>
<thead>
<tr>
<th>Data</th>
<th>Name</th>
<th>Resource</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat</td>
<td>Google Earth</td>
<td>Geospatial Data Cloud</td>
<td>-</td>
</tr>
<tr>
<td>Daily Rainfall</td>
<td>ASTGTM2 DEM</td>
<td>Local weather station</td>
<td>-</td>
</tr>
<tr>
<td>Soil Type Distribution</td>
<td>Harmonized World Soil Database Version 1.1</td>
<td>Statistical Yearbook</td>
<td>-</td>
</tr>
</tbody>
</table>
and key of eco-security assessment in RE mining area. The choice of eco-security evaluation index depended on the actual situation of ecological environment in RE mining area, the change of potential influence factor, the influence of natural factors, and the social and economic factors with human activities as the main body. On the basis of such principles as scientific, representative, comprehensive, concise, operational, applicable and hierarchical [9], the eco-security evaluation system of RE mining area was constructed by PSR model. The evaluation system includes three levels of target, criterion and index as shown in Table 3.

3.1.1 Pressure Layer Criterion
Large areas of tailings produced by RE mining resulted in desertification in the mining area; The southern China often rains, which led to serious soil erosion in this area; with the continuous exploitation of RE and population growth, the contradiction between local people and land has become increasingly prominent. From the above, the desertification, soil erosion and population in the RE mining area caused potential pressure on its eco-security. Therefore, the pressure of eco-security in RE mining area could be expressed by population density, desertification index and soil erosion modulus. Population density could be obtained from the statistical yearbook and classified according to the world population classification criteria.

(1) Calculation of desertification index
Desertification index could be expressed by DDI in the Albedo – NDVI feature space according to Verstraete and Pinty [10] as follows:

\[ DDI = k \times N - A \]  \hspace{2cm} (1)

\[ A = a \times N + b \]  \hspace{2cm} (2)

where: \( k \) is the negative reciprocal of \( a \), \( N \) is the normalized vegetation index, \( A \) is the normalized surface albedo, \( a \) is the slope of the regression equation and \( b \) is the intercept of the regression equation on the ordinate.

(2) Estimation of soil erosion modulus
The soil erosion modulus could be obtained by the Revised Universal Soil Loss Equation (RUSLE), which is defined as follows [11]:

\[ A = K \times L \times S \times P \times R \times C \]  \hspace{2cm} (3)

where: \( A \) is the average soil loss, \( L \) is the slope length factor, \( S \) is the steepness factor, \( P \) is the factor of conservation practice, \( R \) is the rainfall erosivity factor and \( C \) is the factor of soil and water conservation measures.

3.1.2 State Layer Criterion
The state layer criterion of eco-security evaluation system is the current status or trend of eco-security in mining area. This state layer criterion includes normalized difference vegetation index (NDVI), ecological resilience and biotic abundance index (BAI).

(1) Calculation of NDVI
NDVI is used to quantitatively evaluate the vegetation coverage and growth vigor as follows [12]:

\[ NDVI = \frac{(Band4 - Band3)}{(Band4 + Band3)} \]  \hspace{2cm} (4)

where: \( Band3 \) and \( Band4 \) of Landsat RS imagery are the reflectance or luminance values of red-band and near-infrared band, respectively.

(2) Estimation of ecological resilience
Ecological resilience characterized the ability of ecosystem buffering and regulation, which is defined as follows [13]:

\[ A = B1 \times B2 \times B3 \times C1 \times C2 \times C3 \times C4 \times C5 \times C6 \times C7 \times C8 \times C9 \times C10 \]  \hspace{2cm} (5)

