Heliyon 9 (2023) e20787

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Evaluation and dynamic monitoring of ecological environment quality in mining area based on improved CRSEI index model

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ARTICLE INFO

Keywords:
CRSEI
Open-pit mining area
Ecological quality assessment
Principal component analysis

ABSTRACT

Large-scale open-pit mining in mining areas will cause serious damage to the ecological environment. Building a "green mine" is an essential part of implementing sustainable development. In order to explore the changing characteristics of the environmental quality of the open-pit mining area and provide a scientific basis for improving the ecological environment of the mining area. Taking Sijiying open-pit mining area as the research area, based on four Landsat images from 2000 to 2022, the four index components of greenness, humidity, dryness and heat were integrated, and an improved remote sensing ecological index CRSEI was constructed by principal component analysis to dynamically evaluate and monitor the ecological environment quality of the mining area. The results show that the average correlation between CRSEI and the index components is higher than the average correlation between the components, indicating that it has a favorable expression effect on the ecological quality of the mining area. The ecological environmental quality of the study area experienced a shift to the poor grade, and the poor ecological quality area was mainly distributed in industrial and mining land and construction land, with the mean CRSEI of 0.668, 0.474, 0.460 and 0.494, respectively. The results of dynamic monitoring showed that the proportion of ecological improvement area (41.43 %) was greater than that of ecological deterioration area (33.29 %) in the study area in the past 22 years, and additional restoration efforts should be made to achieve sustainable development of the ecological environment.

1. Introduction

With the rapid development of social economy and the continuous improvement of social productivity, the scale of industrial production is expanding, and the demand for mineral resources represented by coal, oil and natural gas is continuously increasing, while the violent mining activities and violent mining methods have caused great damage to the ecological environment of mining areas. Thus, a series of ecological and environmental problems such as surface vegetation destruction, surface collapse, land degradation, soil and water pollution are triggered [1,2]. In the 13th Five-Year Plan, China has made clear plans to improve the quality of the environment, the quality of the ecosystem and the ecological protection mechanism [3]. Monitoring the ecological quality of mining

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https://doi.org/10.1016/j.heliyon.2023.e20787
Received 4 August 2023; Received in revised form 6 October 2023; Accepted 6 October 2023
Available online 11 October 2023

area can better understand the destruction of ecological environment in mining area, to specify the appropriate restoration strategy.

The ecological environment quality assessment originated from the monitoring and research of environmental pollution. By the 1980s, under the guidance of the concept of sustainable development, it developed into a comprehensive evaluation and monitoring of ecosystem health and ecological quality. Table 1 lists the advantages and disadvantages of the current main evaluation methods. Early manual monitoring of mining area and its ecological environment quality is time-consuming and costly, and it is difficult to collect and process data, which is not conducive to long-term monitoring and dynamic monitoring. For example, Yang et al. [4] made a comprehensive evaluation of the ecological environment of the coal mine subsidence area by combining AHP and weighted method. Yan et al. [5] built a comprehensive evaluation index system of the ecological environment of the mining area based on Pigovian theory and correlation function method. In addition, landscape ecological pattern [6], projection pursuit model [7], spatial niche model [8,9] and evaluation model based on optimization algorithm [10] are also applied to ecological evaluation. Although compared with manual monitoring, the construction of evaluation model simplifies labor cost, it is not suitable for long-term monitoring and dynamic monitoring. The development of remote sensing technology provides development space for this field. The application of remote sensing technology can realize long-term, large-scale, real-time, and rapid dynamic monitoring of the ecological environment in mining areas, which proves information and decision-making services for environmental protection, restoration and management, and sustainable development of mining areas [11,12]. Xu [13] first proposed an ecological quality monitoring and evaluation model based on remote sensing images. In particular, the remote sensing ecological index (RSEI) was established, which is mainly based on natural factors and avoids the interference of artificial activities. The model achieved objective and reliable evaluation results of ecological quality, and excellent monitoring and evaluation effect of ecological environment quality in cities and soil erosion areas [14]. Then, the model was applied to the monitoring and evaluation of ecological environment quality in mining areas, and it achieved favorable results [15]. Tang et al. [16] took Tongling City as the research area and discussed the impact of mining development on urban ecological pattern in typical mining cities based on RSEI index. However, due to the complexity and diversity of mining environment, the RESI index periodically cannot provide sufficient information to express the level of ecological environment, and its representativeness will be affected by images and its universality is low. Therefore, in the research, scholars use more improved RSEI index to make-up for the limitations of inadequate information expression of RSEI index. For example, Nie et al. [16] evaluated the ecological environment quality of Yangquan coal mine based on the RSEI index after terrain correction, and the results showed that the terrain effect of the optimized RSEI index was significantly reduced and the ecological environment was improved. It also established the coal mine Ecology Index (CMEI) based on PSR framework [17]. Xu et al. [18] established ecological index (RE-RSEI) applicable to rare earth mining area based on Landsat images, and achieved positive results.

Due to the excellent evaluation effect and efficiency of RSEI index, based on remote sensing ecological index and combined with the actual situation of Sijiaying mining area, this paper constructs and improves remote sensing ecological index (CRSEI), analyzes the spatio-temporal variation characteristics of ecological environment quality in 2000–2022, and provides scientific basis for ecological restoration and dynamic environmental monitoring in the mining area.

2. Materials and methods

2.1. Overview of the research area

Tangshan is a typical mining city in China. The study area is located in the Sijiaying mining area in the southeast of Luan'zhou City and the Tangshan City of Hebei Province. as shown in Fig. 1. It belongs to Jidong ore lode and is an influential part of Jidong Iron ore area. The geographic range is 39°39′32″N ~39°42′51″N and 118°42′42″E ~118°46′11″E, with an area of about 1641 ha. Pingqing-da Highway passes from the west side of the mining area, with convenient transportation. The total reserves of detected ore resources are 2.348 billion tons, including 322.7 million tons of oxidized ore and 2.025.3 million tons of magnetite. It is one of the three iron mining areas in China, ranking second in Asia.

2.2. Data source and its preprocessing

The data used in this study are the Landsat remote sensing data images of multi-temporal medium-spatial resolution. A total of four

Table 1
Comparison of advantages and disadvantages of evaluation methods.

Evaluation method	advantage	shortcoming
Qualitative evaluation	Based mainly on experience and expert judgment, it is able to systematically describe and evaluate the status and changes of ecological quality	Lack of data support, strong subjectivity
Comprehensive evaluation model	Often combined with quantitative research, it can be objectively and accurately analyzed and evaluated from a multi-dimensional perspective	It needs a lot of data support, has certain subjectivity and uncertainty, and the evaluation model is not uniform, which makes it have certain limitations in practical application
Remote sensing ecological index	It comprehensively considers the impact of multiple aspects on the ecological environment, has a good evaluation result, high reliability, and has strong adaptability to different research scales and time series	The accuracy of information expression in complex regions will be reduced, which often needs to be optimized and corrected in practical application

