

Original Research

Research on Spatiotemporal Evolution of Land Use and Landscape Ecological Security in Mining Subsidence Area with High Groundwater Level

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Received: 6 September 2023

Accepted: 26 January 2024

Abstract

Xuzhou used to be a significant coal resource-based city in eastern China and a typical mining area with a high groundwater level. Prolonged underground mining activities and rapid urbanization have profoundly transformed its regional landscape pattern. Therefore, analyzing the laws of regional land use and the spatiotemporal evolution of landscape ecological security holds significant importance for regional sustainable development. Based on multi-period remote sensing data from 1990 to 2020, this study analyzed the intensity of land use changes and transformation characteristics in the eastern mining area of Xuzhou over a 30-year period. On this basis, the ecological security status of the landscape over different periods was evaluated by the Landscape Ecological Security Index. Lastly, spatial autocorrelation analysis was conducted to reveal the overall characteristics and local variations in the spatial distribution of landscape ecological security. The results indicate the following: (1) Over the course of 30 years, due to mining-induced land subsidence and water accumulation, the water area increased by 67.41%, exhibiting the highest dynamic change in land use; construction land area came next, increasing by 30.75%; cultivated land area declined the most gently. (2) From 1990 to 2010, the overall landscape ecological security status of the study area displayed a deteriorating trend, and areas with low ecological security were closely associated with mining distribution and urbanization zones. From 2010 to 2020, guided by ecological restoration plans, the fragmentation of landscape patches decreased, leading to evident improvements in local landscape ecological security. (3) The results of spatial autocorrelation analysis revealed a significant positive correlation and spatial clustering in the distribution of landscape ecological security areas. The high-high aggregation areas were mainly distributed around cultivated land, while the low-low aggregation areas were primarily distributed within the coal mining subsidence zone. Overall, coal mining subsidence and urbanization were the main factors influencing the landscape ecological security status in the high-water-level mining area. In territorial spatial planning, emphasis should be placed on the connectivity and diversity of landscapes to enhance landscape ecological security. The results offer essential information and decision support for governmental authorities and land use planners, aiming to achieve regional sustainable development.

Keywords: Landscape ecological security, mining subsidence, urbanization, land use evolution

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Introduction

Coal is China's primary energy source, accounting for approximately 70% of primary energy consumption [1]. Coal resource-based cities are urban areas where coal mining and processing constitute the dominant industries. The extraction of coal resources plays a crucial role in promoting national and regional development [2]. In China, 90% of coal extraction is done through underground mining, which disrupts the original stress equilibrium of overlying strata layers after mining, leading to movements such as subsidence, fractures, and bending. This ultimately results in the formation of coal mining subsidence areas [3]. Intensive coal mining severely damages the land in mining areas, causing farmland destruction, coal gangue occupation, and surface water accumulation, as well as other problems. Among these problems, land subsidence not only alters the hydrological cycle of existing rivers and lakes but also gives rise to secondary wetlands formed by water accumulation, changing regional landscape patterns and deeply impacting the ecological, environmental, and socio-economic aspects. Extensive damage to agricultural and forested land has inflicted severe land, ecological, and environmental issues, which are typical on a global scale [4, 5]. Over the past three decades, China has entered a rapid urbanization phase, with the urbanization rate reaching 65.22% in 2022. The continuous expansion of construction land in resource-based cities has altered urban spatial structures, leading to significant changes in landscape patterns and exacerbating hazards such as land functional degradation, habitat destruction, and imbalanced hydrological cycles [6]. Therefore, in China's coal resource-based cities, the landscape ecological pattern is doubly affected by coal mining subsidence and urbanization, posing a significant threat to landscape ecological security. Conducting spatiotemporal evolution research on landscape ecological security in mining areas and exploring the coupled relationship between land use evolution and landscape ecological security are of vital importance for establishing a sound landscape ecological security pattern in mining areas, scientifically conducting territorial spatial planning, and achieving the transformation and development of coal resource-based cities.

The purpose of landscape ecological security is to explore the ecological and environmental issues arising from regional land use changes from the perspective of landscape ecology. It utilizes the interaction between spatial patterns and processes to address regional ecological problems so as to optimize regional ecological spaces and achieve the integrity and sustainability of regional ecosystem functions [7]. With the intensification of human-environment conflicts, landscape ecological security assessment, which is based on land use evolution, has become a research hotspot. Regional land landscape ecological security assessments are of great importance for maintaining regional ecological security and achieving scientific planning. Currently, research on regional landscape ecological security assessment often focuses on urban areas [8–10], wetlands [7, 11, 12], cultivated land

[13, 14], and other regions characterized by prominent human-environment conflicts and environmental vulnerability. Specifically, the existing studies on landscape ecological security in mining areas mainly target open-pit mines, with scarce efforts spared on mining subsidence and waterlogged mining areas. Different mining methods also exhibit notable differences in the ways and outcomes of landscape disturbance. In terms of constructing the landscape ecological security assessment framework, researchers commonly employ landscape disturbance indices, landscape fragmentation indices, landscape vulnerability indices, and other landscape pattern indices [12, 15–17]. However, traditional landscape ecological security assessment models often overlook the impact of landscape component changes on the environmental state, thus failing to fully reflect the regional landscape ecological security status. To better evaluate regional landscape ecological security, some scholars have enhanced traditional landscape ecological security assessment models by introducing indicators such as ecosystem service value indices [18] or ecological quality indices [19], which are suitable for their respective study areas [20].

Mining activities result in extensive land degradation, and subsequently, changes in the regional landscape's ecological security. Conducting landscape ecological security assessments in mining areas has become a crucial component of ecological restoration planning for coal resource-based urban land use and spatial development [21]. Currently, research related to mining areas often employs landscape ecology methods to analyze landscape ecological risks and their evolution. This type of research, mostly centered on the evolution of landscape patterns in mining areas [22–24], analyzes regional landscape ecological security from the perspective of the impact of mining activities on landscape pattern elements. In terms of conducting landscape ecological security assessments in mining areas, researchers should adhere to the principle of local adaptability, considering the actual conditions of the mining area, to construct a suitable landscape ecological security assessment indicator system. Therefore, in the context of landscape ecological security assessment in high-groundwater mining areas, some scholars have optimized the assessment framework, taking into account both the ecological effects and the pressures faced by the mining area. They select indicators such as construction land development intensity, mining pressure, landscape structure safety index, biodiversity, vegetation coverage, and landscape ecological service value to construct a landscape ecological security indicator system [25, 26]. However, few studies have considered the impact of waterlogging areas caused by coal mining subsidence on the regional hydrological environment. Currently, in China's high-groundwater mining areas in the eastern part of the Yellow River-Huaihe River region, after decades of intensive mining, numerous areas of coal mining subsidence waterlogging areas have been formed on the surface, making subsidence-related water accumulation a primary ecological environmental issue for high-groundwater mining areas [27]. Therefore, when conducting landscape ecological security assessment

research in high groundwater mining areas, it is essential to pay special attention to the factors related to coal mining subsidence and subsidence-induced water accumulation and their impacts on the hydrological environment.

Based on a comprehensive review of domestic and international research, this study utilized GIS technology and selected the eastern mining area of Xuzhou as the research area. The dynamic changes in land use within the study area over a 30-year period were analyzed by identifying land use data for 1990, 2010, and 2020. Considering landscape elements, mining area factors, and watershed hydrology, the evaluation method was adjusted from the perspectives of landscape, ecology, and society. A landscape ecological security assessment system suitable for the study area was constructed based on previous research. The ecological security status for the years 1990-2020 in the study area was evaluated and classified. The study explored the coupling relationship between land use evolution and changes in landscape ecological security within the research area. Furthermore, an analysis of the spatial correlations of landscape ecological security in the study area was conducted, aiming to reveal the spatiotemporal differentiation characteristics of landscape ecological security. These efforts are intended to provide a scientific basis for the rational formulation of regional land use planning, guidance for regional ecological construction, and the realization of sustainable land resource utilization within the region.

Materials and Methods

Study Area

Defining the Study Scope. The study area is situated within the Jiawang District of Xuzhou City, Jiangsu

Province, China. It encompasses over ten coal mines, including Dahuangshan Coal Mine, Qishan Coal Mine, and QuanTai Coal Mine, constituting a typical high-groundwater level mining region. Historical intensive coal mining activities have led to extensive surface subsidence in the region. According to subsidence area divisions, there are three coal mining subsidence zones: Dahuangshan Zone, Jiawang Zone, and Dongzhuang Zone (Fig. 1). The area boasts a rich water network, including the Beijing-Hangzhou Grand Canal, Bulao River, Tuntou River, and Fangting River. Under the complex disturbances of coal mining subsidence and urbanization, the hydrological environment has undergone changes, resulting in significant alterations to land use patterns. To investigate the spatiotemporal evolution of land use and landscape ecological security more scientifically within the region, this study employed the SWAT model to delineate watersheds within the Jiawang District's water system and overlaid it with the administrative boundaries of Jiawang District to define the study scope. The results are shown in Fig. 1.

Selection of the Study Period. Under the impact of mining activities, the study area has experienced severe surface waterlogging and surface fragmentation. In order to address issues like regional ecological degradation and prominent human-environment conflicts, the Pan'an Lake area within the study region was designated as a model zone for the transformation of subsided land. The comprehensive subsidence control project officially commenced in this area in 2010. Therefore, to better explore the spatiotemporal patterns of landscape ecological security within the study area under the dual disturbances of coal mining subsidence and urbanization, and considering the availability of historical data, this study selected the following three time points for investigation:

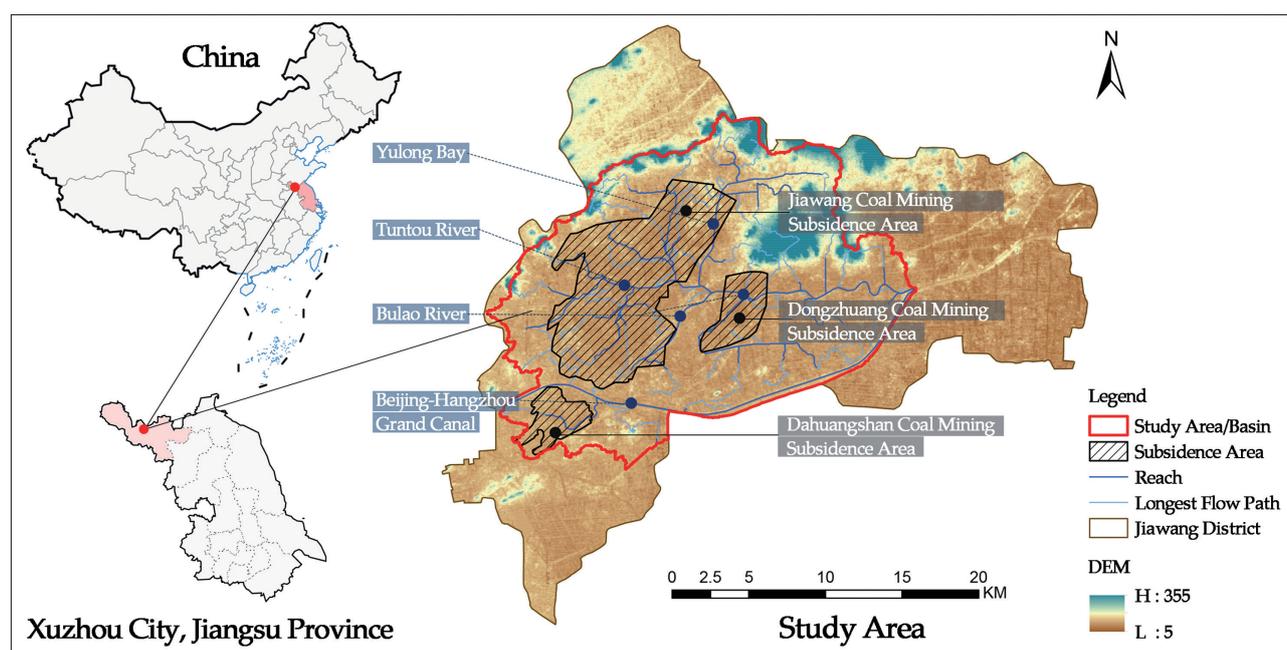


Fig. 1. Overview map of the study area.

