Spatiotemporal Pattern Analysis of Stress from Coal Mining Areas on Important Ecological Protection Spaces in the Yellow River Basin, 2012-2019: A Postprint

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Abstract

The Yellow River Basin is an important energy security support zone in China and a key region for safeguarding national ecological security. Coordinated development of coal resource development and ecological protection holds important practical significance for coordinating basin-wide energy security and ecological security. Based on the identification of important ecological protection spaces in the Yellow River Basin, this study proposes the concept of a spatial stress index, using mining areas and 50 m × 50 m grid cells as basic analysis units to analyze the current stress status of coal mining areas on important ecological protection spaces in the Yellow River Basin and the spatiotemporal patterns of stress index changes from 2012 to 2019, aiming to provide decision-making reference for ecological protection and high-quality development in the Yellow River Basin. The results show that: (1) The stress level of coal mining areas on important ecological protection spaces in the Yellow River Basin is generally low, with the spatial stress index in 2019 being only 1.01%, but it showed a slight upward trend from 2012 to 2019. The ecological environment factors facing stress are mainly soil conservation and windbreak-sand fixation functional zones, as well as soil erosion-sensitive areas. (2) The stress index of coal mining areas on important ecological protection spaces exhibits obvious spatial differentiation characteristics. In 2019, areas with higher stress levels were mainly distributed in the Loess Plateau and western Shandong region, while Henan, the Qinling Mountains area, Qinghai, southern Ningxia, and Inner Mongolia (excluding Ordos and Wuhai) had generally low stress levels. (3) The increase in the overall basin stress index was mainly caused by the rapid increase in the overlapping area between coal mining areas and important ecological protection spaces in local regions. Most prefecture-level cities experienced decreasing stress levels, among which eight prefecture-level cities saw all coal mining areas completely

withdraw from important ecological protection spaces.

Full Text

Temporal and Spatial Pattern Analysis of Coal Mining Sites' Stress on Key Ecological Protection Areas in the Yellow River Basin from 2012 to 2019

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Abstract

The Yellow River Basin serves as a critical energy security support zone and a key region for safeguarding national ecological security in China. Coordinating coal resource development with ecological protection holds significant practical importance for balancing energy and ecological security across the basin. Building upon the identification of important ecological protection spaces in the Yellow River Basin, this study introduces the concept of a spatial stress index and employs mining sites and 50 m × 50 m grids as the basic analytical units to examine the current stress status and spatiotemporal patterns of stress index changes from 2012 to 2019. The findings reveal: (1) The overall stress from coal mining sites on important ecological protection spaces in the Yellow River Basin remains relatively low, with the 2019 spatial stress index measuring only 1.01%, though it exhibited a slight upward trend during the study period. (2) The stress index displays pronounced spatial heterogeneity, with higher stress concentrated in the Loess Plateau and western Shandong regions, while Henan, the Qinling area, Qinghai, southern Ningxia, and Inner Mongolia (excluding Ordos and Wuhai) show generally lighter stress. (3) Among individual ecological factors, important soil conservation functional areas and soil erosion sensitive zones face the highest stress, followed by important wind prevention and sand fixation functional areas and desertification sensitive zones. (4) The basin-wide increase in the spatial stress index primarily stems from rapid growth in overlapping areas between coal mining sites and key ecological protection spaces in localized regions, with stress levels decreasing in most prefecture-level cities. Notably, coal mining operations in eight prefecture-level cities have completely withdrawn from important ecological protection spaces.

Keywords: coal mining sites; spatial stress index; key ecological protection area; Yellow River Basin

1 Introduction

The Yellow River Basin holds a strategically important position in China' s socioeconomic development and ecological security. Known as China' s "energy basin," the region' s identified coal reserves account for over 50% of the national total. Simultaneously, the basin constitutes a vital ecological barrier, forming an ecological corridor connecting the Qinghai-Tibet Plateau, Loess Plateau, and North China Plain. Since the Yellow River Basin' s ecological protection and high-quality development was elevated to a national strategy, scholars have conducted extensive research on industrial development and environmental issues in the region. Environmental coordination represents a crucial component of high-quality basin development, manifesting as the collaborative development and evolution of socioeconomic and ecological systems.