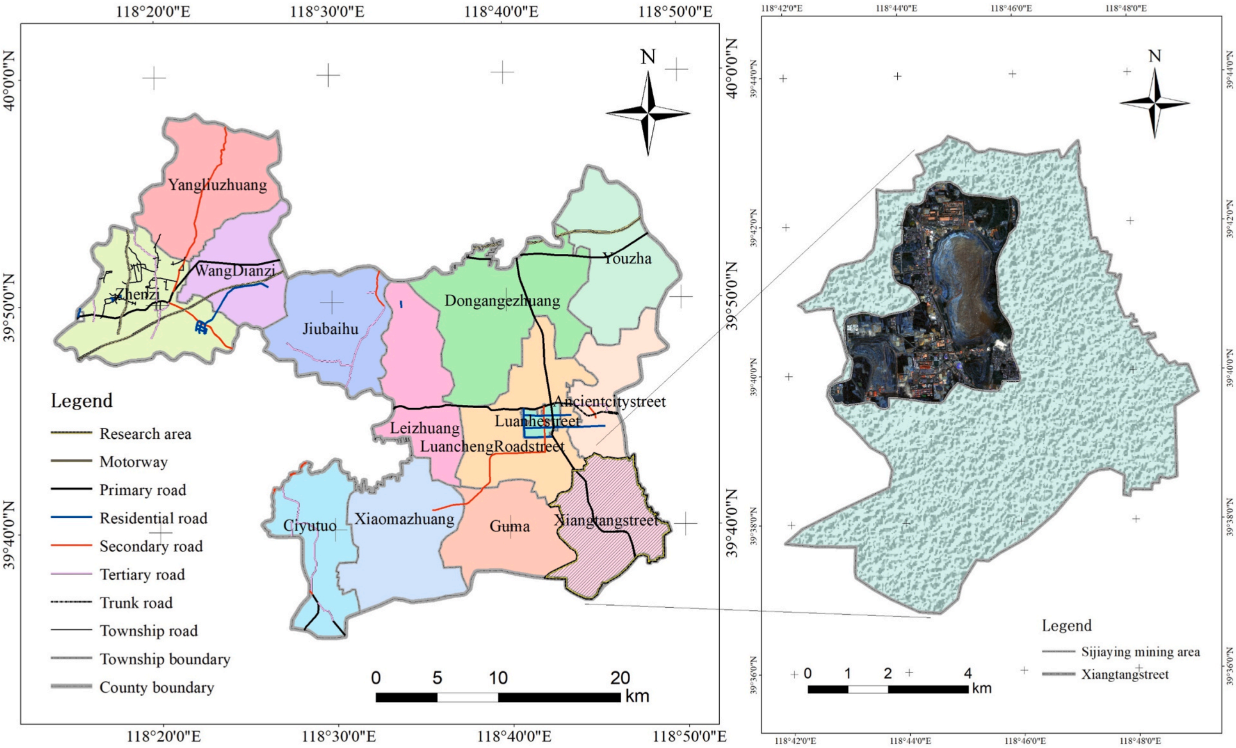

Fig. 1. The geographical location of the study area.

periods with less cloud cover and better data quality from 2000 to 2022 were selected, namely 2000, 2008, 2016, and 2022. The four periods have similar seasonal phases to avoid the impact of phenological state differences. The image data are obtained from the Geospatial Data Cloud website, where the data in 2000 and 2008 are Landsat 4–5 TM images, and the data in 2016 and 2022 are Landsat 8 OLI images. Table 2 presents the detailed information of the images.

To eliminate the impact of various disturbances and maximize useful information, a series of image preprocessing operations are required, including radiometric calibration, atmospheric correction, geometric correction, image registration, image fusion, and image cropping.

2.3. RSEI model

RSEI is a fresh index to comprehensively reflect the current situation of the ecological environment in the study area. In this study, RSEI is coupled with additional four indices that humans can intuitively judge the quality of the ecological environment, including greenness, humidity, heat, and dryness. The four indices are represented by vegetation index, humidity index, construction index and bare soil index, and surface temperature, respectively.

2.3.1. Greenness

The greenness index can directly reflect the growth and coverage of surface vegetation, and it is related to the vegetation index. As the most widely used index of plant growth status, normalized difference vegetation index (NDVI) can effectively express the changes in soil background [19]. Therefore, NDVI is selected as the greenness index in this study, and its calculation is shown in Eq. (1).

Table 2
The details of 2000–2022 remote sensing image data source.

	2000	2008	2016	2022
Satellite sensor	Landsat 4–5 TM	Landsat 4–5 TM	Landsat 8 OLI	Landsat 8 OLI
Imaging date	2000.09.06	2008.09.12	2016.08.26	2022.08.27
Strip/Line number	122/32	122/32	121/33	121/33
Resolution size	30 m	30 m	15 m	15 m
Cloud size	0	0	0.01	0.02
Number of bands	7	7	9	9
Projection indexing band	UTM Zone 50 N	UTM Zone 50 N	UTM Zone 50 N	UTM Zone 50 N
Datum plane	WGS-1984	WGS-1984	WGS-1984	WGS-1984

$$NDVI = (\rho_{nir} - \rho_{red}) / (\rho_{nir} + \rho_{red}), \tag{1}$$

where ρ_{nir} and ρ_{red} represent surface reflectance in the near-infrared band and surface reflectance in the visible red band, respectively.

2.3.2. Humidity

The humidity index reflects the state of surface water content in a region and can be used to evaluate the balance of water and heat. The humidity component obtained from the remote sensing tasseled cap transformation can well express the status of surface soil, water body, and vegetation, and reflects the changes in ecological conditions such as land degradation. Thus, the humidity component WET [20] after the tasseled cap transformation is selected as the humidity index in this study. For remote sensing images of different sensors, the calculation of the humidity index is different.

The calculation of the humidity index for Landsat TM images is Eq. (2):

$$WET_{TM} = 0.0315\rho_{blue} + 0.2021\rho_{green} + 0.3102\rho_{red} + 0.1594\rho_{nir} - 0.6806\rho_{swir1} - 0.6109\rho_{swir2}, \tag{2}$$

The calculation of the humidity index for Landsat OLI images is Eq. (3):

$$WET_{OLI} = 0.1511\rho_{blue} + 0.1972\rho_{green} + 0.3283\rho_{red} + 0.3407\rho_{nir} - 0.7117\rho_{swir1} - 0.4559\rho_{swir2}, \tag{3}$$

where ρ_{blue}, ρ_{green} , ρ_{red}, ρ_{nir}, ρ_{swir1} , and ρ_{swir2} respectively represent the surface reflectance in bands 1, 2, 3, 4, 5, and 7 of TM images and the surface reflectance in bands 2, 3, 4, 5, 6 and 7 of OLI images.

2.3.3. Dryness

The dryness index represents the degree of the surface without vegetation. With the rapid development of the economy, people's demand for iron ore resources is increasing, and mining activities become increasingly intense. As a result, the vegetation is destroyed, which makes the surface exposed. With the acceleration of urban construction, the degree of ground drying has increased. Therefore, the dryness index (normalized difference soil index, NDSI) was calculated from the average of the construction index (index-based built-up index, IBI) and the bare soil index (SI) [21]. See Eq. (4), Eq. (5) and Eq. (6) for the calculation formula.

$$IBI = \left[\frac{2\rho_{swir1}}{\rho_{swir1} + \rho_{nir}} - \left(\frac{\rho_{nir}}{\rho_{nir} + \rho_{red}} + \frac{\rho_{green}}{\rho_{green} + \rho_{swir1}}\right)\right] \Big/ \left[\frac{2\rho_{swir1}}{\rho_{swir1} + \rho_{nir}} + \left(\frac{\rho_{nir}}{\rho_{nir} + \rho_{red}} + \frac{\rho_{green}}{\rho_{green} + \rho_{swir1}}\right)\right], \tag{4}$$

$$SI = [(\rho_{swir1} + \rho_{red}) - (\rho_{nir} + \rho_{blue})] / [(\rho_{swir1} + \rho_{red}) + (\rho_{nir} + \rho_{blue})], \tag{5}$$

$$NDSI = (\mathrm{IBI} + \mathrm{SI})/2, \tag{6}$$

where, *IBI* stands for building index; *SI* is bare soil index; *NDSI* represents dryness index; Other parameters are the same as above.

2.3.4. Heat

Nowadays, heat pollution has an increasing impact on people's production and daily life. However, the heat index is not included in the ecological environment monitoring system of China. Therefore, this study replaces the heat index with the temperature index (land surface temperature, LST). The inversion methods of surface temperature include split-window algorithm, single-channel algorithm, and radiative transfer equation method. According to the actual situation of the Sijiaying mining area, a relatively stable radiative transfer equation method is employed by this study to invert the surface temperature in the research area [22]. The calculation formula is shown in Eqs. (7)–(12).

$$L_{6/10} = gain \times DN + bais, \tag{7}$$

$$P_V = (NDVI - NDVI_{soli}) / \left(NDVI_{veg} - NDVI_{soli}\right), \tag{8}$$

$$\varepsilon_{surface} = 0.9625 + 0.0614P_V - 0.0461P_V^2, \tag{9}$$

$$\varepsilon_{building} = 0.9589 + 0.086P_V - 0.0671P_V^2, \tag{10}$$

$$B(LST) = \left[L_{6/10} - L\uparrow - T\cdot(1-\varepsilon)L\downarrow\right] / T\cdot\varepsilon, \tag{11}$$

$$LST = K_2 / \ln[K_1 / \mathrm{B}(TS) + 1] - 273, \tag{12}$$

where $L_{6/10}$ represents the radiance value of the 6-th band in the TM image or the 10-th band in the OLI image; *DN* represents the gray value of the pixel; *gain* represents the gain value of the band; *bais* represents the offset value of the band; $\varepsilon_{surface}$ represents the emissivity of the natural surface pixel; $\varepsilon_{building}$ represents the emissivity of the pixel in the urban area; $B(LST)$ represents the radiance value of the blackbody; $L\uparrow$ and $L\downarrow$ represent the upward and downward radiance of the atmosphere, respectively; T represents the transmittance of the atmosphere in the thermal infrared band; K_1 and K_2 are scaling parameters. In the Landsat TM data, K_1 and K_2 are 607.76 and 1260.56, respectively; in Landsat OLI images, K_1 and K_2 are 480.89 and 1201.14, respectively.