the year 1990, i.e., subsidence formation period, which was characterized by intense mining activities within the study area [28]; the year 2010, i.e., the subsidence control period, when mining activities slowed down and subsidence conditions became relatively stable. During this period, subsidence water patterns were essentially formed and relevant control measures were gradually implemented; and the year 2020, i.e., the late subsidence control period, when mining activities ceased and relevant policies and regulations were fully implemented. The study was conducted at these three time points.

Data Sources and Methods

Data Sources

The primary data used in this study consisted of Landsat series remote sensing imagery for the years 1990, 2010, and 2020 in the Jiawang District of Xuzhou City. This data was obtained from the Geographic Spatial Data Cloud platform (<https://www.gscloud.cn/search>) with a spatial resolution of 30 m. Firstly, the remote sensing data underwent preprocessing, including radiometric calibration, atmospheric correction, and image enhancement using ENVI 5.3 software [29]. Subsequently, according to the land use characteristics of the study area and referencing the national standard “Classification of Land Use Status GB/T21010-2017” and the national “Classification Specification for Remote Sensing Survey of Ecological Environment,” the remote sensing images were subjected to supervised classification using ENVI 5.3 and ArcGIS 10.2 software. The land use and land cover of the study area were classified into six categories: cultivated land, forest land, grassland, waters, construction land, and unused land. The classification results were further validated and refined using Google Maps so as to finally determine the land use classification for the years 1990, 2010, and 2020 (Fig. 2). After verification, both the classification accuracy and kappa coefficient were above 85%, meeting the requirements for classification accuracy.

Land Use Dynamics

Land Use Dynamics is an indicator used to measure the extent of human-induced land use changes over different periods, reflecting the rate of change in land use area within a specific time frame [30]. It can be expressed as:

$$K = \frac{U_{i+} - U_{i-}}{U_{i+T}} \times 100\% \quad (1)$$

where K represents the Land Use Dynamics, %; U_{i-} and U_{i+} denote the areas of the i land use type at the beginning and end of the study period, respectively, km^2 ; T represents the duration of the study period.

Land Use Transfer Matrix

The Land Use Transition Matrix reflects the transformation relationships between different land use types within a specific period in the study area, indicating the structural characteristics and transition directions of various land use changes [31]. It can be expressed as follows:

$$U = \begin{pmatrix} U_{11} & U_{12} & U_{13} & \cdots & U_{1n} \\ U_{21} & U_{22} & U_{23} & \cdots & U_{2n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ U_{n1} & U_{n2} & U_{n3} & \cdots & U_{nn} \end{pmatrix} \quad (2)$$

where U_{ij} represents the area of land use type conversion from the i category to the j category during the study period, km^2 ; n is the total number of land use types, and in this study, a first-level classification of land use types is adopted, where $n = 6$. (First-level land use types: cultivated land, forest land, grassland, waters, construction land, and unused land).

Delineation of Evaluation Units

Based on the study area extent and the sizes of regional landscape patches, considering the scale effect, a grid sampling method was employed. Using the ArcGIS platform, a grid of $1\text{km}^2 \times 1\text{km}^2$ cells was constructed to perform systematic sampling across the region. A total of

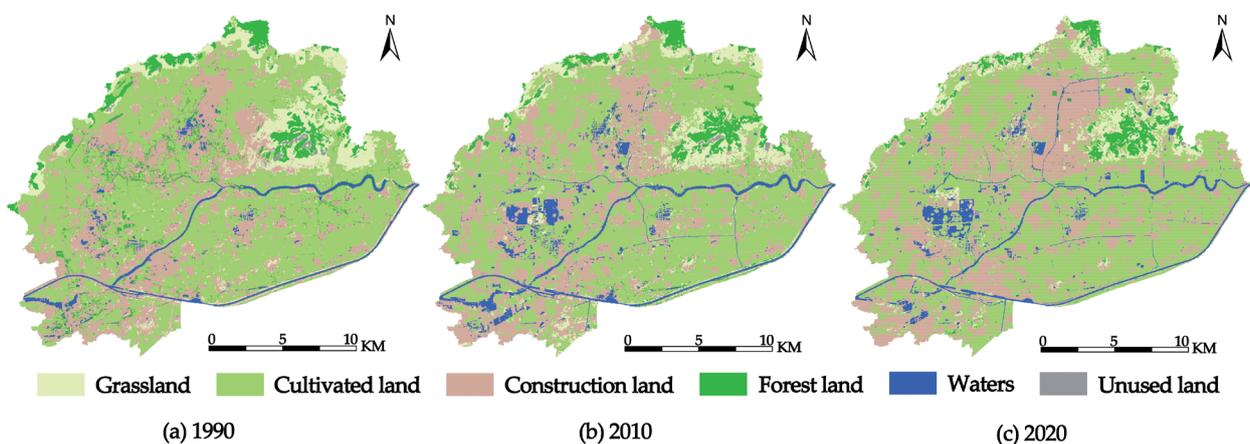


Fig. 2. Land use classification maps for the study area from 1990 to 2020.

430 ecological security assessment units were collected. Utilizing the ecological security assessment framework developed in this study, the ecological security index for each assessment unit sample was calculated, serving as the ecological security value for the central point of each sample plot.

Construction of a Landscape Ecological Security Evaluation System and Weight Determination

Construction of an Indicator System

The landscape ecological security in the study area is influenced by various factors, including natural conditions, socio-economic factors, and mining activities. To conduct a scientific and reasonable assessment of ecological security in the study area, it is necessary to establish a tailored multidimensional landscape ecological security evaluation system. Different landscape pattern characteristics reflect whether the structure of the regional land ecosystem is coordinated. As the foundation of landscape ecological security, the resistance to disturbance of the ecological environment is a key determinant of whether the regional land ecosystem can function normally. Additionally, social and policy factors serve as the driving force and support for the sustainable development of the land ecological environment [32]. Therefore, based on landscape ecology theory, this study constructed an indicator system from three dimensions: landscape attributes, ecological attributes, and social attributes.

According to previous research [26, 32–34], considering that the study area belongs to the high groundwater mining area in the eastern part of the Yellow River-Huaihe River region of China, historically intense coal mining activities have led to extensive land subsidence and subsequently aroused wide concerns over the impact of subsidence-related waterlogging on the hydrological environment. Thus, in the selection of evaluation factors, factors such as “Is it a subsidence area” and “Flood situation of a 50-year recurrence interval” were introduced to characterize the extent of disturbance caused by coal mining subsidence and the impact of subsidence-related waterlogging on the regional hydrological environment. The specific nature and calculation methods of each indicator are detailed in Table 1.

Weight Determination

The method of combining subjective and objective weights was adopted in this study. Firstly, the entropy weight method [35, 36] was used to calculate the weights of indicators, obtaining entropy weights W_{1j} . Then, the Analytic Hierarchy Process [37] was employed to determine the weights W_{2j} , which were used to refine the weights obtained from the entropy weight method. This ensured a more rigorous evaluation of the ecological security status in the study area. The calculation of combined weights, as shown in formula (3), employs the Lagrange formula to optimize the indicator weights and derive the combined weight value W_j [38].

Table 1. Landscape ecological security assessment system for the eastern mining area of Xuzhou.

Goal Layer	Criterion Layer	Indicator Layer	Nature of Indicators
	Regional landscape pattern characteristics 0.266	SHDI 0.078	Shannon’s Diversity Index - Landscape richness, +
		LPI 0.068	Largest Patch Index - Landscape dominance, +
		LSI 0.063	Landscape Shape Index - Degree of human activity disturbance, -
		CONTAG 0.034	Contagion Index - Spatial adjacency between landscapes, +
		PD 0.023	Patch Density - Measure of landscape fragmentation degree, -
	Ecological environment’s anti-interference capability 0.498	Slope 0.022	DEM elevation data, -
		NDVI 0.134	Normalized Vegetation Index - Reflects vegetation coverage, +
		Is it a subsidence area 0.128	Indication of disturbance from mining activities, reflecting the regional natural ecological foundation, yes or no
		Water network density 0.189	Characterize water environmental status, degree of water system development, and calculate using GIS software, +
		Flood situation of a 50-year recurrence interval 0.025	Resilience against rainstorm and flood disturbances, reflecting changes in subsidence and accumulated water, calculated using MIKE21 software, -
	Regional social and policy factors 0.236	Legal regulations and policy management in coal mining subsidence areas 0.173	Level of importance attached to the ecological security status of the land, research relevant policies and regulations, yes or no
		Population density 0.063	Pressure on the land, statistics data, -

Note: In the table, “+” indicates positive indicators, and “-” indicates negative indicators

$$W_j = \frac{\sqrt{W_{1j}W_{2j}}}{\sum_{j=1}^n \sqrt{W_{1j}W_{2j}}} \quad (3)$$

Integrated Ecological Security Evaluation Model

Drawing on previous research findings [39], the Ecological Security Index model was employed to calculate the Landscape Ecological Security values for different periods in the study area.

$$ESI = \sum_{i=1}^n A_i \times W_i \quad (4)$$

Where *ESI* represents the Landscape Ecological Security Index of the study area; *A_i* stands for the normalized data of various ecological security assessment indicators; *W_i* signifies the weight of safety evaluation indicator *i* obtained through the combined weight method; where *n* denotes the total number of indicators. By inputting the data into the model and conducting spatial overlay operations within GIS software, the Landscape Ecological Security Index values for different periods in the study area were obtained. In terms of the categorization of ecological security levels, as guided by previous research [40], the GIS platform’s natural break classification method was employed to classify the ecological security values.