Table 3. Ecological security assessment index in the rare earth mining area

<table>
<thead>
<tr>
<th>Target</th>
<th>Criterion</th>
<th>Index</th>
<th>Attribute</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B1</td>
<td>C1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C2</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>C4</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C5</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C6</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>C7</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C8</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C9</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C10</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: \( C1 = \) Population density, \( C2 = \) Desertification index, \( C3 = \) Soil erosion modulus, \( C4 = \) Vegetation index, \( C5 = \) Ecological elasticity, \( C6 = \) Biotic abundance index, \( C7 = \) Landscape fragmentation, \( C8 = \) Shannon diversity, \( C9 = \) Fractal dimension, \( C10 = \) Surface temperature.
\[
\text{ECO}_{\text{net}} = \sum_{i=1}^{n}(S_i \times P_i)
\]

(5)

where: \(S_i\) is the area of \(i\)-th land use type, \(P_i\) is the elastic score of \(i\)-th land use type and \(n\) is the number of land use types.

(3) Calculation of BAI

BAI reflected the abundance degree of regional biodiversity is defined as follows [14]:

\[
\text{BAI} = A_{\text{bio}} \times \left( \sum_{i=1}^{n}(S_i \times P_i) / S \right)
\]

(6)

where: \(A_{\text{bio}}\) is normalization coefficient, \(S_i\) is the area of \(i\)-th land use type, \(P_i\) is the biological abundance weight of \(i\)-th land use type, \(S\) is the regional total area and \(n\) is the number of land use types.

3.1.3 Response Layer Criterion

The response layer criterion of eco-security evaluation system is the reflection of the RE mining area against the current environmental pressure. Landscape fragmentation, Shannon diversity, fractal dimension could quantitatively describe the composition of the landscape spatial pattern of the study area. The tailings produced by RE mining have small specific heat capacity and the characteristics of fast heat absorption and heat dissipation, which make it different from the surface temperature of other land use types. Accordingly, this response layer criterion includes landscape fragmentation, Shannon diversity, fractal dimension and surface temperature.

(1) Calculation of Landscape fragmentation

Fragmentation index \((FI)\) is used to measure landscape fragmentation as follows [15]:

\[
FI = N_p / N_c
\]

(7)

where: \(N_c\) is the total area of landscape and \(N_p\) is the total number of plaques in the landscape.

(2) Estimation of Shannon diversity

Shannon diversity \((SHDI)\) is defined as follows [16]:

\[
SHDI = -\sum_{i=1}^{n}(p_i \times \ln p_i)
\]

(8)

(3) Calculation of fractal dimension

Fractal dimension is defined as follows [17]:

\[
D = 2 \ln (P / 4) / \ln (A)
\]

(9)

where: \(D\) is fractal dimension, \(P\) is plaque circumference, \(A\) is Plaque area, and when the value of \(D\) is larger, the more complex the plaque shape is.

(4) Estimation of surface temperature

Surface temperature is defined as follows [18]:

\[
T_s = T / [1 + (\lambda \times T / \rho) \times \ln \varepsilon]
\]

(10)

\[
\varepsilon = 0.004 P_v + 0.986
\]

(11)

where: \(T_s\) is the surface temperature, \(T\) is the pixel brightness temperature detected by the thermal infrared band at the satellite height, \(\lambda\) is the central wavelength of the thermal infrared band, \(\delta\) is Boltzmann constant, \(\rho = hc / \delta\), \(h\) is Plank constant, \(c\) is light speed, \(\varepsilon\) is the surface emissivity and \(P_v\) is vegetation coverage acquired by pixel dichotomy method.

3.2 Calculation of the Weight of Eco-security Assessment Index in RE Mining Area

AHP is widely used in calculating the weights of the evaluation index system, which can make the complex problem hierarchical, and it is a flexible multi-dimensional target decision-making and statistical method [19]. Based on this method, all weights of eco-security evaluation index could be got as shown in Table 4. And the random consistency ratio of the target layer of the judgment matrix is less than 0.1.

3.3 Normalization of Eco-security Assessment Index in RE Mining Area

The index factors obtained by the above method are not comparable because the dimension is not uniform. Accordingly, it is necessary to normalize the raw data in-
index factors so that the values of all the index factors are within the range of 0 to 10 after being standardized.