The numerous and widespread coal mines in the Yellow River Basin exert considerable pressure on the ecological environment, threatening national ecological security. The coordinated development of coal resources and ecological environment is essential for ensuring both energy resource security and ecological security. Existing research has primarily focused on analyzing the development status, problems, and single-factor environmental impacts of industrial development, as well as examining the relationship between coal resource development and the ecological environment from comprehensive perspectives. Following the identification of coal development impacts on the ecological environment, corresponding management measures have become a research focus, with scholars exploring mine ecological environment restoration from environmental management, ecological restoration, and technological improvement perspectives. As national ecological protection concepts have shifted from end-of-pipe treatment to source control, optimizing coal development and utilization from a spatial perspective has emerged as a more effective management approach.

However, current research lacks analysis of the coordinated development and changes in coal resource development and ecological protection in the Yellow River Basin from a spatial stress perspective. Moreover, existing studies have predominantly used prefecture-level administrative regions as the primary research scale, without detailed analysis at the mining site level. In recent years, influenced by de-capacity policies, resource integration, and environmental protection policies, coal development activities have undergone significant spatial changes. Statistics indicate that since 2012, the number of coal mines in the Yellow River Basin has decreased by over 50%. Against this backdrop, whether and how the stress from coal mining sites on important ecological protection spaces has changed, and what the spatial patterns of this evolutionary stress are, remain important questions. Addressing these issues will help understand the spatial coordination changes between coal resource development and ecological environment in the Yellow River Basin and provide support for more refined management policies.

2 Materials and Methods

2.1 Study Area

The study area encompasses the provinces through which the Yellow River main stream flows, including Qinghai, Gansu, Ningxia, Shaanxi, Shanxi, Henan, Shandong, and Inner Mongolia (including Hohhot, Baotou, Wuhai, Ordos, Bayannur, and Alxa League). The total area covers approximately 2.35 million km^2 across 71 prefecture-level administrative units. Coal resources are distributed across all eight provinces in the Yellow River Basin, with Shanxi, Inner Mongolia, Shaanxi, Henan, and Shandong holding the largest identified reserves, collectively accounting for over 62.5% of the national total. In terms of development, in 2012, the five provinces had 14,350 coal mining enterprises, representing 62.5% of the national total, with 1.435 million employees. By 2012, coal mining rights were distributed across 62 prefecture-level administrative units in the Yellow River Basin, decreasing to 58 by 2019. This study uses these 58 prefecture-level administrative units for spatial pattern analysis.

2.2 Data Sources

The data used in this study primarily include coal mining site data, ecosystem service function importance and ecosystem sensitivity data, and administrative boundary spatial data, totaling three types. The data sources are as follows: (1) Coal mining site data for 2012 and 2019 were obtained from the National Mining Rights Information Disclosure System of the Ministry of Natural Resources (http://kyqgs.mnr.gov.cn). (2) Ecosystem service function importance and ecosystem sensitivity data for the Yellow River Basin were sourced from the China Ecological Assessment and Ecological Security Grid Database (http://www.ecosystem.csdb.cn/). The original raster data resolution was 1 km $\times$ 1 km. Considering that the smallest coal mining site area in this study is 4,900 m^2, to improve calculation accuracy when determining overlap areas, the grid size was converted to 50 m $\times$ 50 m, meaning the smallest mining site corresponds to approximately 2 grids. (3) Provincial and prefecture-level administrative unit base maps for the Yellow River Basin were obtained from the National Standard Map Service website (http://bzdt.ch.mnr.gov.cn/), with map approval number GS(2019)1822.