Spatial Autocorrelation Analysis

Spatial autocorrelation analysis is a spatial statistical method to study the correlation of the attributes of the proximity location. To be specific, this method is to calculate the degree of spatial autocorrelation between a certain spatial unit and its surrounding units for a certain characteristic attribute, so as to analyze the characteristics of the distribution of these spatial units,

such as spatial discretization or aggregation, as well as the evolution of the law [41]. Spatial autocorrelation analysis includes global autocorrelation analysis and local autocorrelation analysis, which reveal the overall characteristics and local variations of the study area [42]. The global autocorrelation, a comprehensive evaluation of the variable space aggregation characteristics, is characterized by the Global Moran’s I, calculated as in formula (5). Local autocorrelation, which is characterized by the local Moran’s I and calculated as formulas (6) and (7), expresses the clustering phenomenon or outliers in a local region and describes the spatial divergence pattern.

$$I = m \frac{\sum_{i=1}^m \sum_{j=1}^m w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{[\sum_{i=1}^m \sum_{j=1}^m w_{ij} \sum_{i=1}^m (x_i - \bar{x})^2]} \quad (5)$$

Where *I* represents the Global Moran’s index; *m* is the total number of spatial units in the region; *x_i* and *x_j* are the attribute values of the random variable *x* at geographical units *i* and *j*, respectively; $\bar{x} = \frac{1}{m} \sum_{i=1}^m x_i$ is the mean of the attribute values for the *m* units; *w_{ij}* is the spatial adjacency weight matrix for regions *i* and *j*, representing the spatial adjacency relationship of objects. When regions *i* and *j* are adjacent, *w_{ij}* = 1; otherwise, *w_{ij}* = 0. The range of *I* values is [-1,1], where *I* > 0 indicates positive spatial autocorrelation, implying spatial clustering; *I* < 0 indicates negative spatial autocorrelation, implying lack of spatial clustering; *I* close to 0 indicates no spatial autocorrelation, implying random distribution.

$$I_i = \left(\frac{x_i - \bar{x}}{s_i^2} \right) \sum_{j=1, j \neq i}^m w_{ij} (x_j - \bar{x}) \quad (6)$$

$$s_i^2 = \sum_{j=1, j \neq i}^m (x_j - \bar{x})^2 / (m - 1) \quad (7)$$

Where *I_i* denotes the local Moran’s index. When the value of *I_i* is positive, it indicates the existence of

Table 2. Land use structure in the study area from 1990 to 2020 (km²).

Land Use Types	1990		2010		2020	
	Area/km²	Proportion/%	Area/km²	Proportion/%	Area/km²	Proportion/%
Grassland	44.169	11.325	35.692	9.151	26.530	6.802
Cultivated land	202.847	52.011	201.773	51.736	198.821	50.979
Construction land	98.883	25.354	107.830	27.648	129.286	33.150
Forest land	31.581	8.097	21.381	5.482	15.722	4.031
Waters	11.519	2.953	22.617	5.799	19.284	4.944
Unused land	1.004	0.257	0.710	0.182	0.360	0.092
Total	390.00	100.000	390.00	100.000	390.00	100.000

Table 3. Dynamics of land use changes in the study area from 1990 to 2020.

Period	Grassland	Cultivated land	Construction land	Forest land	Waters	Unused land
1990-2010	-0.90%	-0.02%	0.43%	-1.52%	4.53%	-1.38%
2010-2020	-2.31%	-0.13%	1.79%	-2.38%	-1.33%	-4.64%
1990-2020	-1.20%	-0.06%	0.92%	-1.51%	2.02%	-1.97%

spatial aggregation of high (or low) values; and when the value of I_i is negative, it indicates spatial aggregation of dissimilar values.

Results and Analysis

Land Use Dynamics Analysis

The areas of different land use types in the eastern mining area of Xuzhou from 1990 to 2020 were calculated, and the results are presented in Table 2. The data shows that cultivated land has consistently been the primary land use type in the study area, exhibiting a declining trend overall. In 1990, the proportion of cultivated land was 52.01%, which decreased to 50.97% by 2020. The second most prominent type is urban land, with its proportion increasing from 25.35% to 33.15% of the total area. Grassland and forest land rank third and fourth in terms of land use proportion, with their overall areas decreasing over the years. In 1990, the proportion of grassland was 11.32%, which had reduced to 6.08% by 2020. Similarly, forest land decreased from 8.09% in 1990 to 4.94% in 2020. The water area differs from other land use types. Between 1990 and 2010, the proportion of water area increased from 2.95% to 5.79%. However, from 2010 to 2020, the water area decreased from 5.79% to 4.94%.

By calculating the dynamics of land use changes in the study area (Table 3), it can be observed that during the entire study period (1990-2020), the change rates of grassland, cultivated land, forest land, and unused land were negative, indicating an overall decreasing trend. Conversely, urban land and waters show positive values, indicating an overall increasing trend. Among these,

waters exhibit the highest dynamic value, undergoing the most significant changes.

There are variations in the change rates of different land use types across different time periods. The change rates of grassland, cultivated land, forest land, and unused land are negative in all periods, indicating a continuous shrinking trend. Among these, the change in cultivated land is relatively gradual, which is due to the orderly reclamation of subsided land within the study area since the enactment of policies such as the “Regulations on the Reclamation of Subsided Land from Coal Mining in Xuzhou City” in 2001, resulting in comparatively minor overall changes. Primarily due to rapid urbanization, the area of construction land shows positive change rates in all periods, indicating a consistent expansion trend. The change rate of water area is positive in the period 1990-2010 and has the largest dynamic value compared to other land types in the same period. It indicates that the water area increased drastically in this stage, which was mainly affected by mining activities, and a large amount of subsidence water appeared. With the introduction and implementation of management measures related to coal mining subsidence wetlands, the change rate of water area was negative during 2010-2020, and the water area decreased in this stage.

Analysis of the Land Use Transfer Matrix

The land use transfer matrix for the eastern mining area of Xuzhou is calculated, and the land use transition diagram (Fig. 3) is generated. As shown in Table 4, during the entire study period (1990-2020), the conversion between cultivated land and construction land was the most pronounced. Of this, 50.42 of cultivated land was

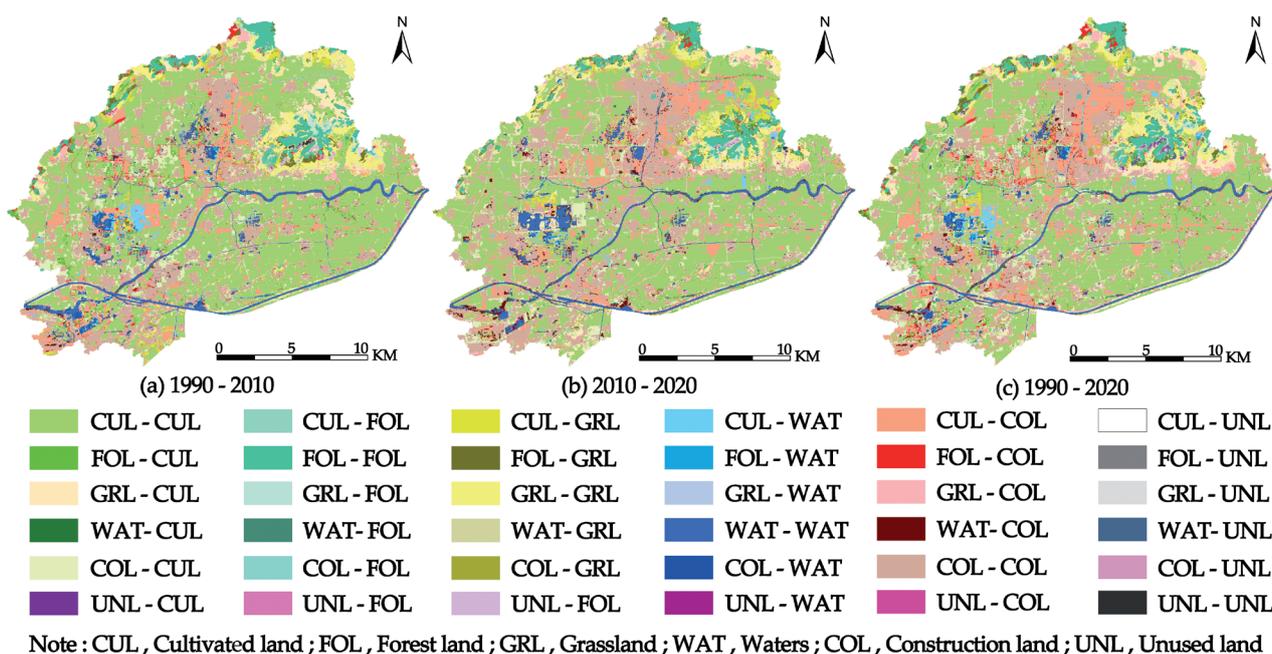


Fig. 3. Land use transition diagram for the study Area.

Table 4. Dynamics of land use changes in the study area from 1990 to 2020.

1990/2010	Grassland	Cultivated land	Construction land	Forest land	Waters	Unused land	Total
Grassland	19.227	13.368	7.299	3.647	0.317	0.310	44.169
Cultivated land	6.535	156.560	32.135	3.019	4.562	0.033	202.847
Construction land	4.917	24.187	60.901	2.472	6.353	0.045	98.876
Forest land	4.357	7.219	5.705	12.059	1.999	0.242	31.582
Waters	0.081	0.398	1.494	0.159	9.383	0.001	11.518
Unused land	0.570	0.038	0.292	0.025	0.001	0.076	1.004
Total	35.690	201.773	107.827	21.381	22.617	0.710	390.00
2010/2020	Grassland	Cultivated land	Construction land	Forest land	Waters	Unused land	Total
Grassland	12.428	13.948	6.883	2.031	0.247	0.149	35.687
Cultivated land	6.910	154.384	35.976	1.688	2.747	0.062	201.769
Construction land	3.005	24.544	77.648	0.910	1.667	0.009	107.820
Forest land	3.545	4.389	2.210	10.848	0.338	0.044	21.378
Waters	0.316	1.459	6.416	0.139	14.285	0.000	22.617
Unused land	0.324	0.095	0.106	0.104	0.000	0.079	0.710
Total	26.530	198.822	129.277	15.722	19.286	0.343	390.00
1990/2020	Grassland	Cultivated land	Construction land	Forest land	Waters	Unused land	Total
Grassland	13.677	17.828	9.435	2.667	0.322	0.234	44.165
Cultivated land	4.105	141.797	50.421	1.088	5.414	0.015	202.842
Construction land	2.729	30.624	59.839	1.308	4.300	0.081	98.882
Forest land	5.415	7.516	6.656	10.502	1.471	0.013	31.574
Waters	0.172	0.839	2.647	0.083	7.775	0.000	11.519
Unused land	0.429	0.213	0.278	0.071	0.001	0.000	1.004
Total	26.529	198.821	129.286	15.722	19.284	0.343	390.00

converted to construction land, while 30.62 of construction land was converted to cultivated land. Apart from the conversion to construction land, cultivated land also underwent a conversion of 5.41 to waters. This is due to the impact of mining activities in the study area, leading to water accumulation in certain subsided coal mining areas. Both forest land and grassland underwent conversions to cultivated land and construction land. Specifically, 17.82 of grassland was converted to cultivated land and 9.43 to construction land. Additionally, 7.51 of forest land was converted to cultivated land and 6.65 to construction land. Mutual conversions between forest land and grassland were also observed. Furthermore, through analyzing the transitions of land use types across different time periods, it is revealed that, besides the conversion of 6.40 of waters to construction land between 2010 and 2020, the transition patterns between various other land use types remained largely consistent with those observed over the entire study period. The reason for the conversion of waters to construction land between 2010 and 2020 was the commencement of remediation efforts for subsided waterlogged areas during that period. Guided by ecological restoration planning, the integration of subsided water areas, the construction of regional water networks, and the creation of a sustainable wetland landscape system have improved and promoted the regional economy. As a result,

a portion of water bodies and previously unused land have been converted into construction land.