2.3.5. Construction of improved remote sensing ecological index

The traditional RSEI is the first principal component in the results of principal component analysis. However, due to the tiny study area and the wide distribution of the industrial and mining land, mining activities have a large impact on the ecological environment, resulting in poor ecological quality. As a result, only using the first principal component cannot guarantee that most of the effective information in images is concentrated. Meanwhile, according to the principle of principal component, when the cumulative contribution reaches 85 %, the data is considered valid. To ensure a comprehensive, accurate, and reliable monitoring of the ecological quality in the Sijiaying mining area, the first principal component (PC1) and the second principal component (PC2) are taken to construct the RSEI of the Sijiaying mining area based on the cumulative contribution of the variance obtained from the principal component analysis results. Meanwhile, the direction correction of the index is carried out based on Li et al. [23]. The calculation formula is shown in Eq. (13).

$$RSEI_0 = \begin{cases} PC1 * p + PC2 * q, \mathrm{V_{NDVI}}, \mathrm{V_{Wet}} > 0 \\ 1 - (PC1 * p + PC2 * q), \mathrm{V_{NDVI}}, \mathrm{V_{Wet}} < 0 \end{cases}, \tag{13}$$

where p and q represent the contribution degree of PC1 and PC2, respectively; $\mathrm{V_{NDVI}}$ and $\mathrm{V_{Wet}}$ refer to the eigenvector values of NDVI and WET on PC1, respectively.

$RSEI_0$ is normalized so that it falls within [0, 1]. Then, the improved remote sensing ecological index called CRSEI is obtained according to the following formula. The calculation formula is shown in Eq. (14).

$$CRSEI = (RSEI_0 - RSEI_{0_{\min}}) / (RSEI_{0_{\max}} - RSEI_{0_{\min}}), \tag{14}$$

where $RSEI_{0_{\min}}$ represents the minimum value of $RSEI_0$; $RSEI_{0_{\max}}$ represents the maximum value of $RSEI_0$. The larger the value of CRSEI, the better the ecological environment quality of the Sijiaying mining.

2.3.6. Model test on the improved remote sensing ecological index

The average correlation indicates the closeness of the relationship between different objects. In correlation analysis, the correlation coefficient is calculated to represent the average correlation. The closer the average correlation is to 1, the higher the correlation is [24]. In this study, the representativeness of CRSEI is tested by establishing the correlation coefficient matrix between the four index components and CRSEI and analyzing the degree of correlation between them. If the average correlation between CRSEI and the four index components is higher than that between the four index components, it is indicated that CRSEI can comprehensively represent the four index components and can be used to describe the ecological quality in the Sijiaying mining area. The calculation formula is shown in Eq. (15).

$$\overline{C}_P = (|C_S| + |C_Q| + \cdots + |C_R|) / n, \tag{15}$$

where $\overline{C}_P$ represents the average correlation of index P; C_S, C_Q, and C_R respectively represent the correlation coefficients of index components S, Q, and R in the same period; n represents the number of indices.

2.4. Moran index

Spatial autocorrelation analysis is to analyze whether variables are clustered, discrete, or random in space. Global Moran's I index is used to analyze the spatial autocorrelation of Sijiaying mining area. The calculation formula is shown in Eq. (16).

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}}, \tag{16}$$

where I is the global Moran's index, the value range is [-1,1]. The closer the value is to 1, the higher the spatial positive correlation is; the closer the value is to −1, the higher the spatial negative correlation is; x_i, x_j is the CRSEI index and $\overline{x}$ is the CRSEI mean.

Local spatial autocorrelation is used to study the spatial distribution and agglomeration in local areas. Local Moran's I index was used to explore the spatial distribution of ecological environment quality in mining areas. The calculation formula is shown in Eq. (17).

$$I_i = \frac{(x_i - \overline{x})}{S^2} \sum_{j=1}^{n} w_{ij}(x_j - \overline{x}), \tag{17}$$

where I_i is the local Moran's I index, and the greater the absolute value of the local Moran's I index, the higher the degree of spatial agglomeration.

3. Results

3.1. Results and analysis of principal component analysis

The results of principal component analysis are shown in Table 3. In each year, the contribution of the first principal component is the largest, its value is above 60 %, and the value of the second principal component is greater than 10 %. The traditional RSEI method holds that the first principal component contains a large amount of information in the image without being affected by noise. When it reaches above 85 %, it represents most of the characteristics of the four index components and can be used to create an ecological index. However, due to the particularity of the study area, there are additional mines in Sijiaying mine area. The mining surface, storage field and transfer field occupy land resources, causing vegetation destruction and surface exposure. The results of principal component analysis show that the contribution rate of the first principal component is about 70 %, but not up to 85 %. The expression of ecological information in the mining area is insufficient, and the RSEI index constructed with the first principal component definitely cannot meet the needs of environmental monitoring in the mining area. Therefore, according to the results of principal component analysis, the RSEI index was constructed by using the weighted superposition method of the first principal component and the second principal component to reflect the ecological status of the study area. The results showed that the cumulative contribution rate of the first and second components in the four time periods could reach more than 85 %, indicating that they contained most of the characteristics of environmental information and could completely express their environmental quality level.

The results of principal component analysis showed that the green index NDVI and humidity index WET in 2000, 2016 and 2022 were negative values less than 0, while the dry index NDSI and heat index LST were positive values, while the opposite results were presented in 2008. Because the improved CRSEI index is based on NDSI and WET index to judge the direction of principal component vector, NDVI and WET play a positive role in the ecological environment of Sijiaying mining area, and the increase of their values promotes the increase of remote sensing ecological index, while NDSI and LST have a negative impact, and the increase of their values will have a reverse inhibition effect on remote sensing ecological index.

3.2. Verification of the improved remote sensing ecological index in the Sijiaying mining area

It can be seen from Table 4 that, for the four index components, the dryness index has the highest average correlation in the four years, i.e., 0.787, 0.770, 0.815, and 0.855, and the average correlation value in the four years was 0.807. The temperature index has the lowest average correlation in the four years, i.e., 0.671, 0.611, 0.661, and 0.742, and the average correlation value in the four years is 0.671. This indicates that, among the four index components, NDSI dryness is the most representative to describe the ecological environment quality in the Sijiaying mining area, and this is related to the widely distributed mines in this area. The average correlation between the CRSEI and the four index components in each year is 0.813, 0.790, 0.872, and 0.867, which is higher than that of each index component, and the average correlation in the four years is 0.836. It is 3.59 % higher than that of the highest average correlation among the index components, 24.96 % higher than the lowest average correlation among the index components, and 16.27 % higher than the four-year average correlation of the four index components (0.719). This indicates that CRSEI can well represent each index component and comprehensively reflect the ecological quality of the Sijiaying mining area.

3.3. Analysis of the ecological quality in the Sijiaying mining area

As shown in Table 5, during the 22 years of the research period, the index components of greenness and humidity in Sijiaying mining area have obvious changing trends. Specifically, the mean value of the greenness index component NDVI first decreases from 0.810 in 2000 to 0.612 in 2008 (a decrease of 24.44 %), then decreases to 0.547 in 2016 (a decrease of 10.62 %), and finally increases to 0.687 in 2022 (an increase of 25.59 %). Although the NDVI value in 2022 is improved, it is still significantly lower than that in 2000. The humidity index component WET changes from 0.505 in 2000 to 0.583 in 2008 (an increase of 15.45 %) and then increases to 0.679 in 2016 (a rise of 16.47 %). Its mean value in 2022 is 0.662, a decrease of 2.50 %. The mean value of the dryness index component NDSI first increases from 0.375 in 2000 to 0.57 in 2008 (a rise of 52 %). By 2016, NDSI has a mean value of 0.577 (a rise of 1.23 %), and it continues to increase to 0.578 in 2022 (a rise of 0.17 %). Additionally, the mean value of the heat index component first decreases from 0.484 in 2000 to 0.4 in 2008 (a decrease of 17.36 %). By 2016, the average LST had not changed at 0.4. By 2022, it continues to decrease to 0.375 (a decrease of 6.25 %). The decrease and increase of NDSI and WET correspond exactly to the rise and fall of NDVI

Table 3
Principal component analysis of each index component.