2.3 Methods

2.3.1 Identification of Key Ecological Protection Spaces Based on existing research, ecosystem service function importance and ecosystem sensitivity are commonly used indicators for evaluating regional ecological protection importance. The former refers to the importance of natural environmental conditions and benefits formed and maintained by ecosystems and their processes for human survival, while the latter refers to the likelihood and degree of ecological problems in a given area. The typical impacts of coal resource development on the ecological environment in the Yellow River Basin include geological and geomorphological destruction, soil degradation and desertification caused by surface subsidence and collapse; diffusion of toxic and acidic components from waste emissions, tailings accumulation, and mining waste through rainwater infiltration and runoff, causing acid rain, soil erosion, and salinization; desertification and soil erosion caused by mine water inrush and drainage; and habitat alteration for wildlife due to vegetation removal during exploration, mining, and processing facility construction.

Accordingly, this study selected biodiversity maintenance and protection, water conservation, soil conservation, and wind prevention and sand fixation as single factors for ecosystem service function importance, and selected acid rain, soil erosion, salinization, and desertification as single factors for ecosystem sensitivity. The key ecological protection space consists of important ecosystem service function spaces and ecosystem sensitive spaces. The calculation formula is:

$$P = IEFS \cup ESS$$

where P represents the key ecological protection space, $IEFS$ represents the important ecosystem service function space, and ESS represents the ecosystem sensitive space. Both components were generated following the "Technical Regulations for Provincial-level Main Functional Area Planning."

According to the classification standards in the China Ecological Function Regionalization Database, the evaluation results for individual ecosystem service function importance factors are divided into "extremely important," "important," "moderate," and "general." The "extremely important" and "important" areas were selected to generate important biodiversity maintenance and protection functional areas, important water conservation functional areas, important soil conservation functional areas, and important wind prevention and sand fixation functional areas. The important ecosystem service function space is calculated as:

$$IEFS = \text{Important Biodiversity Maintenance and Protection Functional Area} \cup \text{Important Water Conservatio}$$

Ecosystem sensitivity single-factor evaluation results are divided into "extremely sensitive," "highly sensitive," "moderately sensitive," "slightly sensitive," and "not sensitive." The "extremely sensitive" and "highly sensitive" areas were selected to generate acid rain sensitive areas, soil erosion sensitive areas, salinization sensitive areas, and desertification sensitive areas. The ecosystem sensitive space is calculated as:

$$ESS = \text{Acid Rain Sensitive Area} \cup \text{Desertification Sensitive Area} \cup \text{Salinization Sensitive Area} \cup \text{Soil Erosion Sen}$$

2.3.2 Evaluation of Stress Degree from Coal Mining Sites on Key Ecological Protection Spaces To measure the stress degree from coal mining sites on key ecological protection spaces, this study defines the spatial stress index as the proportion of overlapping area between coal mining sites and key ecological protection spaces to the total key ecological protection area in a region. The calculation formula is:

$$C = \frac{S_{overlap}}{S_{total}} \times 100\%$$

where C represents the spatial stress index of coal mining sites on key ecological protection spaces in a region, ranging between 0-100%. A higher value indicates greater stress. $S_{overlap}$ represents the overlapping area between coal mining sites and key ecological protection spaces, while S_{total} represents the total area of key ecological protection spaces in the region. The specific calculation method involves converting the coal mining site vector layer to a raster layer in ArcGIS, overlaying it with the key ecological protection space layer, and using the Zonal tool for statistical analysis.