By cumulatively summing up the three main land use transition modes across different periods, the accumulated values of land conversion from cultivated land to construction land, from construction land to cultivated land, and from grassland to cultivated land for the years 1990 to 2020 are 68.07, 48.69, and 27.30, respectively. In contrast, the direct calculation of conversion areas for the years 1990 to 2020 is 50.42, 30.62, and 17.82, respectively. A comparison of these data reveals that the cumulatively obtained conversion areas for the years 1990 to 2020 are significantly larger than the directly calculated conversion areas for the same period. This indicates the existence of a complex, multi-stage, multi-objective conversion relationship between different land use types, which also influence the evolution of the landscape ecological security pattern in the study area.

Analysis of the Spatiotemporal Evolution of Landscape Ecological Security

Based on the landscape ecological security assessment system constructed in this study for the eastern mining area of Xuzhou, the ecological security values from 1990 to 2020 were calculated on the GIS platform. The ecological

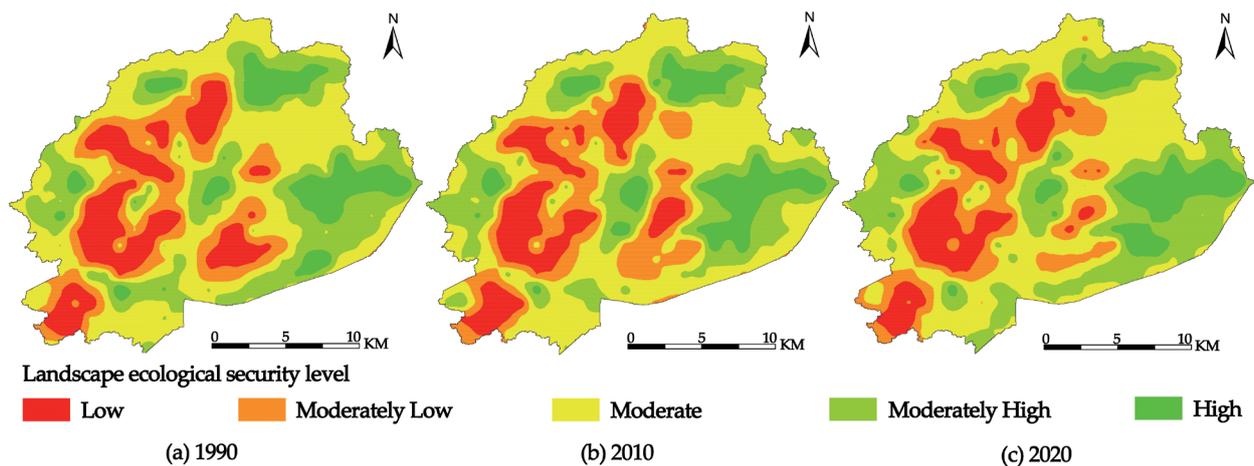


Fig. 4. Distribution of landscape ecological security levels in the study area from 1990 to 2020.

security situation in the study area was classified using the Natural Breaks method, and the annual distribution of landscape ecological security was generated using the Kriging interpolation method [43] (Fig. 4). On this basis, an analysis was conducted to investigate the spatiotemporal evolution of landscape ecological security from 1990 to 2020.

The land use changes caused by coal mining subsidence and urbanization would inevitably impact the landscape pattern in the study area. The study first analyzed the state of landscape ecological security from 1990 to 2020 in terms of area changes in each landscape ecological security zone and index changes in the landscape pattern. By calculating the area and proportion of ecological security zones of each level within the study area (Table 5), it was observed that: from 1990 to 2020, the sum of areas of low and moderately low ecological security zones increased initially and then decreased; conversely, the sum of areas of high and moderately high ecological security zones decreased initially and then increased; the area of moderately ecological security zones decreased gradually over the years. Accordingly, the overall landscape ecological security status deteriorated initially and then improved. Meanwhile, the landscape indices of the study area were analyzed from 1990 to 2020 (Fig. 5), and it was found that the patch density (PD) and landscape shape index (LSI) increased; the largest patch index (LPI) and Shannon’s diversity

(SHDI) decreased between 1990 and 2010. During this period, overall landscape fragmentation and disturbance by human activities increased, and landscape dominance and landscape richness decreased. Accordingly, the overall landscape ecological security of the study area deteriorated during this period. By 2020, patch density (PD) and landscape shape index (LSI) significantly decreased in the study area; Shannon’s diversity (SHDI) slightly decreased; while the largest patch index (LPI) and contagion index (CONTAG) significantly increased. All coal mines in the study area ceased to be mined during this phase, and the degree of fragmentation of landscape patches and the degree of disturbance by human activities in the region were reduced under the guidance of ecological restoration planning. Although the landscape richness decreased slightly, landscape dominance and landscape connectivity increased significantly [44]. Accordingly, the overall landscape ecological security of the study area improved in this stage.

Using the moving window method in Fragstats software, the spatial distribution of various landscape indices in the study area from 1990 to 2020 (Fig. 6) was generated. Combined with the land use classification (Fig. 2) and the distribution of landscape ecological security levels (Fig. 4) in the study area from 1990 to 2020, the evolution of landscape ecological security in the study area was analyzed from a spatial perspective. Overall, the low and moderately low landscape ecological security

Table 5. Statistics of landscape ecological security zones in the study area from 1990 to 2020.

Landscape Ecological Security Level	1990		2010		2020	
	Area/km ²	Proportion/%	Area/km ²	Proportion/%	Area/km ²	Proportion/%
Low	64.96	16.67%	65.96	16.92%	54.49	13.98%
Moderately Low	47.54	12.20%	52.15	13.38%	62.66	16.08%
Moderate	146.81	37.67%	145.33	37.29%	127.45	32.70%
Moderately High	84.43	21.66%	77.29	19.83%	93.13	23.90%
High	45.99	11.80%	49.00	12.57%	52.00	13.34%

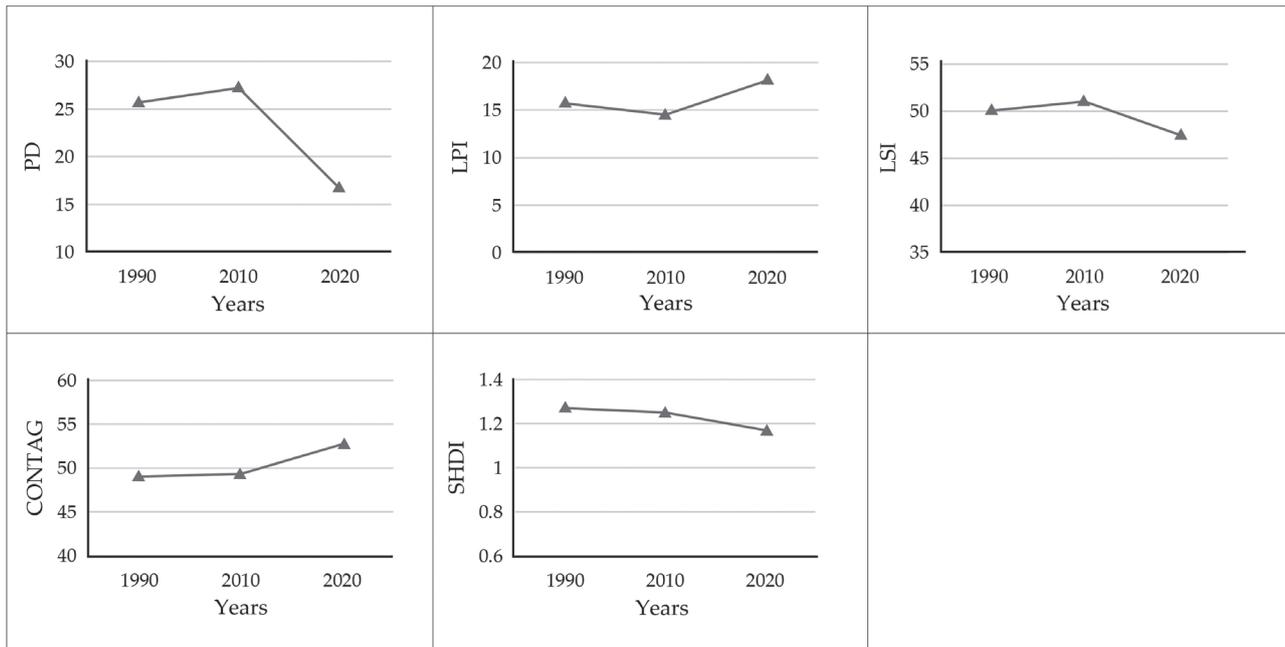


Fig. 5. Evolution of landscape pattern indices in the study area from 1990 to 2020.

zones in the study area are concentrated within three subsided coal mining areas. Within these areas, there is severe subsidence-induced waterlogging and dense construction land, resulting in a high degree of landscape fragmentation and a relatively low level of landscape dominance. Moderate landscape ecological security zones are mainly distributed in the grassland and forest land areas of the northwest and northeast parts of the study area, as well as along the Beijing–Hangzhou Grand Canal and the north-south flow of the Bulao River. On the other hand, the moderately high and high landscape ecological security zones are predominantly situated within areas of lower construction land density, relatively intact landscape patches, distinct landscape dominance, and limited human disturbance, particularly within cultivated land areas.

From 1990 to 2010, there was a complex transformation among various levels of landscape ecological security zones. Within the Dahuangshan coal mining subsidence area and Jiawang coal mining subsidence area in the study area, there are areas whose landscape ecological security levels noticeably declined. The large-scale subsidence-induced waterlogging caused by coal mining and the extensive new construction land have affected the landscape ecological security within the study area. In the central part of the Jiawang coal mining subsidence area, cultivated land and construction land are gradually being organized into contiguous patches, and some low landscape ecological security zones have transitioned to moderately low ones. In the southeastern part of the study area, some low landscape ecological security zones have transitioned to moderately low ones. By 2010, the concentration of low-landscape ecological security zones within the region was observed around the water accumulation in the Dongzhuang coal mining subsidence area, indicating the

impact of subsidence water caused by coal mining on the regional landscape ecological security. Along the Grand Canal, there is a phenomenon where some moderately high landscape ecological security zones have transitioned to moderately low and moderate ones. The ecological security of the landscape along the Grand Canal has decreased due to unreasonable development activities. Moderately high and high landscape ecological security zones are primarily distributed within the cultivated land area of the study area. Some moderate landscape ecological security zones have transitioned to moderately high and high zones, while the landscape ecological security status of the cultivated land area in the study area remains relatively stable.