Index	2000		2008		2016		2022	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
NDVI	−0.878	−0.463	0.838	0.485	−0.901	−0.198	−0.914	−0.241
WET	−0.755	0.551	0.819	−0.3	−0.817	0.534	−0.795	0.587
NDSI	0.946	0.233	−0.944	−0.271	0.977	−0.066	0.974	−0.07
LST	0.784	−0.269	−0.708	0.588	0.840	0.389	0.84	0.375
Eigenvalue	2.851	0.644	2.766	0.745	3.140	0.503	3.122	0.547
Contribution rate	71.274 %	16.104 %	69.141 %	18.614 %	78.510 %	12.577 %	78.046 %	13.687 %

Table 4
The average correlation of each index component and between each index component and CRSEI.

Year	Index	NDVI	WET	NDSI	LST	CRSEI
2000	NDVI	1.00	0.416	−0.923	−0.559	0.959
	WET	0.416	1.00	−0.641	−0.542	0.615
	NDSI	−0.923	−0.641	1.00	0.583	−0.974
	LST	−0.559	−0.542	0.583	1.00	−0.705
	Average correlation	0.725	0.650	0.787	0.671	0.813
2008	NDVI	1.00	0.452	−0.886	−0.388	0.936
	WET	0.452	1.00	−0.705	−0.567	0.713
	NDSI	−0.886	−0.705	1.00	0.489	−0.981
	LST	−0.388	−0.567	0.489	1.00	−0.531
	Average correlation	0.682	0.681	0.770	0.611	0.790
2016	NDVI	1.00	0.551	−0.908	−0.705	0.933
	WET	0.551	1.00	−0.809	−0.550	0.718
	NDSI	−0.908	−0.809	1.00	0.729	−0.955
	LST	−0.705	−0.550	0.729	1.00	−0.881
	Average correlation	0.721	0.637	0.815	0.661	0.872
2022	NDVI	1.00	0.547	−0.909	−0.737	−0.941
	WET	0.547	1.00	−0.784	−0.504	−0.686
	NDSI	−0.909	−0.784	1.00	0.728	0.948
	LST	−0.737	−0.504	0.728	1.00	0.891
	Average correlation	0.798	0.709	0.855	0.742	0.867
Average correlation in four years		0.732	0.669	0.807	0.671	0.836

Table 5
The statistical values of each index component and improved ecological index.

Index	2000		2008		2016		2022	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
NDVI	0.810	0.154	0.612	0.153	0.547	0.200	0.687	0.165
WET	0.505	0.088	0.583	0.118	0.679	0.127	0.662	0.093
NDSI	0.375	0.208	0.570	0.174	0.577	0.169	0.578	0.17
LST	0.484	0.128	0.400	0.146	0.400	0.159	0.375	0.177
CRSEI	0.668	0.218	0.474	0.186	0.460	0.237	0.494	0.227

and LST. The changes of the four index components are directly related to the surface mining activities in the Sijiaying mining area. Due to the large area of industrial and mining land in the study area, mining activities are conducted commonly. This inevitably leads to changes in land use. Meanwhile, the surface vegetation is continuously destroyed, and the surface of the mining area is mostly exposed and continually dried. Besides, the changes in the rock structure, the force between the rocks, and the groundwater activities cause the surface temperature of the mining area to vary.

From 2000 to 2022, the CRSEI of the Sijiaying mining area showed a trend of first decreasing, then increasing, and then decreasing. The mean value of CRSEI is 0.668 in 2000 and 0.474 in 2008, indicating a decrease of 29.04 %. In 2016, the CRSEI was 0.460, and it decreased by 2.95 % between 2008 and 2016. The CRSEI in 2022 is 0.494, which increases by 7.39 % compared with that of 2016. Although CRSEI has consistently fluctuated, the CRSEI index in 2022 is better than that in 2008 and 2016, indicating that attention has been paid to and ecological environment governance has been carried out in the mining process of open pit. However, with the continuous expansion of the mining area of open pit, the governance effect is not particularly ideal, the ecological restoration and management of mining areas is a sustainable process that requires a prolonged period of persistence and governance.

As shown in Fig. 2, from 2000 to 2022, the areas with poor ecological quality in the Sijiaying mining area are mainly distributed in the industrial and mining land, followed by urban construction areas. In those areas where forest land, grassland, and cultivated land are distributed, the CRSEI has a higher value, indicating better ecological quality. According to Fig. 2(a), in 2000, because the mining area had not been developed, the areas with poor ecological quality were concentrated in residential areas and villages, and the rest areas had strong vegetation coverage and excellent ecological quality. From 2000 to 2008, As shown in Fig. 2(b), Sijiaying Iron Mine began to be put into operation, and the land area of mining areas expanded. In this period, a large number of mines are mined, and the amount of iron ore mining continues to increase, with intensified mining activities. As a result, enormous mineral wastes are accumulated, and soil and vegetation are extensively damaged, which significantly affects the surrounding environment. By 2008, the area with low CRSEI value increased significantly, and the ecological quality was severely poor. Compared with 2000, the vegetation in the eastern region has been reduced to different degrees, and the vegetation in the western region is the most critically damaged. The CRSEI index of most regions is significantly reduced, and the ecological environment is severely damaged. In 2016, the environment of the mining area showed an obvious differentiation pattern, and the quality of ecological environment in the marginal zone around the mining area was improved. As can be seen from Fig. 2(c and d), the environment in the northern and western marginal zone of the mine was restored. In 2022, the ecological environment of Sijiaying mining area was continuously restored, compared to 2016. The vegetation coverage is relatively concentrated, and the improvement of the mining area is relatively obvious, especially because the

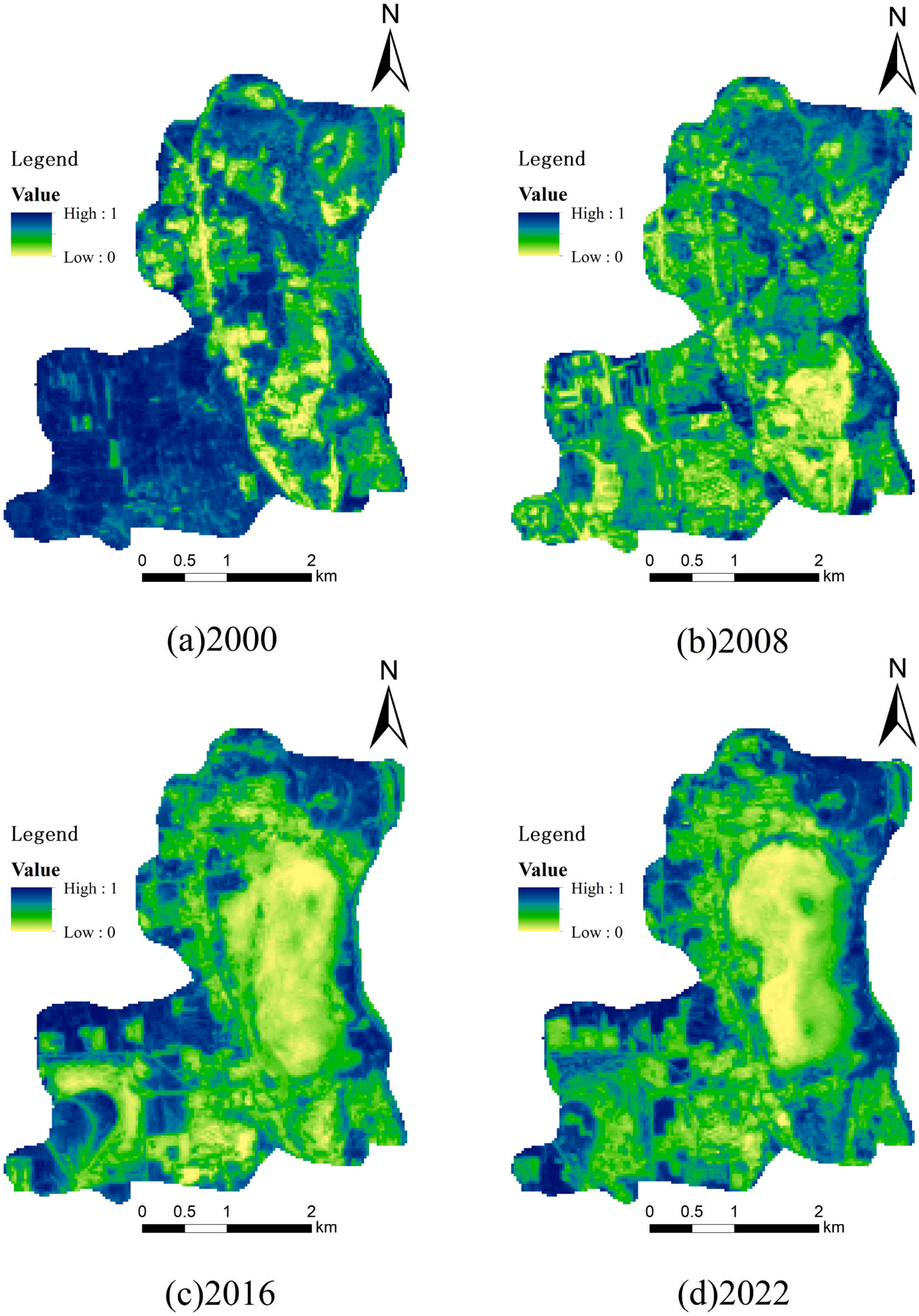

Fig. 2. The spatial distribution of the improved remote sensing index in Sijiaying.