The eco-security standardization for the positive evaluation factor index is defined as follows:

$$P_i = 10 \times \frac{(X_i - X_{\min})}{(X_{\max} - X_{\min})}$$  \hspace{1cm} (12)

The eco-security standardization for the negative evaluation factor index is defined as follows:

$$P_i = 10 \times \frac{1 - (X_i - X_{\min})}{(X_{\max} - X_{\min})}$$  \hspace{1cm} (13)

where: $X_i$ ($i = 1, 2, \ldots, n$) is the original value of $i$-th evaluation index, $X_{\max}$ is the maximum value, $X_{\min}$ is the minimum value and $P_i$ is the standardized value.

3.4 Estimation Evaluation Index of Eco-security in RE Mining Area

Eco-security evaluation index is obtained by weighted summing of each index factor as follows:

$$ESI = \sum_{i=1}^{n} (w_i \times x_i)$$  \hspace{1cm} (14)

where: $ESI$ is the eco-security evaluation index in RE mining area, $x_i$ is the evaluation vector of $i$-th evaluation factor, $w_i$ is the weight vector of $i$-th evaluation factor and $n$ is the number of the evaluation indexes.

At present, there are no uniform classification standards for the eco-security. Based on the existing research results, combined with the eco-security status of the RE mining area, this eco-security in study area was divided into five levels of excellent, good, moderate, poor and severe by using the natural breakpoint method [20]. A classification criteria of eco-security level was defined as Table 5.

4. Results and Discussion

The land use types in study area were divided into five categories: tailings, farmland, water, sparse forest land and dense forest land. According to the above methods, the eco-security indexes of two years in RE mining area were calculated and their eco-security level maps were drawn as Figure 2.

4.1 Eco-security of RE Mining Area

The eco-security statistics of RE mining area showed that the average value of eco-security in 2008 was 6.99, which was in good eco-security level. In 2014, its average value was 7, and it was also in good eco-security level. Therefore, the eco-security in the mining area remained relatively stable from 2008 to 2014.

The grid numbers of each level of eco-security in 2

Table 4. The weight of eco-security assessment index in the RE mining area

<table>
<thead>
<tr>
<th>Index</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$C_4$</th>
<th>$C_5$</th>
<th>$C_6$</th>
<th>$C_7$</th>
<th>$C_8$</th>
<th>$C_9$</th>
<th>$C_{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>0.0308</td>
<td>0.1846</td>
<td>0.1846</td>
<td>0.1079</td>
<td>0.0594</td>
<td>0.0327</td>
<td>0.0702</td>
<td>0.0702</td>
<td>0.0299</td>
<td>0.2297</td>
</tr>
</tbody>
</table>

Table 5. Classification criteria of eco-security level

<table>
<thead>
<tr>
<th>Year</th>
<th>Severe</th>
<th>Poor</th>
<th>Moderate</th>
<th>Good</th>
<th>Excellent</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>(0, 5.8)</td>
<td>[5.8, 6.2)</td>
<td>(6.2, 7.1)</td>
<td>[7.1, 10]</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>(0.5, 9)</td>
<td>[5.9, 6.2)</td>
<td>(6.2, 7.1)</td>
<td>[7.1, 10]</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. The 2008a and 2014a eco-security level in RE mining area.
periods were counted. Their proportions were calculated relatively and histogram was draw as Figure 3.