Between 2010 and 2020, within the scope of the Dahuangshan coal mining subsidence area, there was a transformation of some low-landscape ecological security zones into moderately low ones, indicating the initial effectiveness of subsidence-related land remediation measures. Within the Jiawang coal mining subsidence area, some moderate landscape ecological security zones have transitioned to moderately low ones. Despite the intense expansion of construction land within this phase, the changes in low and moderately low landscape ecological security zones are relatively moderate. This illustrates that, under the guidance of scientific and reasonable planning and ecological restoration, comprehensive management of subsidence land can, to some extent, mitigate the deterioration of landscape ecological security. Significant changes are observed in the low and moderately low landscape ecological security zones in the southeastern part of the study area. Some low-landscape ecological security zones have transitioned to moderately low ones, and moderately low zones have transitioned to moderate ones. The landscape ecological

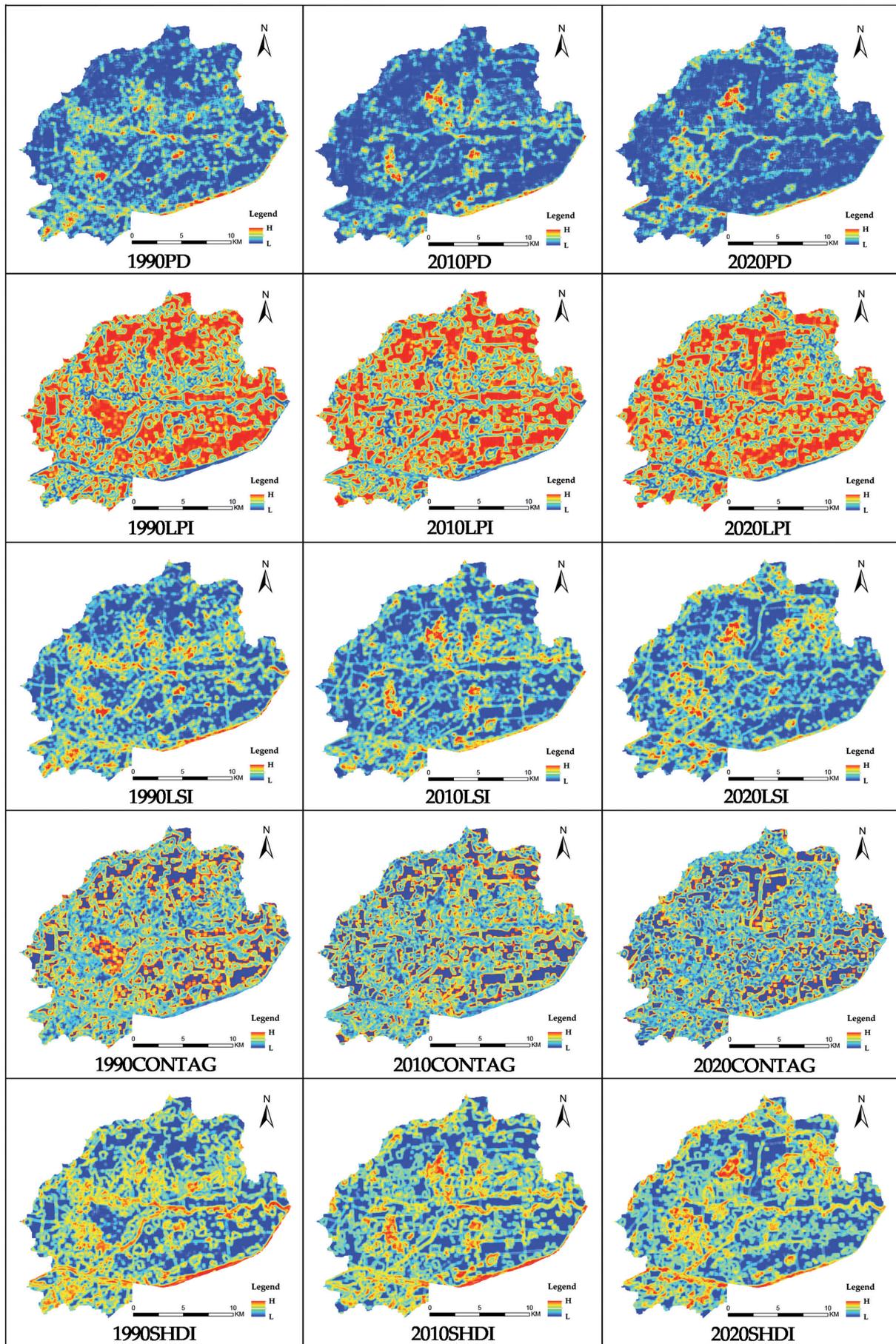


Fig. 6. Distribution of various landscape pattern indices in the study area from 1990 to 2020 based on the moving window method.

security situation in this region has improved. In the study area, some moderate landscape ecological security zones have transitioned to moderately high ones, especially noticeable along the Beijing-Hangzhou Grand Canal. However, in terms of the overall spatial distribution, high and moderately high landscape ecological security zones remain concentrated within the cultivated land areas with relatively intact landscape patches and high landscape dominance. The land use evolution is closely intertwined with the spatiotemporal distribution of landscape ecological security in the study area.

In summary, during 1990-2020, the landscape ecological security status in the study area deteriorated initially and then improved. Regions with poorer landscape ecological security were primarily distributed within the coal mining-induced subsidence areas that were greatly disturbed by coal mining subsidence and urbanization. Meanwhile, areas with better landscape ecological security were mainly concentrated in the cultivated land zones. The land use changes and landscape pattern alterations between 1990 and 2020 in the study area were closely intertwined with the spatiotemporal evolution of landscape ecological security.

Analysis of Spatial Autocorrelation of Landscape Ecological Security

Global Spatial Autocorrelation Analysis of Landscape Ecological Security

Based on the Landscape Ecological Security Index data from the eastern mining area of Xuzhou from 1990 to 2020, Moran's I scatter plots for the three years (Fig. 7) were obtained by using Geoda software to conduct

a correlation analysis. The Moran's I values for 1990, 2010, and 2020 are 0.528, 0.512, and 0.554, respectively (Table 6). All the Moran's I values for each year are positive, and the significance levels do not exceed 0.05 (Fig. 8). This indicates that the spatial distribution of ecological security values in the study area is not random, but exhibits a certain positive correlation, demonstrating an aggregated distribution phenomenon. This reflects the spatial diffusion growth characteristics of the increase in ecological security values in the study area. Furthermore, Moran's I index for the year 2020 is higher than the other two years, suggesting an enhanced self-correlation and spatial clustering degree of ecological security in the study area. It exhibited an aggregation pattern in regions with both low and high ecological security values, conforming to the "low-low" and "high-high" clustering modes.

Local Indicators of Spatial Autocorrelation Analysis of Landscape Ecological Security

The study used the Local Indicators of Spatial Autocorrelation (LISA) to explore the local spatial correlation and clustering patterns of landscape ecological security within the study area. The LISA clustering map is shown in Fig. 9. There is a high degree of coupling between the distribution of landscape ecological security and regional land use in the study area. The degree of human activity aggregation corresponds to the spatial clustering of landscape ecological security. The primary clustering patterns of landscape ecological security in the study area are characterized by High-High (H-H) and Low-Low (L-L) clustering modes. The High-High clustering areas of landscape ecological security are mainly distributed in the eastern and northeastern

Table 6. Moran's index of spatial autocorrelation for landscape ecological security in the study area from 1990 to 2020.

Index	1990	2010	2020
Moran's I	0.528	0.512	0.554

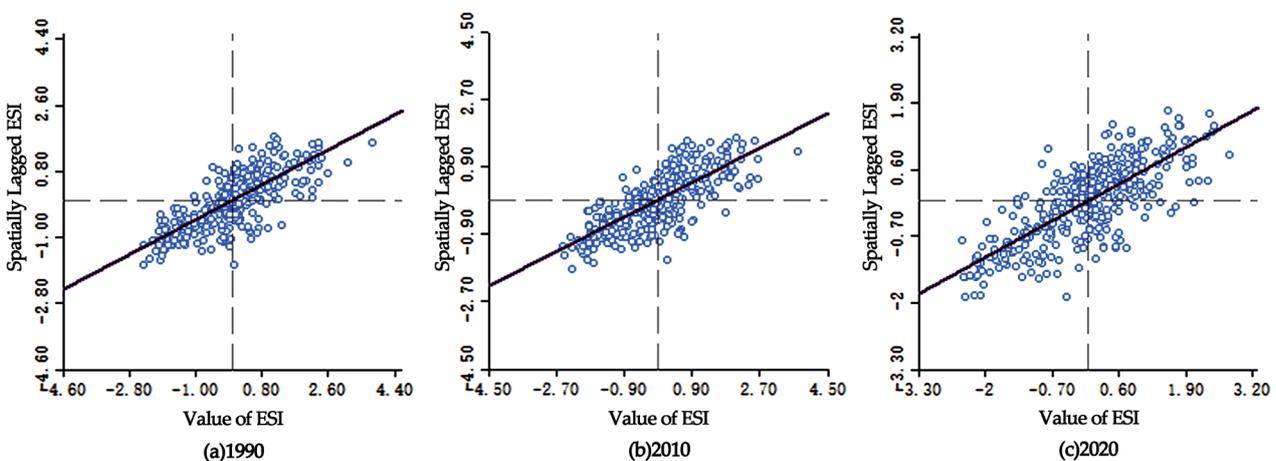


Fig. 7. Scatter plot of spatial correlation analysis in the study area from 1990 to 2020.