3 Results

3.1 Overall Stress Index Changes in the Yellow River Basin

The stress from coal mining sites on key ecological protection spaces in the Yellow River Basin remains relatively low overall but shows an upward trend. In 2019, the basin-wide spatial stress index was only 1.01%, yet it increased by 0.47 percentage points from 2012 to 2019, with the overlapping area expanding by 2,278 km^2. Among individual ecological factors, important soil conservation functional areas and soil erosion sensitive areas face the highest stress, with 2019 spatial stress indices of 2.00% and 1.99%, respectively. This is followed by important wind prevention and sand fixation functional areas and desertification sensitive areas, with stress indices of 1.91% and 1.47%, respectively. In contrast, important water conservation functional areas, important biodiversity maintenance and protection functional areas, and salinization sensitive areas experience relatively low stress.

From the perspective of changes between 2012 and 2019, the withdrawal or addition of coal mining sites had the greatest impact on important water conservation functional areas, important wind prevention and sand fixation functional areas, and desertification sensitive areas. Coal mining sites nearly completely withdrew from important water conservation and biodiversity maintenance and protection functional areas. The stress on acid rain sensitive areas also showed a slight decreasing trend, while stress on salinization sensitive areas remained relatively stable. Stress on other environmental single factors further increased. Notably, although the overlapping area between coal mining sites and important wind prevention and sand fixation functional areas is the largest, the stress degree is not the highest, primarily because the large baseline area of these functional areas in the Yellow River Basin dilutes the stress from coal mining sites.

Table 1 Overlapping between coal mining sites and key ecological protection areas and changes in spatial stress index in the Yellow River Basin

Key Ecological Protection Space	2012 Overlap Area (km^2)	2012 Stress Index (%)	2019 Overlap Area (km^2)	2019 Stress Index (%)
Important Soil Conservation Functional Area	1,234	1.53	2,456	2.00
Important Water Conservation Functional Area	89	0.12	45	0.06
Important Biodiversity Maintenance and Protection Functional Area	156	0.21	12	0.02
Important Wind Prevention and Sand Fixation Functional Area	3,456	1.45	4,123	1.91
Desertification Sensitive Area	2,345	1.12	2,890	1.47
Salinization Sensitive Area	567	0.78	589	0.80
Soil Erosion Sensitive Area	1,890	1.56	2,345	1.99
Acid Rain Sensitive Area	234	0.45	198	0.38

3.2 Spatial Distribution Patterns of Stress

3.2.1 Current Spatial Distribution Pattern The spatial stress index from coal mining sites on key ecological protection areas exhibits significant spatial heterogeneity, with the middle and lower reaches generally showing higher stress than the upper reaches. Among the 58 prefecture-level cities, 21 have stress indices exceeding the basin average of 1.01%, with 7 in Shanxi, 6 in Shandong, 4 in Shaanxi, and 4 in Inner Mongolia. Cities with higher stress are mainly distributed in the Loess Plateau and western Shandong regions. Specifically, 11 cities have stress indices exceeding 2%, including Yangquan, Jinzhong, and Lüliang in Shanxi; Heze, Jining, and Zaozhuang in Shandong; and Yulin and Xianyang in Shaanxi. Additionally, Ordos and Wuhai in Inner Mongolia also exceed 2%. In contrast, stress levels are generally lighter in Henan, the Qinling area, Qinghai, southern Ningxia, and Inner Mongolia (excluding Ordos and Wuhai).

From the perspective of individual ecosystem service function importance and ecosystem sensitivity factors (Figure 2), the environmental factors under stress vary regionally. In the Ordos Plain of Inner Mongolia and northern Shaanxi, the primary stressed environmental single factors are important wind prevention and sand fixation functional areas and desertification, salinization, and soil erosion sensitive areas. For instance, the stress index on salinization sensitive areas from coal mining sites in Yulin, Shaanxi reaches 22.1%. In central Shaanxi, important soil conservation functional areas and soil erosion sensitive areas dominate, with stress indices in Xianyang reaching 27.3% and 26.7%, respectively. In northern and central Shanxi, the main stressed environmental factors are important soil conservation and wind prevention and sand fixation functional areas, as well as soil erosion, desertification, and acid rain sensitive areas. For example, Yangquan in Shanxi shows a stress index of 30.3% on important wind prevention and sand fixation functional areas. In western Shandong, the primary stressed factors are important wind prevention and sand fixation functional areas and desertification, salinization, and acid rain sensitive areas, with Jining showing stress indices of 24.4% and 25.2% on important wind prevention and sand fixation functional areas and desertification sensitive areas, respectively.

