Postprint: Process Analysis of Land Damage and Reclamation in Coal Mining Areas Based on Ecological Risk Assessment

Authors: Sun Qi, Bai Zhongke, Cao Yingui

Date: 2017-11-09T00:00:00+00:00

Abstract

Coal mining and reclamation activities induce intense land surface changes and ecological environmental disturbances. This study takes the Pingshuo mining area in Shanxi Province as a case study and analyzes the dynamic changes of ecological risk in coal mining areas by constructing an evaluation model. Specifically, the minimum cumulative damage model is adopted to calculate the cumulative damage impact value of risk sources, while remote sensing imagery combined with field measurement data is utilized to compute the ecological vulnerability index. The ecological risk values of the mining area for 2001 and 2010 were thus obtained, and the changes in ecological risk due to mining and reclamation activities across different mining years were analyzed. The results demonstrate that with increasing coal production, the cumulative impact area of land damage in 2010 expanded by 7,095.17 hm^2 compared to 2001. However, the cumulative damage hazard of reclaimed waste dumps decreased significantly, and as the disturbance area of the mining area shifted eastward, the impact of mining on the western part of the study area also diminished. Following 10 years of land reclamation and ecological reconstruction measures, the ecological risk values of reclaimed waste dumps exhibited a declining trend, and the ecosystem tended toward stability. In the mining disturbance area, the proportion of regions at medium risk and below was 0.02% in 2001, which increased to 16.77% in 2010. Although extra-large coal mining areas exhibit extensive disturbance ranges, post-mining land reclamation contributes to reducing the impact of local ecological risks. By investigating land damage conditions, reclamation processes, and post-reclamation status in mining areas, and analyzing the dynamic changes of ecological risks across different regions, this study can provide references for ecological environment management and regional development planning in mining areas, as well as a scientific basis for mining area management and related decision-making.

Full Text

Process Analysis of Land Destruction and Reclamation in Coal Mining Areas Using Ecological Risk Assessment

SUN Qi[1], **BAI Zhongke**[1,2]**,** CAO Yingui**[1,2]
(1. School of Land Science and Technology, China University of Geosciences, Beijing 100083, China;
2. Key Laboratory of Land Consolidation and Rehabilitation, Ministry of Land and Resources, Beijing 100035, China)

Abstract: Coal mining and reclamation activities cause intense surface changes and ecological disturbances. This study used the Pingshuo Mining Area in Shanxi Province as a case study to analyze the dynamic changes in ecological risk in coal mining areas through the construction of an evaluation model. The minimum cumulative destruction model was employed to calculate the cumulative destruction impact values of risk sources, while remote sensing imagery combined with field measurement data was used to calculate the ecological vulnerability index. The ecological risk values for the mining area in 2001 and 2010 were obtained to analyze changes in ecological risk caused by mining and reclamation activities across different mining years. The results showed that with increasing coal production, the cumulative impact area of land destruction in 2010 increased by 7,095.17 hm^2 compared to 2001. However, the cumulative hazard of reclaimed dumps decreased significantly, and as the disturbed area of the mining area shifted eastward, the impact of mining on the western part of the study area also weakened. After 10 years of land reclamation and ecological reconstruction measures, the ecological risk values of reclaimed dumps showed a downward trend, and the ecosystem tended to stabilize. In the mining-disturbed area, regions at medium risk and below accounted for 0.02% in 2001, increasing to 16.77% in 2010. Although large-scale coal mining areas have extensive disturbance ranges, post-mining land reclamation helps reduce local ecological risk impacts. By studying land destruction conditions, reclamation processes, and post-reclamation status in mining areas, and analyzing the dynamic changes in ecological risk across different regions, this research can provide references for ecological environmental management and regional development planning in mining areas, offering a scientific basis for mining area management and related decision-making.

Keywords: Ecological risk assessment; Ecological vulnerability; Land destruction; Land reclamation; Coal mining area

As an important component and scientific support for environmental risk management, ecological risk assessment represents a key focus and challenge in current environmental management. Previous research has demonstrated that mining and energy production activities trigger a series of ecological and environmental problems that threaten regional ecosystem stability and sustainability.

Scholarly studies on ecological risk assessment in mining areas have primarily focused on heavy metal pollution risk assessment and landscape risk assessment based on land use changes, attempting to explore the probability and severity of ecological risks through risk occurrence probability, ecological loss degree, ecological carrying capacity, and landscape pattern indices. With intensifying land disturbance from mining activities, research on ecological risk in mining areas continues to deepen, and the exploration of quantitative evaluation methods has become a trend in China’ s mining area ecological risk research.