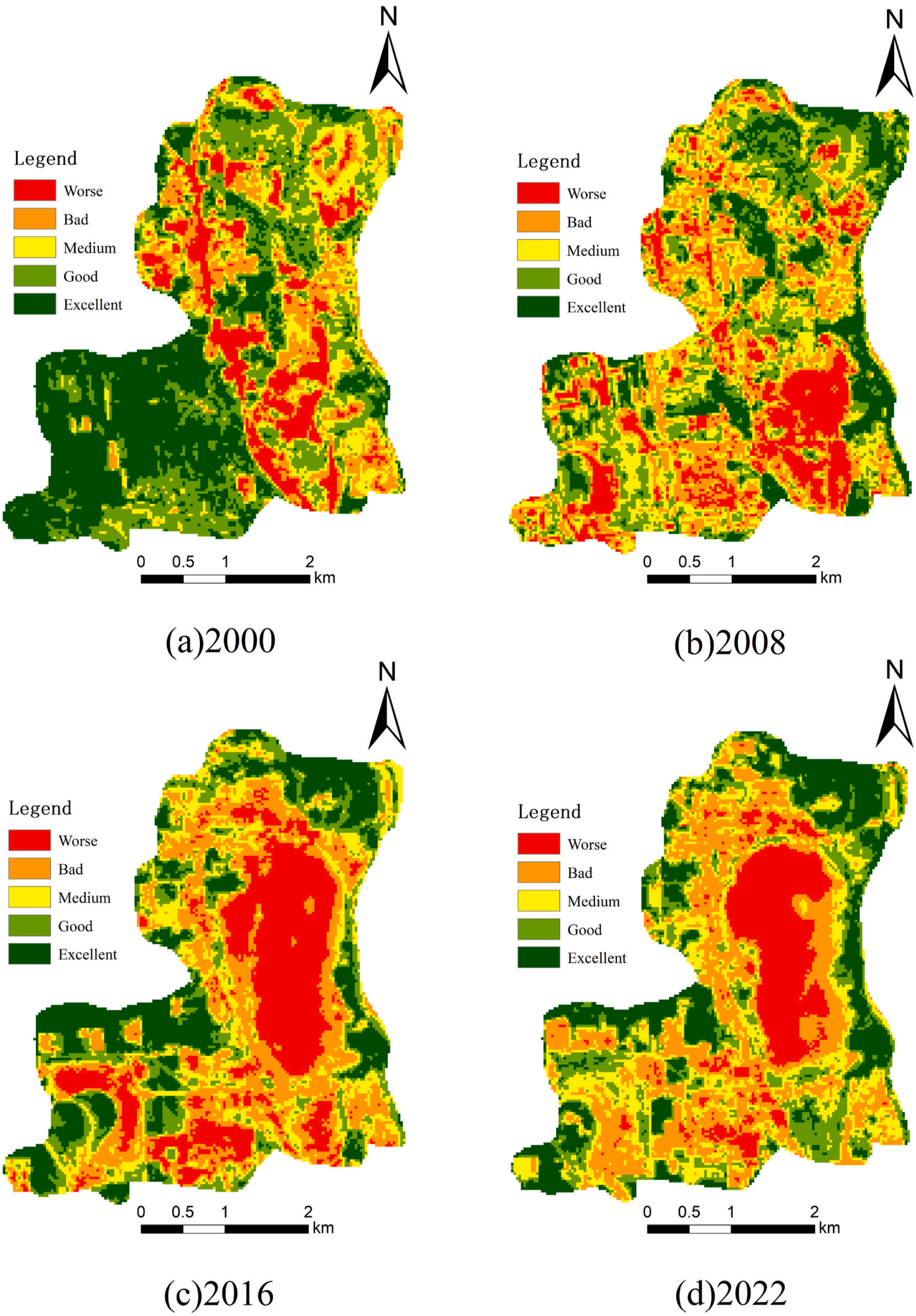

Fig. 3. Classification maps of the improved remote sensing ecological index CRSEI in Sijiaying.

ecological improvement of the southern mine has been obvious. However, due to the large scale of open-pit mining, overly substantial bare land, the overall ecological environment quality is poor.

3.4. Temporal and spatial variation analysis of ecological environment quality in mining areas

To further monitor and analyze the ecological environmental quality in the Sijiaying mining area, based on the research and analysis of the ecological environmental quality, this study classifies the spatial distribution of the CRSEI in the Sijiaying mining area. In this way, clearer and more comprehensive analysis results of the ecological environmental quality in the Sijiaying mining area can be obtained [25].

As shown in Fig. 3, the areas with poor and worse ecological quality are mainly concentrated in the industrial and mining land and construction land; The areas with medium ecological quality are mainly distributed on the edges of the industrial and mining land and urban construction land; the areas with acceptable and excellent ecological quality are mainly distributed in farmland, woodland, and grassland. According to Fig. 3(a and b), since 2000, with the continuous development of social productive forces, the demand for iron ore resources has increased considerably. As the main supplier of the Beijing-Tianjin-Tangshan Iron and Steel Base, the iron ore mining of the Sijiaying Iron Mine has continuously increased. By 2008, most of the areas with favorable ecological quality in the Sijiaying mining area were transferred, and the areas with poor ecological quality increased sharply, mainly in the Changyu Village, Xuzhaizi Village, and Xiaosiying Village in the east region, the Yinyu Village, and Duyu Village in the north region. Since 2008, the misconception of developing the economy has been first acknowledged, and ecological restoration work has been conducted in mining areas to protect the environment. By 2016, the areas with worse ecological quality have shown a great shift, i.e., shift to areas with poor ecological quality or even better ecological quality. The most obvious effect can be observed in the tailings reservoir of the Sijiaying Iron Mine and the dumpsite, and the ecological quality of the two areas changes from poor to excellent or favorable. According to the changes in Fig. 3(c and d) from 2016 to 2022, the areas of worse ecological quality continue to decrease, and their ecological environment develops to a better condition.

In this study, ArcGIS10.2 is employed to count the area and percentage of each grade of CRSEI. According to the statistical results in Table 6, the ecological quality of the Sijiaying mining area in 2000 is excellent, with an area of 505.80 ha. The areas of excellent and medium grades are comparable, i.e., 435.51 ha and 275.49 ha, respectively. The proportion of areas with poor grades is mainly related to the particularity of the numerous mines in the Sijiaying mining area. In 2008, the ecological quality changed significantly. The area of poor quality is the largest with 388.62 ha. The area of worse quality also increases rapidly, reaching 248.76 ha, an increase of 35.03 %. Correspondingly, the area of excellent grades decreases rapidly to 258.03 ha. By 2016, the area of poor grade area was still the largest, 416.34 ha, and the area of absolutely poor grade area increased rapidly to 371.34 ha, an increase of 49.27 % compared with 2008. The area of medium grade and excellent grade decreased by 23.23 % and 31.07 %, respectively. Only the area of superior grade increased to 309.78 ha, with an increase of 20.06 %, indicating that the ecological quality of Sijiaying mining area continued to deteriorate and was slightly serious with a large amount of mining, and the overall level of ecological quality was relatively low. The improvement of superior grades indicated that people began to pay attention to the restoration and management of the ecological environment. According to remote sensing image observation, vegetation reconstruction has been carried out at the edge of the mining area to improve the damaged ecological environment. In 2022, the situation improved. Although the area of poor grades is still the largest (457.38 ha), the area of medium grade exceeds that of poor grade by 348.93 ha, and the area of decent grade increases to 248.20 ha. Although the area of excellent grades declines, the overall trend develops in a positive direction.