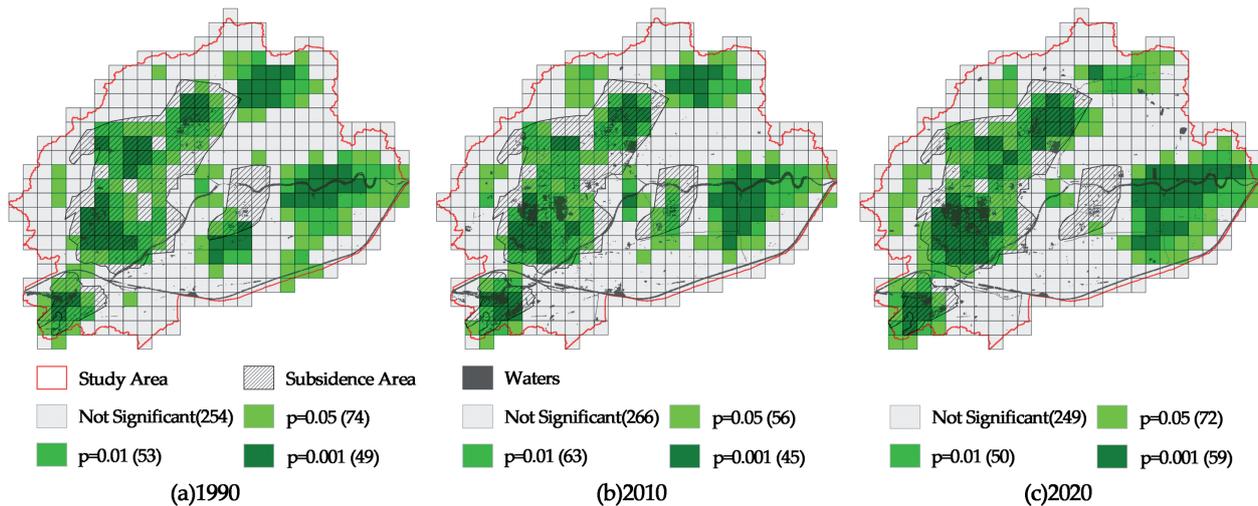


Fig. 8. Distribution of spatial autocorrelation significance in the study area from 1990 to 2020.

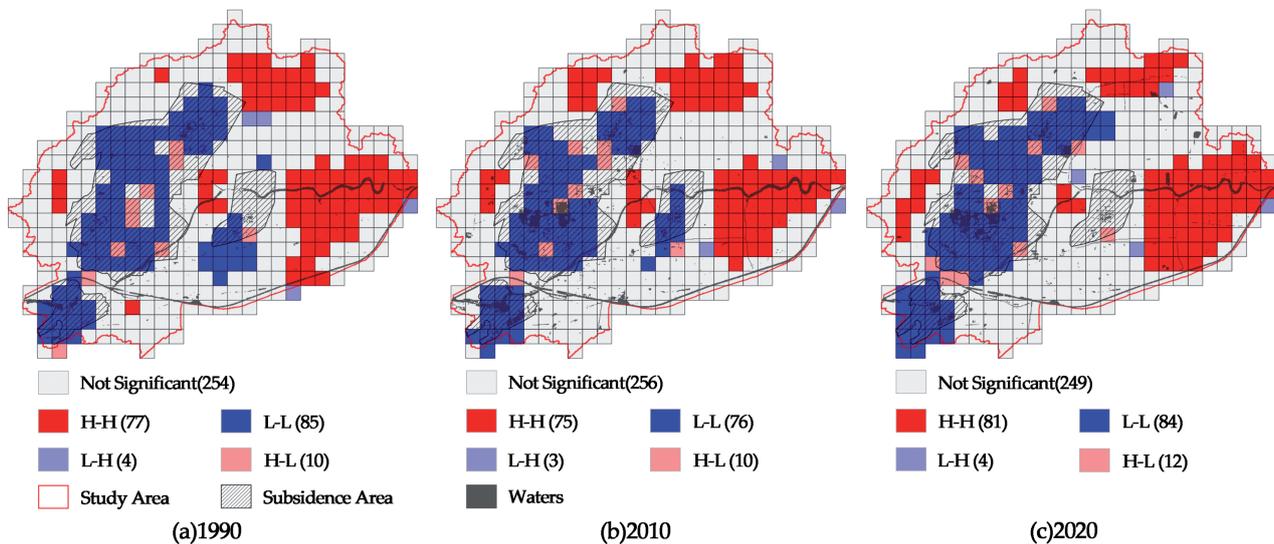


Fig. 9. Local indicators of spatial autocorrelation LISA cluster map of the study area from 1990 to 2020.

regions, which are less affected by human activities, encompassing cultivated land, grassland, and forest areas. In these regions, landscape fragmentation is low, landscape dominance is high, and ecological security is relatively high. This pattern is consistent with the spatial distribution of landscape ecological security during the same period. The Low-Low clustering areas of landscape ecological security are mainly concentrated within the coal mining subsidence areas, which are characterized by relatively high levels of urbanization, dense populations, and lower landscape ecological security due to severe human activity disturbances. Surrounding the Low-Low clustering areas are some High-Low (H-L) clustering areas, which have a high possibility of being transformed from high landscape ecological security areas to low landscape ecological security areas. These areas should be particularly emphasized in future landscape planning.

The analysis of regional spatial autocorrelation reveals distinct differences in landscape ecological security characteristics between coal mining subsidence areas and non-subsidence areas within the study area. This underscores the spatial variability in the distribution of landscape ecological security across different levels.

Discussion

Reasons for the Evolution of the Landscape Ecological Security Pattern

In the third section of this study, the spatiotemporal evolution of landscape ecological security in the eastern mining area of Xuzhou is analyzed in three phases, aiming to provide scientific and reasonable planning suggestions for the region's future development. In this subsection,

the specific reasons for the changes in the landscape ecological security pattern within the study area are to be discussed. The factors influencing the evolution of regional landscape ecological security patterns are multifaceted, with the study area having long been subjected to dual disturbances from mining activities and urbanization. On this basis, this study primarily focused on exploring the impact of the dual disturbances of coal mining subsidence and urbanization on the evolution of the landscape ecological security pattern.

Impact of Coal Mining Subsidence on the Evolution of Landscape Ecological Security Pattern

Overall, from 1990 to 2020, regions with relatively poor landscape ecological security were primarily concentrated within three coal mining subsidence areas, with the low-level landscape ecological security zones mainly surrounding the subsidence water. The study area belongs to the high groundwater level mining area in the eastern part of the Huang-Huai region of China, where numerous coal mining subsidence water areas [45] are formed due to surface subsidence caused by underground mining. Intensive mining activities have varying impacts on both surface water and groundwater resources [46]. For surface water resources, the appearance of surface water affects the quality and hydrological characteristics of surface runoff, transforming certain regions from terrestrial ecosystems to water-land hybrid ecosystems, thereby altering the regional ecological environment. The impact on groundwater resources primarily involves changes in groundwater levels, which alter the distribution and migration patterns of water resources in the region and have a broader impact on the ecological environment [47]. Water, being an inherently unstable natural factor, possesses a vulnerable ecosystem with high ecological risks. Numerous coal mining subsidence water areas are formed due to intensive mining activities in the study area, resulting in a significant increase in water body patch areas. Prior to the remediation of these water areas, the ecological environment in the study area was marked by fragmentation, singularity, poor connectivity, and imbalanced hydrological processes, negatively affecting the regional landscape ecological security. After entering a stable subsidence period and implementing ecological restoration plans in the mining area, the subsidence water areas were integrated and managed, leading to a reduction in subsidence water areas, improved connectivity in the water network, regularization of landscape patches, increased regional ecological environment connectivity, and an enhancement of landscape ecological security. The Dahuangshan coal mining subsidence area can be used as an example. The large subsidence water area and increased water body fragmentation in 2010 resulted in deteriorating landscape ecological security. With the implementation of subsidence land remediation projects, water body restoration strategies were introduced [48], including the design of a circular water network system, retention of certain original river

channels, transformation of some hard revetments into permeable artificial ecological revetments, and local widening of river channels through bridge construction to facilitate flood control and storage. And a complete lake was formed by thoroughly restoring river channels and integrating subsidence water areas so as to create a wetland landscape. These remediation measures improved the regional ecological environment, mitigated further deterioration of the ecological environment, and led to an improvement in landscape ecological security in the area by 2020.

Meanwhile, studies conducted by researchers such as EFFah [49] and Zhengfu Bian [50] also support this finding. Among them, EFFah conducted research on the relationship between land use changes and habitat diversity in the Schlabendorf Süd mining area in Lower Lusatia, Germany. Using a set of nine landscape pattern indices, including Patch Density (PD), Landscape Shape Index (LSI), and Shannon's Diversity Index (SHDI), the study indicated that the water body expanded rapidly after mine closure, resulting in a fragmented, linear, and singular ecological landscape. Similarly, Zhengfu Bian analyzed the evolution of regional land use patterns by using landscape indices such as the Largest Patch Index (LPI) and Patch Density (PD). The results demonstrated that, under the influence of coal mining subsidence, the number and area of inundation patches increased significantly, with patches becoming more complex in shape. Additionally, the speed and extent of fragmentation were higher in comparison to other land classes.

Impact of Urbanization on the Evolution of Landscape Ecological Security Pattern

In addition to the impact of coal mining subsidence on regional landscape ecological security, the continuous expansion of construction land areas also exerts some influence on regional landscape ecological security. Between 1990 and 2020, the urbanization rate in the study area increased from 17.11% to 65.63%. However, the area of high and moderately high landscape ecological security zones within the study area consistently increased over the years (Table 5), indicating that the rapid urbanization did not lead to a continuous deterioration of the overall landscape ecological security status in the study area. To investigate the influence of urbanization on landscape ecological security, this study selected three typical areas of construction land expansion within the study area and analyzed the characteristics of land expansion and its impact on landscape ecological security. The southeastern part of the study area can be taken as an example. As is revealed, significant changes can be observed in the low and moderately low landscape ecological security zones between 1990 and 2020. Despite the expansion of construction land, the overall landscape ecological security status gradually improved. This can be attributed to the clustered expansion of construction land and integrated planning among different land types, leading to a significant reduction in landscape fragmentation and

subsequently enhancing the landscape ecological security status. In the northeastern urban areas where construction land expansion was intense, some low and moderately low landscape ecological security zones witnessed a slight increase in 2020 compared to 2010, resulting in a slightly deteriorated landscape ecological security status. This was due to the reduction in landscape diversity caused by the expansion of construction land. Therefore, in addition to the expansion of construction land, the diversity of the regional landscape should also be taken into account in land use planning. In the southern part of the Jiawang coal mining subsidence area, ecological restoration planning was implemented to address subsidence issues in 2010 [51]. However, the overall landscape ecological security status did not significantly improve despite the implementation of these measures. This suggests that in the process of ecological restoration planning, the effectiveness of improving regional landscape ecological security may be limited by inadequate spatial layout and planning.

Urbanization is bound to have an impact on the ecological environment, but the impacts on regional ecological conditions vary depending on different planning approaches. By controlling the total amount, spatial layout, and growth direction of construction land through spatial planning, the concentrated growth of construction land can reduce its fragmentation effect on ecological spaces. This approach helps mitigate landscape fragmentation caused by the expansion of construction land and reduces disturbances to landscape ecological security. Despite a 30.75% increase in construction land area by 2020, the overall landscape ecological security status in the study area remained stable and even improved. This indicates that a rational and relatively concentrated form of construction land expansion can contribute to enhancing landscape ecological security in the study area. Similar viewpoints are echoed in studies by researchers like Rao [52], Hou [53], and Zhao [54]. Among them, Rao and his team quantified the impact of China's urban growth patterns on landscape ecological security at the spatial level. Their study revealed that a certain degree of clustered development has a positive effect on urban landscape ecological security. Zhao and his colleagues analyzed the relationship between urban expansion types and changes in ecological landscape types. The results indicated that infill-type urban expansion gradually aggregates some construction land, leading to improvements in the regional ecological environment.