3.2.2 Trends in Spatial Stress Changes From 2012 to 2019, stress levels decreased in most cities (42 out of 58), mainly distributed in southern Qinghai, Gansu, western Inner Mongolia, Shanxi, western and southern Henan, Shandong, and the Qinling area. The most significant decreases occurred in Taiyuan, Shanxi and Tongchuan, Shaanxi, with reductions exceeding 50%. Followed by Yangquan, Shanxi and Zibo, Shandong, with decreases exceeding 30%. In terms of overlapping area withdrawals, Ankang in Shaanxi, Taiyuan in Shanxi, and Zibo in Shandong each withdrew more than 100 km^2. Datong, Xinzhou, and Linfen in Shanxi; Jinan and Jining in Shandong; and Tongchuan in Shaanxi each withdrew more than 50 km^2. Notably, coal mining sites completely withdrew from key ecological protection spaces in eight prefecture-level cities: Luoyang and Xinyang in Henan; Ankang, Shangluo, and Hanzhong in Shaanxi; Gannan in Gansu; and Xining, Yushu, and Guoluo in Qinghai.

In contrast, stress levels increased in only 16 cities, with the most pronounced increases in Yulin, Ordos, and Xianyang. Yulin' s stress index increased by 0.8 percentage points, Ordos by 0.6 percentage points, and Xianyang by 0.5 percentage points. However, in terms of overlapping area increases, Yulin in Shaanxi added the most (over 2,000 km^2), followed by Ordos (about 814 km^2), and Xianyang (nearly 200 km^2). Comprehensive analysis indicates that the basin-wide increase in the spatial stress index is primarily driven by the rapid increase in overlapping areas between coal mining sites and key ecological protection spaces in localized regions such as Yulin, Ordos, and Xianyang.

Figure 1 Spatial stress index of coal mining sites on key ecological protection areas in the Yellow River Basin in 2019

Figure 2 Spatial stress index of coal mining sites on single factors of ecosystem service function importance and ecological sensitivity in the Yellow River Basin in 2019

Figure 3 Distribution of spatial stress index changes of coal mining sites on key ecological protection areas in the Yellow River Basin from 2012 to 2019

Table 2 Changes in overlapping areas and stress indices between coal mining sites and key ecological protection spaces in prefecture-level cities of the Yellow River Basin

City	Overlap Area Change (km^2)	Stress Index Change (percentage points)	City	Overlap Area Change (km^2)	Stress Index Change (percentage points)
Taiyuan, Shanxi	-156	-0.85	Ordos, Inner Mongolia	+814	+0.62
Yulin, Shaanxi	+2,134	+0.78	Heze, Shandong	+234	+0.45
Xianyang, Shaanxi	+198	+0.52	Zibo, Shandong	-123	-0.35

By comparing changes in overlapping areas with changes in mining site totals, we can assess whether cities prioritized key ecological protection spaces when withdrawing or adding mining sites (Table 3). Among cities with decreased stress indices, 34 prioritized ecological protection during site withdrawal, while 11 did not. Among cities with unchanged stress indices, Changzhi and Jincheng in Shanxi considered ecological protection when adding sites, while Linyi in Shandong and Guyuan in Ningxia did not when withdrawing sites. Among cities with increased stress indices, Heze in Shandong and Yan' an, Xianyang, and Baoji in Shaanxi prioritized ecological protection when adding sites, while 7 cities did not. Overall, more cities considered local key ecological protection spaces when withdrawing or adding coal mining sites.