Overall, from 2000 to 2022, the variation trend of the area of worse grade in the Sijiaying mining area increases firstly and then decreases continuously. The area ratio increases rapidly from 11.23 % to 15.16 %, then continued to increase to 22.63 %, and continues to decrease to 15.13 %. The variation trend of the area of poor grade continues to increase from 14.63 % to 23.87 %. The variation trend of the area of medium grade increases first, then decreases and then increases, and the area ratio is 16.78 %, 23.04 %, 17.68 %, and 21.26 %, respectively, and the overall proportion remains unchanged. The variation trend of the area of acceptable grade decreases firstly and then increases continuously. The area ratio is 26.54 %, 22.40 %, 15.44 %, and 17.44 %, respectively. The variation trend of the area of excellent grade first decreases, then increases and finally decreases, and the area ratio decreases from 30.82 % to 15.72 % and then increases to 18.88 %; by 2022, it decreases slightly to 18.30 %. The variation trend of each CRSEI grade is different, and there is no uniform variation trend. This indicates that the ecological environment system is unstable, which is highly correlated to the violent ground activities in the Sijiaying mining area. From 2008 to 2016, the mining activities have been intense. Since 2016, with the development of the restoration work in the mining area, the quality of the ecological environment has begun to improve. Ecological restoration and management is a long-term sustainable process, and it requires persistence. However, at the same time, the iron ore

Table 6
Sijiaying CRSEI index results and classification statistical results.

CRSEI grade	2000		2008		2016		2022	
	Area/hm^2	Percentage/%	Area/hm^2	Percentage/%	Area/hm^2	Percentage/%	Area/hm^2	Percentage/%
Worse	184.23	11.23	248.76	15.16	371.34	22.63	248.31	15.13
Bad	240.03	14.63	388.62	23.68	416.34	25.37	457.38	27.87
Medium	275.49	16.78	378.09	23.04	290.25	17.68	348.93	21.26
Good	435.51	26.54	367.56	22.40	253.35	15.44	286.20	17.44
Excellent	505.80	30.82	258.03	15.72	309.78	18.88	300.24	18.30

mining activities in the Sijiaying mining area continue. Therefore, the ecological environment is not stable, and there can be fluctuations.

4. Discussion

4.1. The degree of spatial change of ecological environment quality

Based on the classification of CRSEI, the change detection analysis is performed in this study to investigate and analyze the temporal and spatial changes of the ecological environment quality in the Sijiaying mining area from 2000 to 2022 more intuitively. Subsequently, the change information of the CRSEI from 2000 to 2022 is obtained, and the increase and decrease are categorized into four levels. A total of nine variation categories are presented in spatial locations.

As shown in Table 7, from 2000 to 2022, the area where the ecological quality of Sijiying mining area remained unchanged was 389.79 ha, accounting for 23.75 % of the total area. The ecological improvement area is 450.63 ha, accounting for 27.46 % of the total area. The area of the first level of ecological quality improvement is 262.89 ha. The area of ecological deterioration is 800.64 ha, accounting for 48.79 % of the total area. The main deterioration was a one-level decline in ecological quality, with an area of 282.15 ha. As shown in Fig. 4, the areas where the ecological quality remained unchanged and improved were mainly concentrated near Xiazuangzi village and Duyu Village in the north and Baoxing village and Xinglizhuang village in the west. The areas of deteriorating ecological quality are mainly concentrated in most areas of Changyugou Village and Xucazi village in the middle, and a modest part of Xiaopo village in the west. Continued mining activities, incomplete ecological restoration and urbanization are the reasons for the deterioration of ecological quality in these areas. Sijiaying Iron Mine was put into operation in 2007, and has huge mineral reserves, which is a fledgling iron mining area. From the preliminary exploration of the mining area, it can be seen that the first and second phases of Sijiaying Iron mine are mainly open-pit mining, and the mining scale is about 21 million tons. The design mining scale of the third and fourth phases of the South is 25 million tons, mainly using the underground filling method. The scale of mineral mining is on a trend of continuous expansion, and the environmental quality will not be optimistic for a long time in the future. Although the area of the ecological quality improvement area is smaller than that of the ecological quality deterioration area, the restoration and management of the ecological environment in Sijiaying mining area is still in progress, and the traditional model of development-destruction-management-restoration has been abandoned in the planning and design of the mining area, and the concept of green ecological construction of mining while management has been upheld, which is a long-term and sustainable process. According to the current trend, the quality of the ecological environment in the future is expected to recover to the level of 2000 or even better.

4.2. Vegetation cover change analysis of ecological environmental quality

In order to better understand the relationship between vegetation change degree and ecological environment quality during mining, a binary pixel model based on NDVI was adopted to calculate vegetation coverage in different years of the study area with cumulative frequency of 5 % and 95 % as thresholds, and according to the classification and Classification Standard of Soil Erosion issued by the Ministry of Water Resources of China, the vegetation coverage classification standard was calculated. Vegetation coverage is divided into five levels, as shown in Fig. 5:

According to the change trend of Fig. 5(a, b, c, d), it can be seen that vegetation coverage in the study area decreased significantly during 22a, especially in the central and western regions, there was a significant decrease in FVC in the study area during 22a, especially in the central and western regions. The average FVC in the four years was 0.68, 0.51, 0.48 and 0.47, respectively, and the FVC showed a downward trend, especially in the event period from 2000 to 2008. Then the vegetation coverage decreased gradually, but the shift was not large. It is worth noting that according to the results of CRSEI, the ecological environment quality in 2022 is better than that in 2008, but the trend of vegetation coverage reduction has not changed significantly. Although vegetation coverage is not the only standard to measure ecological environment quality, this minor shift is still worth our attention. In mining activities, attention should be paid to the encroachment of vegetation to prevent irreversible damage to the original ecosystem due to excessive vegetation.

Table 7
The statistics of the CRSEI grade variations in Sijiaying from 2000 to 2019.

Category	Grade	Grade area/hm2	Category area/hm2	Percentage/%
Ecological deterioration	−4	47.34	800.64	48.79 %
	−3	199.80		
	−2	271.35		
	−1	282.15		
Ecological non-change	0	389.79	389.79	23.75 %
Ecological improvement	+1	262.89	450.63	27.46 %
	+2	126.90		
	+3	52.38		
	+4	8.46		

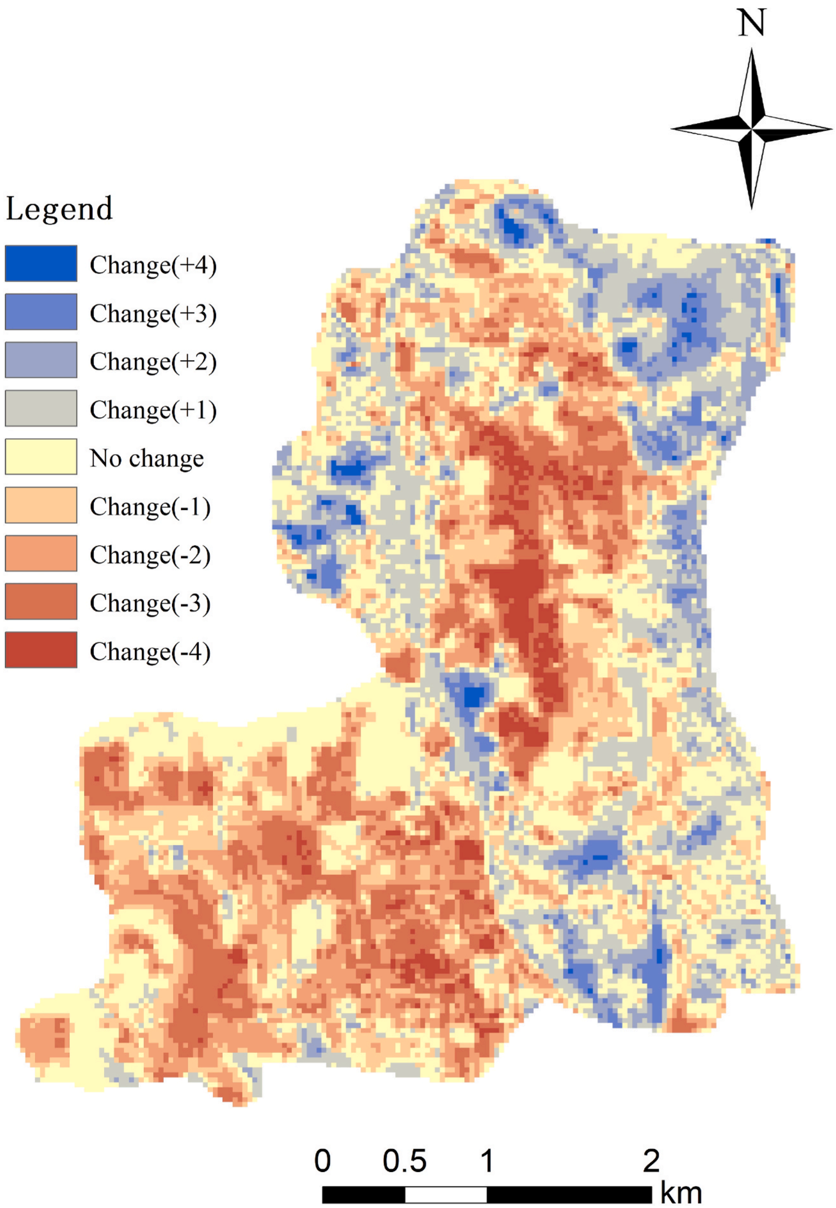

Fig. 4. The distribution of the CRSEI grade variations in Sijiaying from 2000 to 2022.