Impact of Relevant Planning Policies on Landscape Ecological Security in the Study Area

As an important coal resource-based city in East China, Xuzhou City has faced increasingly severe environmental pollution issues caused by coal extraction. This has necessitated urban transformation as an imperative path forward. The study area is a significant coal mining region within Xuzhou City. In addition to the impacts of

coal mining subsidence and urbanization on landscape ecological security, the planning policies during the process of regional transformation and development have also exerted influence on the landscape ecological security status of the study area.

In 2000, guided by national land spatial planning and land reclamation policies, Xuzhou proposed an integrated management model called "Comprehensive Treatment of Basic Farmland, Reclamation of Coal Mining Subsidence Land, Ecological Environment Restoration, and Wetland Landscape Development" [55]. The study area initially adopted a land reclamation model with a focus on agriculture, forestry, and fisheries. Partial coal mining subsidence land was reclaimed for agricultural use through methods such as "deep excavation and shallow filling," "filling", and "unrestricted development". The distribution chart of various landscape pattern indices generated through a three-year moving window method (Fig. 6) reveals that the landscape fragmentation (PD) of arable land has been decreasing year by year, while the landscape dominance (LPI) has been increasing annually. The implemented measures have effectively alleviated the changes in the cultivated land area in the study area. And the landscape ecological security status of some agricultural areas gradually improved. Furthermore, ecological restoration was conducted in the coal mining subsidence areas of the study area. A stable and sustainable wetland landscape system centered around Pan'an Lake Wetland Park was developed [56] by integrating subsidence water bodies, establishing a regional water network, and creating a sound ecological foundation. The landscape fragmentation (PD) of some water patches has decreased, while the landscape dominance (LPI) and landscape contagion (CONTAG) have increased. The landscape ecological security status of some coal mining subsidence areas has improved. With the cessation of coal mining activities in the study area and the transition of regional development to a new stage, the focus has shifted from ecological transformation to comprehensive regional transformation [57]. Some industrial and mining land as well as coal mining subsidence land in the study area have been transformed into residential land, educational and research land, emerging industry land, park green space, and ecological wetland. The industrial structure has shifted from a single structure dominated by coal to a diversified structure of "resources-ecology-market-consumption," fostering regional harmony and urban-rural integration. This has significantly optimized the land use structure in the study area and improved the ecological environment. By 2020, the patch density (PD) and landscape shape index (LSI) in the study area significantly decreased; in contrast, the largest patch index (LPI) and landscape contagion (CONTAG) significantly increased; and the landscape ecological security status of the study area remains stable and even experiences certain improvements.

Understanding the future development direction of the study area is also conducive to improving the state of landscape ecological security. Based on agricultural space, ecological space, and urban space, "Xuzhou City's

Overall Land Spatial Planning (2021-2035)” proposes a coordinated delineation of three control lines - Permanent Basic Farmland, Ecological Protection Redline, and Urban Development Boundary. Simultaneously, the Xuzhou municipal government aims to integrate the Jiawang area comprehensively into the main urban area, making urbanization a major developmental prospect for the study area. The continuous expansion of urban space will inevitably impact agricultural and ecological spaces. To better adjust the regional land use structure to urban transformation and development, the study area needs to focus on protecting the “Da Huang Mountain - Bu Lao River - Pan An Lake” ecological corridor, emphasize the creation of riverside ecological spaces along the Beijing-Hangzhou Grand Canal, strengthen ecological restoration in coal mining subsidence areas and comprehensive treatment of river and lake systems, safeguard high-quality arable land and promote the construction of Xuzhou’s urban agricultural development zone, and develop land resources rationally while ensuring the orderly expansion of construction land.

Research Limitations and Prospects

This study conducted an analysis of land use and the spatiotemporal evolution of landscape ecological security in a mining area with high ground water levels. By combining spatial correlation analysis, this study revealed the overall characteristics and localized variations of the spatiotemporal distribution of landscape ecological security. Since the impact of coal mining subsidence on regional ecosystems is a complex process, this study primarily focused on exploring the influence of subsidence water accumulation on landscape ecological security in the study area. Further research is needed to investigate the impacts of various ecological environmental issues arising from coal mining subsidence at different stages on landscape ecological security.

The current study was conducted at the scale of one single mining area. In future research, a multi-scale analysis can be undertaken, encompassing both broader and finer perspectives, to yield comprehensive conclusions. Investigations at macro and micro scales can be integrated to provide a systemic understanding. Future research could also involve dynamic prediction and simulation of different stages of coal mining subsidence, quantitatively exploring their impacts on landscape ecological security. This approach could offer guidance for the sustainable development of other mining subsidence areas with high ground water levels.

Conclusion

The study area is located in the eastern mining area of Xuzhou. Utilizing Landsat satellite imagery for the years 1990, 2010, and 2020 as the study periods, this study was conducted in three aspects: land use change within the Xuzhou eastern mining area, the evolution of landscape

ecological security, and spatial correlation analysis. The following conclusions were drawn:

- (1) From 1990 to 2020, dynamic transitions were observed in all six land use types within the study area. Influenced by rapid urbanization, the area of construction land consistently increased, experiencing 30.75% growth over the span of 30 years. Cultivated land remained the predominant land use type in the study area. The dynamic changes in the area of waters, which are mainly mutual transformations with construction land and cultivated land, were most pronounced due to the influence of management measures related to subsidence water and subsided land. There exist complex and multi-stage, multi-objective transformation relationships among different land use types.
- (2) From 1990 to 2020, evident spatiotemporal variations in the landscape ecological security status were observed within the study area. From the temporal dimension, the overall landscape ecological security status exhibited a pattern of initial deterioration-later improvement. Between 1990 and 2010, the landscape ecological security status worsened, characterized by an increase in landscape fragmentation and a decrease in landscape dominance. By 2020, the landscape ecological security status of the study area has been improved, marked by reduced landscape fragmentation and enhanced landscape dominance. From a spatial perspective, areas with low and moderately low landscape ecological security were primarily concentrated in coal mining subsidence areas, certain waters, and densely developed construction land areas. Conversely, areas with moderate, moderately high, and high landscape ecological security were mainly distributed within cultivated land, grassland, and forest land. The evolution of land use within the study area was closely intertwined with the pattern of landscape ecological security.
- (3) The landscape ecological security status within the study area exhibits a significant positive spatial correlation. The distribution of local indicators of spatial autocorrelation (LISA) clusters closely aligns with the spatial pattern of landscape ecological security. High-high aggregation areas are primarily located in cultivated land, grassland, and forest land regions, as well as in the northeastern part of the study area, where certain landscape patches of construction land remain relatively intact. Low-low aggregation areas are concentrated in coal mining subsidence regions characterized by dense construction land, complex land use, and dense subsided water areas. High-low aggregation zones in the study area have a higher likelihood of experiencing deteriorating landscape ecological security status. Conversely, low-high aggregation zones are more likely to achieve improvements in landscape ecological security. In future planning, special attention should be paid to the relationships between high-low and low-high aggregation zones and adjacent land parcels.

- (4) The evolution of landscape ecological security status in the study area is the result of multiple interacting factors. Coal mining subsidence and urbanization are the primary factors that influence the changes in the landscape's ecological security status, and their effects are dual-sided. Subsidence-induced water accumulation, while contributing to regional ecological degradation, also enhances landscape diversity. With the implementation of scientifically sound planning policies, the orderly expansion of construction land has the potential to integrate regional landscape patches and reduce landscape fragmentation. Guided by ecological restoration planning, effective treatment of coal mining subsidence areas in the study area can contribute to the enhancement of landscape ecological security, combining with well-coordinated surrounding environments, scientific and rational planning, and balanced interrelations among land classes. By considering the integrity and diversity of landscape patches comprehensively and optimizing multiple factors, it is possible to facilitate mutually beneficial development between regional socio-economy and the ecological environment. This approach can help mitigate the conflicts between resources and the environment, ultimately leading to the improvement of landscape ecological security in the study area.
- (5) In the current international context, landscape ecological security assessments in subsided coal mining areas with high groundwater levels often focus on landscape pattern indices, ecosystem services, biodiversity, and other factors, while paying inadequate attention to the impact of subsidence water on the regional hydrological environment. This study comprehensively considered the factors of coal mining subsidence and the influence of subsidence water on the hydrological environment. The landscape ecological security assessment system is optimized, making the research methodology more comprehensive and the evaluation results more scientific. Subsided coal mining areas with high groundwater levels commonly face severe land resource destruction and deterioration of aquatic ecosystems. The research framework and methods developed in this study can guide other subsided coal mining areas with high groundwater levels in conducting research on landscape reconstruction, biodiversity conservation, ecological security assessment, and ecological network reconstruction. This guidance can provide a basis for government decision-making, ultimately achieving spatial optimization and environmental sustainability in subsided coal mining areas with high groundwater levels.

Acknowledgements

This research was funded by the National Natural Science Foundations of China (grant number 52378082; 52208091) and the Graduate Innovation Program of China University of Mining and Technology (grant number

2023WLJCRCZL301) and the Postgraduate Research & Practice Innovation Program of Jiangsu Province (grant number KYCX23_2637).

Conflict of Interest

The authors declare no conflict of interest.

References and Notes

- XIAO W., LI S., WANG Z., YANG Y., WANG T. Ecological risk identification and assessment for a coal mine with a high groundwater table. *Acta Ecologica Sinica*. **36** (17), 5611, **2016**.
- TANG Q., WANG J., JING Z. Ecological vulnerability of mining resource-based cities: a review. *J. Ecol. Rural Environ*. **36**, 825, **2020**.
- HU Z., LONG J., WANG X. Self-healing, natural restoration and artificial restoration of ecological environment for coal mining. *Journal of China Coal Society*. **39** (8), 1751, **2014**.
- HU Z., YANG G., XIAO W., LI J., YANG Y., YU Y. Farmland damage and its impact on the overlapped areas of cropland and coal resources in the eastern plains of China. *Resources, Conservation and Recycling*. **86**, 1, **2014**.
- HU Z.-Q., XIAO W., WANG P.-J., ZHAO Y.-L. Concurrent mining and reclamation for underground coal mining. *Journal of China Coal Society*. **38** (2), 301, **2013**.
- ZHOU N. Q., ZHAO S. Urbanization process and induced environmental geological hazards in China. *Natural Hazards*. **67** (2), 797, **2013**.
- WEI S., PAN J., LIU X. Landscape ecological safety assessment and landscape pattern optimization in arid inland river basin: Take Ganzhou District as an example. *Human and Ecological Risk Assessment: An International Journal*. **26** (3), 782, **2020**.
- YUAN Y., LUO Z., ZHAO J., QI S. Landscape ecological security evaluation of Nanchang City based on landscape structure and spatial statistics. *Research of Soil and Water Conservation*. **27** (3), 247, **2020**.
- LI X., YANG G. Evaluation of urban landscape ecological security in karst areas based on 3S technologies: An example of Guiyang City. *Caesologica Sinica*. **35** (3), 340, **2016**.
- LIU P., ZHANG X., MA C., ZHANG H., HAN R., LU X. Ecological Security assessment based on remote sensing and landscape ecology model. *Journal of Sensors*. **2021**, 1, **2021**.
- WEI W., XIE B. B. Evaluation of the ecological security in Shiyang River Basin based on Grid GIS and PSR model. *Advanced Materials Research*. **864**, 1042, **2014**.
- LI Y., GENG H. Evolution of land use landscape patterns in karst watersheds of Guizhou Plateau and its ecological security evaluation. *Land*. **11** (12), 2225, **2022**.
- WANG Y., CHENG L., ZHENG Y. An Adjusted Landscape Ecological Security of Cultivated Land Evaluation Method Based on the Interaction between Cultivated Land and Surrounding Land Types. *Land*. **12** (4), 833, **2023**.
- HAN Y., GUO X., JIANG Y., RAO L., SUN K., LI J., WANG L. Cultivated land landscape ecological security: influencing factors and spatial differences in the hilly region of South China. *Shengtai Xuebao*. **39**, 6522, **2019**.
- REN J., YANG K., CHEN Q., MO S., WANG Z. Evaluation on ecological security of land use landscape in Guizhou Caohai wetland. *Environmental Science & Technology (China)*. **41** (5), 158, **2018**.