Mining activities place land use types in mining areas in a rapid state of dynamic change. Land destruction in mining areas serves as a risk source, and its potential harm to ecosystems represents cumulative risk over a certain period. Static landscape ecological risk assessment results are unsuitable for characterizing the organization and renewal of mining area ecosystems. Therefore, it is necessary to quantify ecological risk assessment indicators from a sustainable development perspective to reflect the dynamic changes in mining area ecological risk. Scholars’ ecological environment evaluations of mining areas have primarily focused on applying life cycle theory to evaluate mining cities at different development stages, with remote sensing data mostly used to identify landscape dynamic change characteristics. Research analyzing ecological risk changes in mining areas from spatiotemporal variation trends remains scarce. Under the global environmental situation and China’ s institutional context of balancing economic development and ecological protection, studying land destruction conditions, reclamation processes, and post-reclamation status in mining areas, and conducting ecological risk assessments of potential reclamation areas can provide decision-making references for ecological environmental management and regional development planning in coal mining areas.

Most of China’ s coal resources are located in arid and semi-arid ecological vulnerable zones. During mining, mining areas inevitably cause large-scale surface excavation and subsidence, repeated destruction, soil ecological damage, vegetation loss, soil erosion, and land and water pollution. This study used the Pingshuo Mining Area in Shanxi Province as a case study, utilizing Landsat TM imagery data from 2001 and 2010, combined with surface land destruction characteristics in the mining area and ecological environmental changes caused by mining and reclamation activities, to analyze the process characteristics of ecological risk changes in the mining area over a certain period.

1.1 Study Area Overview

The Pingshuo Mining Area is located in Pinglu District, Shuozhou City, northern Shanxi Province. It has a temperate semi-arid monsoon climate with an average annual temperature of 4.8–7.8°C and annual precipitation of 428.2–449.0 mm. The vegetation type is grassland. The zonal soils are chestnut soil and cinnamon soil, with low organic matter content, poor structure, and weak erosion resistance. This area represents the most severe soil erosion region in the Sanggan River Basin. Additionally, strong winds occur frequently during winter and spring seasons, leaving the surface dry. The ecosystem in this area has poor resistance and resilience, representing a typical ecologically vulnerable zone on the Loess Plateau. The Pingshuo Mining Area is a large-scale combined open-pit and underground mining area, currently containing three large open-pit mines and three underground mines at different mining stages, covering nearly 160 km². The landform consists of loess low hills at elevations of 1,300–1,400 m. Since 2001, production in the mining area has shown a continuous and stable growth trend, with raw coal output increasing from 21.8 million tons in 2001 to 103.88 million tons in 2010, representing a 4.77-fold increase with an average annual growth of 11.74 million tons. By 2010, the reclaimed land area in the mining area reached 1,084.87 hm², accounting for 33.45% of the existing dump area. The main reclamation types were arbor woodland and shrub woodland.

1.2 Data Sources

This study used TM imagery from 2001 and 2010 as the primary data sources, specifically Landsat 5 platform data from August 20, 2001, and July 12, 2010. Using ENVI 4.8 software as the operating platform, the imagery underwent preprocessing including atmospheric radiometric correction, geometric correction, and image clipping. Artificial neural network classification was employed for land use classification.

presents the ecological risk evaluation index system for the mining area. The diffusion cost coefficient (SRI) can be calculated using the Cost Distance module in GIS. The higher the cost value of any unit, the more conducive it is for that unit to resist external risks. Drawing on land use type classification in landscape evaluation, cost values were assigned as follows: forest land = 1, grassland = 0.6, cultivated land = 0.4, residential areas = 0.3, bare land = 0.2, and mining land and transportation facilities = 0.

2.2.2.2 Ecological Vulnerability Assessment

The selection basis and calculation methods for each indicator of risk receptor ecological vulnerability are as follows:

1) **Wetness Index (WET):** Monitoring soil moisture and its variation patterns in mining areas can provide basic information for restoring original landforms and vegetation cover. The index was extracted using the formula proposed by Crist, and soil moisture information for the study area was retrieved using the Temperature Vegetation Dryness Index method based on vegetation index information and surface temperature information.

2) **Bare Soil Index (NDSI):** This index is synthesized from the pure bare soil index (SI) and building index (IBI), as the study area contains not only pure bare soil but also a considerable portion of industrial land with hardened surfaces. Specific indicator selection and calculation methods reference the index calculation method proposed by Xu Hanqiu.