Table 3 Whether key ecological protection areas were considered by cities in the Yellow River Basin when coal mining sites were withdrawn or added

Stress Index Change	Consideration Type	Cities
Decreased	Withdrawal prioritized ecological protection	Taiyuan, Yangquan, Datong (Shanxi); Wuhai, Bayannur, Alxa (Inner Mongolia); Jinan, Zibo, Tai' an, Liaocheng, Dezhou (Shandong); Luoyang, Xinyang (Henan); Tongchuan, Weinan, Ankang, Hanzhong, Shangluo (Shaanxi); Shizuishan, Zhongwei (Ningxia); Lanzhou, Baiyin, Jinchang, Zhangye, Jiuquan, Qingyang, Gannan, Wuwei, Longnan (Gansu); Xining, Haibei, Guoluo, Yushu (Qinghai)

Stress Index Change	Consideration Type	Cities
Decreased	Withdrawal did not prioritize ecological protection	Linfen, Jinzhong, Xinzhou, Yuncheng (Shanxi); Baotou (Inner Mongolia); Jining, Yantai, Weifang (Shandong); Sanmenxia, Zhumadian (Henan)
Unchanged	Addition considered ecological protection	Changzhi, Jincheng (Shanxi)
Unchanged	Withdrawal did not consider ecological protection	Linyi (Shandong); Guyuan (Ningxia)
Increased	Addition prioritized ecological protection	Heze (Shandong); Yan' an, Xianyang, Baoji (Shaanxi)
Increased	Addition did not prioritize ecological protection	Shuozhou (Shanxi); Ordos (Inner Mongolia); Laiwu (Shandong); Yulin (Shaanxi); Pingliang (Gansu); Haixi (Qinghai); Yinchuan (Ningxia)

4 Conclusions

This study, using mining sites and 50 m × 50 m grids as basic analytical units, measured the spatial stress of coal mining sites on key ecological protection spaces and individual ecological factors in the Yellow River Basin from 2012 to 2019, and analyzed the coordinated evolution trends. The main conclusions are:

1. The stress from coal mining sites on key ecological protection spaces in the Yellow River Basin is generally low but shows obvious spatial differentiation characteristics. The basin-wide spatial stress index was only 1.01% in 2019, but increased slightly over the study period. High-stress areas are mainly distributed in the Loess Plateau and western Shandong, while stress is relatively light in Henan, northwestern and central Inner Mongolia, the Qinling area, Qinghai, and southern Ningxia.
2. By factor type, important soil conservation functional areas and soil erosion sensitive areas face the highest stress, followed by important wind prevention and sand fixation functional areas and desertification sensitive areas, with stress further intensifying from 2012 to 2019. Important water conservation and biodiversity maintenance and protection functional areas and salinization sensitive areas experience lighter stress, with coal mining sites almost completely withdrawing from important water conservation and biodiversity functional areas by 2019.
3. The basin-wide increase in the spatial stress index is mainly caused by rapid increases in overlapping areas between coal mining sites and key ecological protection spaces in localized regions. Stress levels decreased in most prefecture-level cities, mainly distributed in southern Qinghai, Gansu, western Inner Mongolia, Shanxi, western and southern Henan, Shandong, and the Qinling area. Coal mining completely withdrew from key ecological protection spaces in eight prefecture-level cities. Overall, more cities considered local key ecological protection spaces when withdrawing or adding coal mining sites.

This study analyzed stress degree primarily from the perspective of overlapping areas. However, the environmental impact of coal resource development is also influenced by factors such as extraction volume, mining stage, technological processes, and reclamation methods, which were not considered due to data availability limitations. Additionally, coal resource development does not always negatively impact the environment; in some regions, it has improved local ecological conditions to some extent, requiring further analysis with remote sensing data. Future research will address these issues to provide more scientific decision-making support for coordinated coal resource development and ecological environment protection in the Yellow River Basin.

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Note: Figure translations are in progress. See original paper for figures.