In 2008 and 2014, the proportion of excellent eco-security rank was the most, and its distribution was more concentrated, among which its proportion reached 41.55% in 2008, and 40.91% in 2014 (Figure 2, Figure 3). According to the classification results of RS imagery, it was found that the region of excellent eco-security rank basically corresponded to the dense forest land, which indicated that the forest land with higher vegetation coverage in the study area had the greatest contribution to the eco-security of the whole area. The proportions of moderate and good eco-security rank in 2008 and 2014 were second only to the excellent eco-security rank. The region of moderate and good eco-security rank mostly corresponded to the sparse forest land, and a few of them were orchards and farmland. In 2008 and 2014, the proportions of severe and poor eco-security rank were smaller, and their distributions were more discrete. The severe eco-security proportion in 2008 accounted for only 1.73%, compared with 1.38% in 2014, its proportion decreased. Combined with the classification result of RS imagery, the severe and poor eco-security level areas in 2008 and 2014 corresponded to the tailings produced by RE mining, which showed that the RE mining activities brought a direct threat to the eco-security of the mining area.

4.2 Eco-security Change of RE Mining Area

The eco-security change diagram was obtained from the 2008 eco-security raster minus that of 2014 as Figure 4. Five localities representing some of the most distinctive changes were chosen as shown in Figure 4. This analysis focused on the types and reasons of eco-security change within these localities. From 2008 to 2014, P1, P2 and P3 localities were improved in eco-security conditions, P4 and P5 areas were deteriorated. Combined with high-resolution Google Earth images in the corresponding regions for 2008 and 2014, P1 stood that forest grows naturally without disturbance from human activity. P2 represented that the vegetation was destructed or burnt in this area, the vegetation naturally recovered after 6 years, which improved the eco-security of the region. P3 stood the region where the tailings left over by RE mining improved the eco-security through government supported reclamation. P4 represented a direct destruction of forest land, which led to the deterioration of its eco-security, and most of the eco-security deterioration in the mining area falls into this category. P5 stood that RE was directly exploited, which worsened the eco-security of the region. To sum up, vegetation reclamation could improve the eco-security of the mining area, but the destruction of the forest land and the exploitation of RE would lead to the deterioration of eco-security in the mining area.

4.3 Eco-security of RE Mine

Representative Chenaoxia mine in Lingbei RE mining area was selected to research the eco-security of RE mine. Eco-security rank diagrams of Chenaoxia mine in 2008 and 2014 as Figure 5(i) and (ii) were clipped by its vector. And the Google Earth high-resolution RS imageries in 2009 and 2013 as Figure 5(iii) and (iv) were selected as the contrast imageries. They were close and have

Figure 3. The percentage of various eco-security level in RE mining area.
a good corresponding spatial relationship. So spatial distribution and changes of the mine eco-security level could be analyzed according to the RE ore exploitation situation of the Google Earth high-resolution RS imageries.

The RE mining areas A, B, and C in Figure 5(iii) and (iv) are highly consistent with the spatial distribution of corresponding regions of the severe eco-security level in Figure 5(i) and (ii), which shows that the tailing land produced by RE mining is the mine source region of severe eco-security level, and the RE mining activities lead to the eco-security deterioration of the mining area. From 2008 to 2014, the area of severe eco-security level decreased from 0.336 km² to 0.162 km². And the area of tailing land produced by RE mining activities has reduced accordingly in high-resolution imageries of Figure 5(iii) and (iv), such as B. Which further confirms that the mining RE activity in the mine would lead directly to the deterioration of its eco-security.

5. Conclusions

In view of process of ionic RE mining and its influence on environment, we developed a comprehensive evaluation system based on the PSR model and AHP method to assess the eco-security of RE mining area in this study. RE mining region and RE mine eco-security, and the change of RE mining area eco-security were analyze by this assessment system, which provided technical support for the evaluation and management of ecological environment in RE mining area.

The average value of eco-security in Lingbei RE mining area increased from 6.99 in 2008 to 7 in 2014. The natural growth and reclamation of vegetation in this mining area could improve the eco-security, but the felling and burning of vegetation and the exploitation of RE would deteriorate its eco-security.

In the RE mining area, the forest land has the greatest contribution to the eco-security of the mining region, and the exploitation of the RE in the mine would lead to the deterioration of the eco-security. The local government departments need to support and promote the protection and reclamation of the forest.

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References


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