3) **Vegetation Coverage:** Vegetation coverage can serve as a quantitative factor for agricultural, environmental remote sensing monitoring, and evaluation analysis. Unlike simply emphasizing green area, vegetation coverage better reflects plant functional attributes and ecosystem health. Drawing on previous research results, this study considered pixels with NDVI > 0.5 as pure vegetation pixels and pixels with NDVI < 0.2 as pure bare soil pixels. Vegetation coverage (Pv) was calculated using the following formula:

$$NDVI_{NDVI}$$

Where: NDVI_max takes a value of 0.5, and NDVI_min takes a value of 0.2.

4) **Ecosystem Service Value:** Land use type is one of the most common landscape expression methods, which can intuitively express human activity processes. This study used ecosystem service value for assignment. Scholars have proposed ecosystem service value equivalents for Shanxi Province based on regional characteristics, while mining area ecosystems have certain particularities. By referencing previous research, ecosystem service values for different land use types were obtained (Table 2).

5) **Soil Erosion Degree:** Soil erosion degree reflects soil stability. Due to mining and dumping activities causing intensified soil erosion, soil erosion in the study area includes wind erosion, water erosion, and engineering erosion, with consideration factors including slope and vegetation coverage. Based on historical statistical data, materials, and maps from the Pingshuo Mining Area, soil erosion in different regions of the study area was determined. Areas with (0 CE < 0.35) are original landforms far from mining development disturbance. The ecological vulnerability calculation method is as follows:

Where: EVI_i represents the ecological vulnerability index on any pixel in the open-pit mine, V_jW represents the weight of each indicator, i_jV is the standardized value of V_ij, V_ij is the corresponding indicator value, j represents the evaluation indicators in ecological vulnerability assessment, and i is a 30 m × 30 m pixel.

2.2.3 Mining Area Ecological Risk Assessment

Drawing on the ideal landscape vector model, the ecological risk assessment calculation method is as follows:

$$ERV_i = EVI_i \times CE_i$$

Where: ERV_i is the ecological risk value on the spatial unit of the study area, EVI_i is the ecological vulnerability value, CE_i is the cumulative land destruction effect value, and i is a 30 m × 30 m pixel unit.

To further illustrate the spatial distribution differences of ecological risk values and changes between land disturbance types, two profile lines were established in the study area, passing through eight types of areas: original landform, reclaimed dump, industrial site, unreclaimed dump, underground mining, combined open-pit and underground mining area, open-pit mining area, and stripping area (Figure 1 [Figure 1: see original paper]). Ecological risk values in different areas were analyzed along these profiles.

3.1 Mining Area Land Destruction Ecological Risk Accumulation

With the advancement of mining activities, the area and types of land disturbance in the study area expanded (Figure 1 [Figure 1: see original paper]). From 2001 to 2010, open-pit mining caused extensive land stripping, excavation, subsidence, occupation, and encroachment, transforming original landforms into stripping areas, mining pits, and dumps. The newly added land destruction area was 2,767.79 hm^2, with the open-pit mining area increasing by 428.09 hm^2 and the unreclaimed dump area increasing by 1,281.32 hm^2, including 1,449.04 hm^2 of secondarily destroyed dumps. By 2010, the study area had reclaimed 1,084.87 hm^2 of dumps, with a ratio of reclaimed to destroyed land of 1:4, lower than the 1:3 ratio in 2001. During the study period, the average annual reclamation area was 46.93 hm^2, while the average annual land destruction area was 276.78 hm^2, indicating that reclamation speed lagged behind land destruction speed. In terms of annual changes in land disturbance types, the stripping area changed most dramatically from 2001 to 2010 with an average annual change rate of 16.92%, followed by unreclaimed dumps at 14.61%.

The spatial distribution and regional extent of land destruction cumulative hazard values (CE) changed significantly from 2001 to 2010 (Figure 2 [Figure 2: see original paper]). In both 2001 and 2010, high-value areas (0.7 CE $<$ 1) were stripping areas, mining areas, and industrial sites. Medium-value areas (0.35 CE $<$ 0.7) were unreclaimed dumps and nearby original landforms. Low-value areas (0 CE $<$ 0.35) were original landforms far from mining development disturbance. With increased coal production and the commissioning of underground coal mines and the eastern open-pit mine in the northeastern part of the study area, the cumulative impact range of land destruction (CE $>$ 0.35) reached 24,113.23 hm^2 in 2010, an increase of 7,095.17 hm^2 compared to 2001. Notably, the cumulative destruction values of reclaimed dumps decreased significantly, and as the disturbed area of the mining area shifted eastward, the impact on the western part of the study area weakened.