4.3. Spatial autocorrelation analysis of ecological environmental quality

According to CRSEI index results, Moran's I index and LISA cluster analysis were used to conduct spatial autocorrelation analysis for the study area. The value of Moran's I index for each year is calculated according to Eq. (16). The calculation results in Fig. 6(a, b, c, d) show the size and distribution of the index, scatter points were mainly distributed in the first and third quadrants, while the second and fourth quadrants were less distributed, which indicated that the spatial distribution was mainly positive correlation, that is, the adjacent samples were similar. The values of Moran's I index in the four years were 0.916, 0.875, 0.948 and 0.939, respectively. From the overall trend of shift, the spatial aggregation degree of samples in Sijiaying mining area showed a fluctuating upward trend.

Based on formula (17), the LISA cluster map of the study area is drawn according to the local Moran's I index, and the clustering characteristics of the spatial distribution of the study area are explained. According to Fig. 7, the study area is mainly dominated by low-low clustering and extreme-elevated clustering. According to Fig. 7(a), in 2000, the spatial clustering characteristics were relatively scattered, except for the non-industrial and mining area in the west, which became extreme-elevated clustering, and the remaining areas were dominated by low-low clustering. According to Fig. 7(b), In 2008, the low-low cluster area expanded, which was in the operation and production stage of the mining area, and the mining surface expanded considerably, resulting in a significant

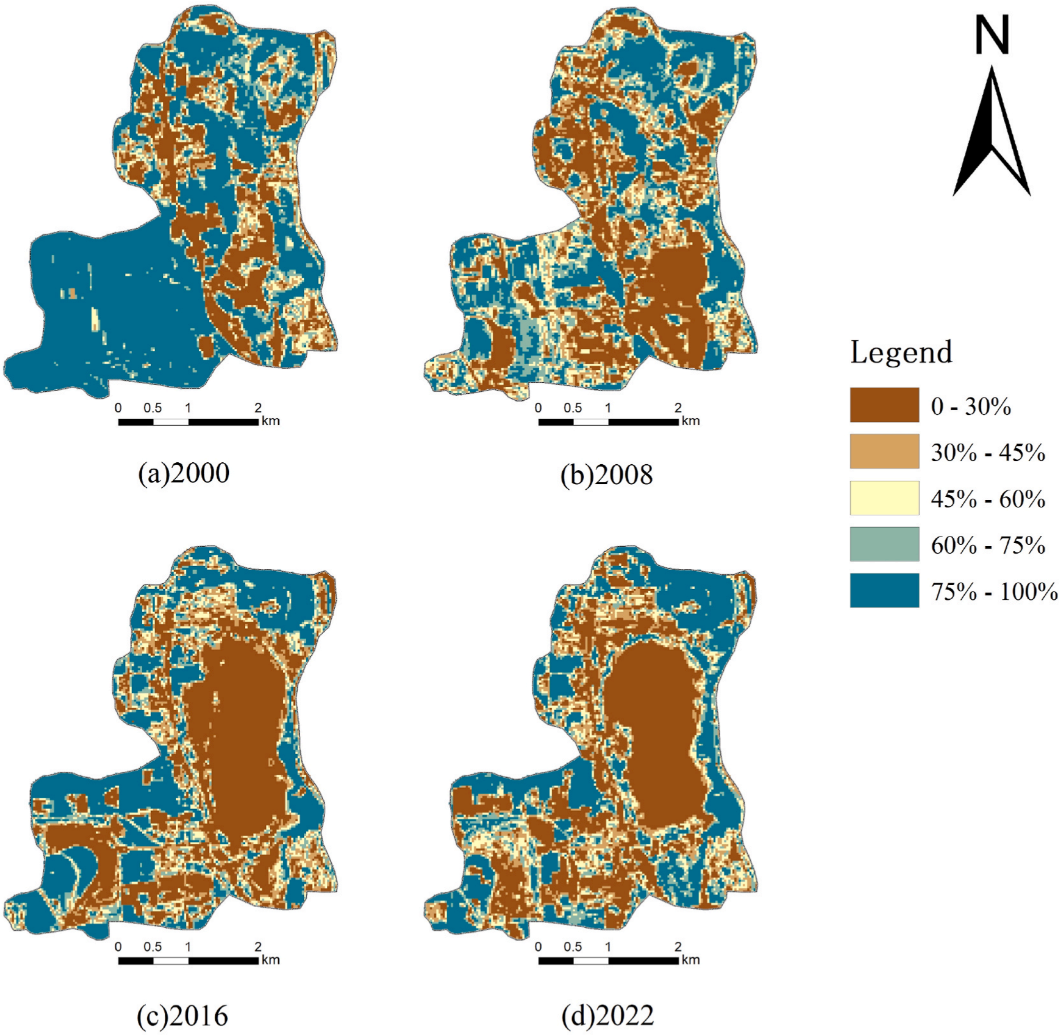

Fig. 5. Change distribution of vegetation coverage level in Sijiaying area from 2000 to 2022.

decline in the ecological quality of the western region. By analyzing the distribution characteristics of Fig. 7(c and d), it can be seen that aggregation characteristics in 2016 and 2022 were similar, and the edge zone of the mining area and the central area of the industrial and mining area formed obvious distribution and aggregation characteristics. It can be obviously seen that the expansion of mining scale has a significant impact on the environment. The extreme-elevated clustering distribution in marginal areas is primarily due to the restoration mode of mining edge restoration, which alleviates the environmental pressure caused by the expansion of mining surface scale.

4.4. *Limitations of traditional RSEI model and advantages of improved model*

RSEI index is a general environmental assessment index, which is widely used in regional ecological environment assessment and sequence change. However, a wide range of applications also means that it is not targeted. The traditional remote sensing ecological index uses the first principal component of principal component analysis to construct the ecological index. However, for a mining area with a limited range, the regional environment is complex and the functional zoning is obvious, so the first principal component cannot sufficiently concentrate most of the characteristics of the index component. The traditional RSEI index cannot reflect its real state. In this paper, based on the traditional RSEI index model and the four indexes of greenness, humidity, dryness, and heat, the first and second principal components of principal component analysis were used to construct the improved remote sensing ecological index. The total contribution rate of PC1 and PC2 from 2000 to 2022 was above 85 %, and most of the information of each ecological factor was integrated. The constructive effect of factors on the ecological index is judged by the direction of eigenvalue. The results are satisfactory and can effectively express the change of ecological environment in the mining area. The improved remote sensing ecological index inherits the traditional ecological index research method, provides a new research idea for the ecological environment