16. CHEN K., QI M., WANG X., HUANG G. Study of urban lake landscape ecological security pattern evolution in Wuhan, 1995-2015. *Acta Ecol. Sin.* **39**, 1725, **2019**.
17. JU L., LIU Y., YANG J., XIANG M., XIANG Q., HU W., DING Z. Construction of Nature Reserves' Ecological Security Pattern Based on Landscape Ecological Risk Assessment: A Case Study of Garze Tibetan Autonomous Prefecture, China. *Sustainability*. **15** (11), 8707, **2023**.
18. ZHOU K., LIU Y., TAN R., SONG Y. Urban dynamics, landscape ecological security, and policy implications: A case study from the Wuhan area of central China. *Cities*. **41**, 141, **2014**.
19. YU X., WU K., YUN W., WEI H., LIU L., SONG Y., GAO X. Analysis on temporal and spatial variation of landscape ecological security in modern agricultural area. *Transactions of the Chinese Society of Agricultural Engineering*. **32** (8), 253, **2016**.
20. ZHANG X., DU H., WANG Y., CHEN Y., MA L., DONG T. Watershed landscape ecological risk assessment and landscape pattern optimization: Take Fujiang River Basin as an example. *Human and Ecological Risk Assessment: An International Journal*. **27** (9-10), 2254, **2021**.
21. QINGLIN S., XIAOMING H., SIVUAN W. Planned Response to the Transformation and Development of Coal Resource-based Cities in the New Era: Taking the "Urban Master Plan of Huainan City (2016-2035)" as an Example. *Urban Development Studies*. **25** (8), **2018**.
22. ZHANG L., ZHANG S., YE HC H. Landscape indices of land damage and land reclamation in an opencast coal mine. *Resour. Sci.* **36**, 55, **2014**.
23. GAO X., CAI X., WANG J., MU Y. Analysis of landscape pattern change and its driving forces in typical mining area of Guizhou Province during 10 years. *Environmental Science & Technology (China)*. **36** (11), 168, **2013**.
24. FENG Y., SHI F., CAO Y. Ecological security pattern tectonics and evaluation analysis of mining brownfield parks. *J. Harbin Inst. Technol.* **49**, 177, **2017**.
25. ZHANG H., YAN Q., XIE F., MA S. Evaluation and prediction of landscape ecological security based on a CA-Markov model in overlapped area of crop and coal production. *Land*. **12** (1), 207, **2023**.
26. DU P., XIA J., DU Q., LUO Y., TAN K. Evaluation of the spatio-temporal pattern of urban ecological security using remote sensing and GIS. *International journal of remote sensing*. **34** (3), 848, **2013**.
27. LIU H., ZHU X., CHENG Y., SU L., DAI L., ZHENG L., FANG S., JIANG M., ZHANG Q., SUN Q., LI Y., LI D. Key technology of human environment and ecological reconstruction in high submersible level coal mining subsidence area: A case study from Lüjin Lake, HuaiBei. *China Coal Soc.* **46**, 4021, **2021**.
28. AN Y., BIAN Z., DAI W., DONG J. Analysis on the gas carbon source and carbon sink in coal mining: A case study of Jiawang, Xuzhou. *J. China Univ. Min. Technol.* **46**, 415, **2017**.
29. SUN L., WEI J., BILAL M., TIAN X., JIA C., GUO Y., MI X. Aerosol optical depth retrieval over bright areas using Landsat 8 OLI images. *Remote Sensing*. **8** (1), 23, **2015**.
30. LI S., DONG B., GAO X., XU H., REN C., LIU Y., PENG L. Study on spatio-temporal evolution of habitat quality based on land-use change in Chongming Dongtan, China. *Environmental Earth Sciences*. **81** (7), 220, **2022**.
31. LIU F., QIN T., GIRMA A., WANG H., WENG B., YU Z., WANG Z. Dynamics of land-use and vegetation change using NDVI and transfer matrix: A case study of the Huaihe River Basin. *Polish Journal of Environmental Studies*. **28** (1), 213, **2018**.
32. YU J., CHEN Y., PENG J., LI J., NIE Y. Comprehensive evaluation on land ecological quality based on GIS and Fragstats: A case study in Xiantao City Hubei Province. *Acta Ecol. Sin.* **40**, 2932, **2020**.
33. XU C., CHEN J., MENG A., ZHOU S. Study on Evaluation of Land Ecological Quality Based on FRAGSTATS—A Case of Yixing, Jiangsu Province. *Soils*. **45**, **2015**.
34. HE W., HUO J., MENG M., YIN S. The land use change and landscape ecological security assessment in Huailai County. *Chin. J. Soil Sci.* **47**, 15, **2016**.
35. WANG L., PANG Y. S. A review of regional ecological security evaluation. *Applied Mechanics and Materials*. **178**, 337, **2012**.
36. HAN B., LIU H., WANG R. Urban ecological security assessment for cities in the Beijing-Tianjin-Hebei metropolitan region based on fuzzy and entropy methods. *Ecological Modelling*. **318**, 217, **2015**.
37. ZHANG J., GAO J. Lake ecological security assessment based on SSWSSC framework from 2005 to 2013 in an interior lake basin, China. *Environmental Earth Sciences*. **75**, 1, **2016**.
38. BAI X., TANG J. Ecological security assessment of Tianjin by PSR model. *Procedia Environmental Sciences*. **2**, 881, **2010**.
39. WEN J., HOU K., LI H., ZHANG Y., HE D., MEI R. Study on the spatial-temporal differences and evolution of ecological security in the typical area of the Loess Plateau. *Environmental Science and Pollution Research*. **28**, 23521, **2021**.
40. LIN X., WANG Z. Landscape ecological risk assessment and its driving factors of multi-mountainous city. *Ecological Indicators*. **146**, 109823, **2023**.
41. KE X., WANG X., GUO H., YANG C., ZHOU Q., MOUGHARBEL A. Urban ecological security evaluation and spatial correlation research----based on data analysis of 16 cities in Hubei Province of China. *Journal of Cleaner Production*. **311**, 127613, **2021**.
42. QIU M., ZUO Q., WU Q., YANG Z., ZHANG J. Water ecological security assessment and spatial autocorrelation analysis of prefectural regions involved in the Yellow River Basin. *Scientific Reports*. **12** (1), 5105, **2022**.
43. SHI R., JIA Q., WEI F., DU G. Comprehensive evaluation of ecosystem health in pastoral areas of Qinghai-Tibet Plateau based on multi model. *Environmental Technology & Innovation*. **23**, 101552, **2021**.
44. MA L., BO J., LI X., FANG F., CHENG W. Identifying key landscape pattern indices influencing the ecological security of inland river basin: The middle and lower reaches of Shule River Basin as an example. *Science of the Total Environment*. **674**, 424, **2019**.
45. LIU H., JIANG Y., MISA R., GAO J., XIA M., PREUSSE A., SROKA A., JIANG Y. Ecological environment changes of mining areas around Nansi lake with remote sensing monitoring. *Environmental Science and Pollution Research*. **28**, 44152, **2021**.
46. XU S., ZHANG Y., SHI H., WANG K., GENG Y., CHEN J. Physical simulation of strata failure and its impact on overlying unconsolidated aquifer at various mining depths. *Water*. **10** (5), 650, **2018**.
47. LIL., LI W., WANG Q. Prediction and zoning of the impact of underground coal mining on groundwater resources. *Process Safety and Environmental Protection*. **168**, 454, **2022**.
48. GUO H. The Ecological Design with Multivariate Landscapes in Coal Mine Subsidence Land: A Case Study in Dahuang Mountain in Xuzhou. *Value Engineering*. **34** (30), 221, **2015**.

49. ANTWI E. K., KRAWCZYNSKI R., WIEGLEB G. Detecting the effect of disturbance on habitat diversity and land cover change in a post-mining area using GIS. *Landscape and Urban Planning*. **87** (1), 22, **2008**.
50. BIAN Z., ZHANG Y. Analysis of the evolution of land use pattern in Xuzhou coal mining area. *Acta Geographica Sinica*. (4), 349, **2006**.
51. ZHANG Y., GUO J. Research on Economic Transformation and Development of Resource Depleted Areas--Taking Xuzhou Pan'an Lake Wetland Park as an Example. *Resources and Habitant Environment*. (5), 37, **2021**.
52. RAO Y., DAI J., DAI D., HE Q., WANG H. Effect of compactness of urban growth on regional landscape ecological security. *Land*. **10** (8), 848, **2021**.
53. HOU L., WU F., XIE X. The spatial characteristics and relationships between landscape pattern and ecosystem service value along an urban-rural gradient in Xi'an city, China. *Ecological indicators*. **108**, 105720, **2020**.
54. ZHAO Y., ZOU Z., ZHANG X., WEI X. The relationship analysis of urban expansion types and changes in ecological landscape types based on LEI and MSPA in the city of Nanchang. *Journal of Natural Resources*. **34** (4), 732, **2019**.
55. Comprehensive Remediation of Coal Mining Subsidence Area in Pan'an Lake, Jiawang District, Xuzhou City, China. Available online: <http://zrzy.jiangsu.gov.cn/xwzx/ztjc/d51gsjdr/jylyzy/2020/04/17110106298938.html> (accessed on 15-07-2023).
56. WENHAN Z. Green development: A new exploration of resource exhausted city's transformation: A case study of Jiawang district, Xuzhou City. **2019**.
57. FENG S., CHANG J., HOU W. A framework for setting restoration priorities for coal subsidence areas based on green infrastructure (GI). *Acta Ecol Sin*. **36** (9), 2724, **2016**.