3.2 Mining Area Ecological Vulnerability Index Analysis

The ecological vulnerability evaluation indicators for the mining area were divided into five levels (Table 3) to quantitatively reveal area changes of the five indicators during the two study periods. In 2001, the WET index was mainly distributed between 0.4–0.8, while in 2010 it was mainly distributed between 0.6–1.0, showing an overall increasing trend. Specifically, the area in the 0.8-

1.0 range increased by 8,394.91 hm^2 in 2010 compared to 2001. The NDSI index was mainly distributed in the 0.4–1.0 range in 2001 but shifted to lower value regions in 2010, primarily distributed between 0.2–0.8, with a significant increase in medium-value area (0.4–0.6) in 2010. The distribution of vegetation coverage across different value ranges remained relatively stable between the two periods, but overall vegetation coverage showed a declining trend in 2010 compared to 2001, with a substantial increase in area with vegetation coverage less than 20%. The low-value area (0–0.4) of ecosystem service value in the mining area doubled in 2010 compared to 2001. From 2001 to 2010, due to coal mining, large areas of original landform cultivated land, forest land, and grassland were converted into stripping areas, open-pit pits, and dumps, leading to decreased ecosystem service capacity. The area in the 0.4–0.6 range also showed a declining trend, as reclaimed land was more suitable for priority restoration to forest and grassland, resulting in reduced cultivated land area. High-value area changes were not significant, as the destruction and restoration levels of forest and grassland in the study area were basically balanced. The original landform of the study area experienced both wind and water erosion, but engineering erosion caused by mining activities was more severe than in the original landform. With the expansion of dump areas, the area with severe soil erosion (0.6–1) also increased.

Interactive analysis with the disturbance change map of the study area (Figure 1 [Figure 1: see original paper]) helps understand the degradation and improvement of the mining area' s ecological environment. As shown in Figure 3 [Figure 3: see original paper], stripping areas and unreclaimed dumps have high ecological vulnerability values, but these values change spatially with the advancement of mining activities and implementation of reclamation projects. These areas basically have no surface vegetation composition, poor water retention capacity, severe soil erosion, and are prone to geological instability, soil erosion, and dust pollution problems. The ecological vulnerability intensity in industrial site areas showed no significant change, manifesting as area expansion in space. The evaluation results for reclaimed dumps were more complex, showing overall low ecological vulnerability and demonstrating positive change trends, with local ecosystem stability being superior to the original landform. Specifically, the ecosystem recovery in the reclaimed inner dump, west dump, and south dump of Antaibao was excellent. A few moderately vulnerable areas were affected by unscientific early dumping technology and improper later management: the southwestern area of the south dump experienced large-scale vegetation death due to gangue spontaneous combustion, with large areas of exposed topsoil and concrete slurry overflow from grouting fire extinguishing operations; some areas of the west dump experienced vegetation degradation due to fire impacts. Changes in ecological vulnerability reflect alterations in mining area ecosystem structure and function accompanying vegetation disappearance and reconstruction and significant soil structure changes.

3.3 Spatial Heterogeneity of Mining Area Ecological Risk

The natural breaks method in ArcGIS was used to classify ecological risk values (ERV). The break points for 2001 were [0.00, 0.13, 0.26, 0.40, 0.53, 0.66, 0.79, 1.00], and for 2010 were [0.00, 0.29, 0.40, 0.50, 0.61, 0.71, 0.82, 1.00]. Based on these, ERV was divided into four levels: high-risk area (0.71 $<$ ERV 1), relatively high-risk area (0.50 $<$ ERV 0.71), medium-risk area (0.26 $<$ ERV 0.50), and low-risk area (0.00 ERV 0.26).