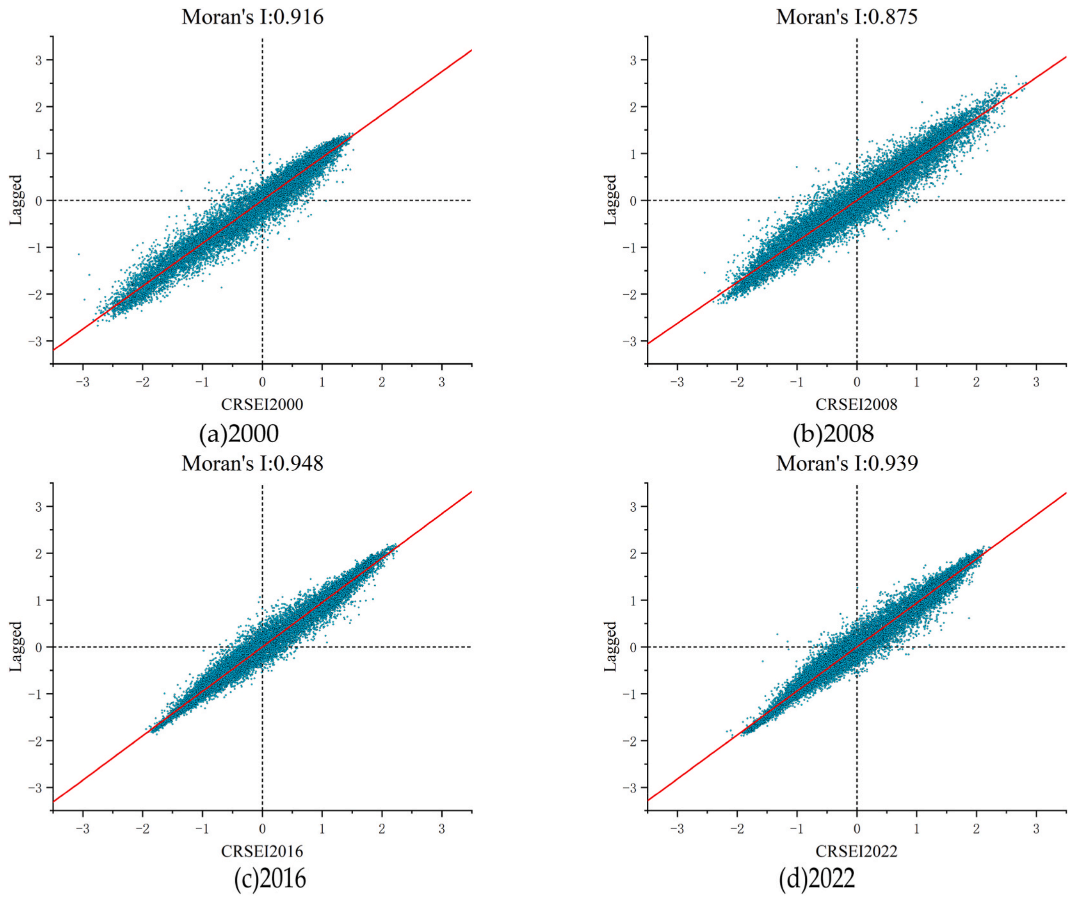

Fig. 6. Moran's scatter plot of CRSEI Index in mining area from 2000 to 2022.

evaluation of mining areas, and can be applied to the ecological environment quality evaluation of open-pit mines.

4.5. Future outlook

Mining has caused a lot of pollution and landscape damage to the regional environment. In addition, the waste of land resources and the potential safety hazard of geological disasters indicate the necessity of ecological restoration. Therefore, mine ecological restoration is imperative. Although we did not pay much attention to the ecological restoration and management of mines in the early stage of human industrial development, with the environmental crisis we are facing and the popularity of the concept of sustainable development, the environmental management of mines should not only include the restoration of abandoned mines, but also implement the mode of parallel mining and management for mining mines. Mine ecological restoration should not only emphasize technology and techniques, but also pay attention to the establishment of management system, regulate and manage ecological restoration and management from the legal level, so that the ecological restoration of mining areas under the auxiliary management of self-repair and maintenance, return to nature, and build a stable ecosystem.

5. Conclusion

By improving the remote sensing ecological index, the ecological environment quality of Sijiaying mining area during 2000–2022 was evaluated and analyzed, and the following conclusions were drawn:

(1) Using the four index components of greenness, humidity, dryness, and heat, the principal component analysis method was used to analyze the improved remote sensing ecological index CRSEI, and it was found that the four-year average correlation coefficient between CRSEI and the four index components was higher than the four-year average correlation coefficient between the four index components and the four index components. Therefore, CRSEI has a favorable expression on the ecological quality of Sijiaying mining area.

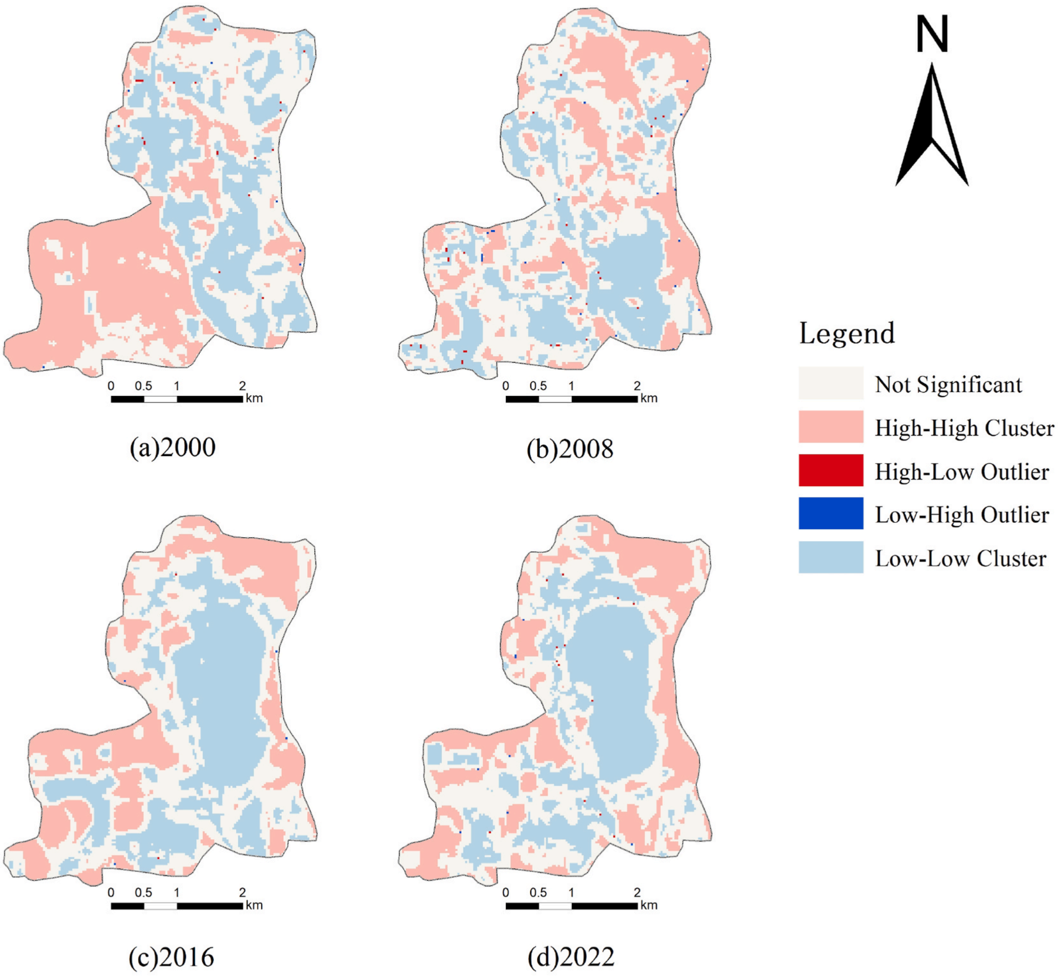

Fig. 7. LISA cluster map of Sijiaying mining area from 2000 to 2022.

(2) During 2000–2022, the mean values of CRSEI were 0.668, 0.474, 0.460, and 0.494, respectively. The ecological quality of the study area was excellent in 2000, poor in 2008 and 2016, and medium in 2022. Although the CRSEI value in 2022 is lower than that in 2000, the grade is mainly medium, but the ecological environment tends to improve.
(3) The change detection and analysis based on CRSEI level show that the deterioration area is larger than the improvement area, and the vegetation coverage continues to decrease, which is caused by continuous mining activities. However, since ecological restoration is a continuous and long-term process, mining activities should be conducted in a standardized and scientific way, and the strengthening of ecological restoration and management should continue.

Author contribution statement

Supported by the National Natural Science Foundation of China (52274166).

Data availability statement

Data included in article/supp. material/referenced in article.

CRediT authorship contribution statement

Yajing Liu: Conceptualization, Funding acquisition, Methodology. **Hongjian Liu:** Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing. **Chaoqun Yan:** Formal analysis, Investigation, Supervision. **Zhengwen Feng:** Project administration, Supervision. **Shuai Zhou:** Supervision, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Tangshan Key Laboratory of Remote Sensing of Resources and Environment, Hebei Institute of Mining Ecological Restoration Industry Technology and Hebei Key Laboratory of Mining Development and Safety Technology provided assistance for this project.

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