As shown in Figure 4 [Figure 4: see original paper], the ecological risk distribution in the Pingshuo Mining Area changed considerably from 2001 to 2010. The number of pixels in mining-disturbed areas (mining and reclamation areas) was 34,377 in 2001 and 105,964 in 2010, accounting for 9.76% and 30.08% of the total study area pixels, respectively. In the disturbed areas, regions at medium risk and below accounted for only 0.02% in 2001, increasing to 16.77% in 2010. This demonstrates that although the mining area's exploitation range expanded, local ecological risk decreased with the implementation of post-mining reclamation work. The Antaibao South Dump and West Dump, which were reclaimed in both evaluation periods, showed significant changes in mean ecological risk values. The South Dump decreased from 0.64 to 0.50, while the West Dump decreased from 0.62 to 0.46. The differences in dump means reflect changes during the multi-year reclamation period in the Pingshuo Mining Area. Due to non-standard early dumping technology, the South Dump experienced ecological problems such as landslides and gangue spontaneous combustion, resulting in relatively high ecological risk evaluation results. Although the West Dump was reclaimed later than the South Dump, its dumping technology was more scientific and reasonable, having a positive impact on ecosystem maintenance, and after 10 years of management, it exhibited low ecological risk.

Profile lines a and b pass through eight types of disturbed areas: original landform, reclaimed dump, industrial site, unreclaimed dump, underground mining, combined open-pit and underground mining area, open-pit mining area, and stripping area (Figure 1 [Figure 1: see original paper]). The risk values of pixels along these lines form profile curves shown in Figure 5 [Figure 5: see original paper]. The ecological risk values along profile line a are represented in Figures 5A and 5C, showing that the ecological risk of original landform remained basically unchanged. The risk value of the reclaimed South Dump increased and fluctuated in 2010 due to large-scale spontaneous combustion causing severe local ecological damage. The ecological risk value of the reclaimed Antaibao inner dump in 2010 decreased significantly. Areas undergoing mining and stripping in 2001 had developed into industrial sites and unreclaimed dumps by 2010, with ecological risk values slightly lower than a decade earlier. The risk values of unreclaimed dumps were much greater than those of reclaimed dumps.

Profile line b passed through relatively simple areas in 2001, but the disturbance types in this region became more diverse with mining advancement in 2010 (Figures 5B and 5D). The original landform area in the southwestern part of the study area experienced no land use type change in 2010, but its ecological risk value increased and became unstable, fluctuating around 0.65 due to underground mining impacts. The risk value of industrial sites remained basically stable. After 10 years of land reclamation measures, the ecological risk value of the Anjialing West Dump decreased significantly, but the risk value changes were unstable with large fluctuations, with low values below 0.45 and high values reaching 0.80. This area belongs to the combined open-pit and underground mining domain affected by underground mining, increasing the probability and intensity of risks such as uneven settlement of dumps, slope stability, and soil erosion. The ecological risk value of the reclaimed Anjialing East Dump remained relatively high due to short reclamation years and proximity to the open-pit mining area. In 2010, the ecological risk value of original landform between two stripping areas showed different changes depending on the distance from the stripping areas.

4 Conclusions and Discussion

1) This study focused on the Pingshuo Mining Area in an ecologically vulnerable zone. By constructing an ecological risk assessment model, it characterized potential ecological risk issues during coal mining and the protection and improvement of regional ecological environments through land reclamation and ecological reconstruction projects. The model evaluated mining area ecosystem damage degree and risk-bearing capacity from two aspects: land destruction cumulative hazard and ecosystem vulnerability, comprehensively reflecting changes in ecological risk in different areas after years of mining and reclamation. The evaluation results align with the actual conditions of the mining area. By integrating remote sensing technology and field measurement data, the study not only quantitatively evaluated mining area ecological risk values but also achieved visualization of evaluation results and changes.

2) The ecological risk assessment results of the mining area are closely related to mining intensity, land destruction area size, mining process scientificity, and land reclamation measures. The evaluation results indicate that after 10 years of land reclamation and ecological reconstruction measures, ecological risk values of reclaimed dumps showed a downward trend, and ecosystems tended to stabilize. Although large-scale combined open-pit and underground mining areas have extensive disturbance ranges, post-mining reclamation helps reduce local ecological risk impacts.

3) By studying land destruction and reclamation processes in mining areas and evaluating dynamic changes in ecological risk, it is possible to identify and determine potential risk impacts at different stages and optimize land use types and mining links. Predicting potential ecological risks before mining, intervening with artificial measures during mining to avoid or reduce ecosystem damage, and timely restoring and reconstructing ecosystems after mining can effectively prevent catastrophic ecosystem damage.

As a risk source for regional ecosystems, mining area land reclamation should shift from focusing solely on the quantity and quality demands of land use types to ecological function demands. How to establish sustainable ecological mining areas and construct systematic and coordinated reclamation mining areas requires further research and has practical significance.

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