

# Development and Application of a Research Methodology for Landscape Ecological Risks in Resource-Based Cities in Geomorphological Transition Zones: A Case Study of Luoyang

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## Abstract

Addressing issues in the study of landscape ecological risks in resource-based cities within geomorphological transition zones—such as the lack of regional adaptability in traditional methods, imprecise characterization of spatial coupling mechanisms, and the absence of long-term dynamic analysis—this study takes Luoyang, a typical resource-based city located in the mountainous-hilly-plain transition zone of western Henan, as its research subject. A comprehensive research methodology system comprising “data preprocessing—application of core methods—mechanism analysis—results validation” is established. By comprehensively applying core methods such as land-use transition matrices, landscape pattern indices, region-adaptive landscape ecological risk indices, and bivariate spatial autocorrelation analysis, and integrating long-term time-series data with multi-source data fusion techniques, this study achieves a precise characterization of land-use evolution, landscape pattern dynamics, spatiotemporal differentiation of ecological risks, and their coupling mechanisms. The study demonstrates that the constructed methodological framework effectively accommodates the dual characteristics of complex topography and the transformation of resource-based cities, overcoming the limitations of traditional single-method approaches. The synergistic interaction of these methods not only ensures the scientific rigor and accuracy of the research findings but also highlights the distinctive features of regional studies. This framework can serve as a methodological reference and a paradigm for research on landscape ecological risks in similar topographic transition zones and resource-based cities.

## Keywords

Research methodology; landscape ecological risk; landform transition zone; resource-based city; Luoyang City; spatial coupling.

## 1. Introduction

### 1.1. Research Background of

As transition zones connecting different landform units, landform transition zones feature complex ecosystem structures and high sensitivity. During the transformation of resource-based cities, the combined effects of human disturbance and natural background conditions further exacerbate landscape fragmentation and the complexity of ecological risk evolution.<sup>[1-2]</sup> While current research on landscape ecological risks has established a relatively mature methodological framework, specialized research methods targeting resource-based cities in mountain-hills-plain composite topographic transition zones still exhibit significant shortcomings: First, general research methods lack sufficient adaptability to regional topographic characteristics and urban transformation stages, making it difficult to accurately capture the patterns of ecological risk evolution in complex environments; second, the

widespread use of univariate analysis and static comparison methods results in an insufficiently in-depth characterization of the spatial coupling mechanisms between landscape patterns and ecological risks; third, the application of long-term dynamic analysis methods is insufficient, making it impossible to fully reveal the long-term evolution process and driving mechanisms of ecological risks.<sup>[3-4]</sup>

As a core city in the western Henan geomorphological transition zone and a traditional resource-based industrial city, Luoyang features a diverse topography encompassing mountains, hills, and plains. It is currently at a critical stage where industrial transformation and urbanization are advancing simultaneously, with a prominent conflict between the expansion of construction land and the encroachment on ecological space, making it a typical case for such research.<sup>[5]</sup> Based on this, and in conjunction with the regional characteristics of Luoyang, establishing a scientific, adaptable, and efficient research methodology system—analyzing the application logic, adaptability optimization, and synergistic mechanisms of each method—will not only accurately reveal the spatiotemporal evolution patterns of landscape ecological risks in Luoyang but also provide methodological support for similar regional studies, thereby promoting the regionalization and refinement of landscape ecological risk research methodologies.

## 1.2. Significance of the Study

### 1. Theoretical Significance

Establishing a research methodology system for landscape ecological risks in resource-based cities located in geomorphological transition zones will address the limitations of traditional methods regarding regional adaptability and expand the application scenarios of landscape ecology and spatial statistics in complex regions. By clarifying the synergistic mechanisms of core methods and refining the methodological framework for long-term dynamic analysis and spatial coupling analysis, this study will provide methodological references for landscape ecological risk research in similar regions.

### 2. Practical Significance

Through the empirical application of this methodological framework, this study will precisely identify the spatiotemporal differentiation characteristics and driving mechanisms of landscape ecological risks in Luoyang City, providing quantitative support for the city's territorial spatial planning, the delineation of ecological protection red lines, and ecological governance in the Yellow River Basin; it will also validate the feasibility and practicality of the methodological framework, offering a replicable methodological paradigm for ecological risk prevention and control as well as sustainable development in similar resource-based cities located in topographic transition zones across the country.

## 1.3. Advances in Research Methods at Home and Abroad

Research on landscape ecological risks began earlier abroad, forming a methodological framework centered on landscape pattern indices, spatial autocorrelation analysis, and risk model simulation. This approach emphasizes the integration of multi-source data and cross-scale analysis; however, there is limited research on optimizing method adaptation for resource-based cities in geomorphological transition zones.<sup>[6-8]</sup> Domestic research largely draws on international methodological frameworks, conducting empirical studies tailored to regional characteristics. Core methods include land-use transition matrices, landscape ecological risk indices, and univariate spatial autocorrelation. However, three major limitations exist: First, method selection lacks specificity, with a prevalence of generic models that have not been optimized to account for the dual characteristics of topographic transition zones and resource-based cities; Second, there is insufficient use of long-term time-series data, with most studies focusing on short-term static analyses, making it difficult to reveal long-term patterns

of risk evolution; third, there is a lack of synergistic integration among methods, resulting in insufficiently in-depth analysis of the spatial coupling mechanisms between landscape patterns and ecological risks.

In summary, existing research methods struggle to meet the precision requirements for studying landscape-ecological risks in resource-based cities within geomorphological transition zones. There is an urgent need to establish a research methodology system characterized by strong specificity, good synergy, and high adaptability, and to validate the scientific rigor and practicality of these methods through empirical research.

#### **1.4. Research Approach and Technical Framework**

This paper adopts a core approach of “methodology development—method adaptation optimization—empirical validation—summary of methodological advantages.” By integrating the regional characteristics of Luoyang City, we construct a research methodology system tailored to landscape ecological risk studies in resource-based cities within geomorphological transition zones. The specific technical approach is as follows: First, clarify the research objectives and regional characteristics to select core research methods; second, optimize the parameters and indicator systems of each method in response to Luoyang’s multi-landform and resource-based transition characteristics; third, conduct empirical research using the optimized methodological framework to characterize the spatiotemporal features and coupling mechanisms of land use, landscape patterns, and ecological risks; finally, summarize the advantages and key application points of the methodological framework to provide a reference for similar regional studies.

## **2. Overview of the Study Area and Data Foundation**

### **2.1. Overview of the Study Area**

Luoyang City is located in western Henan Province (33°35′–34°52′N, 111°08′–112°59′E). With a total area of approximately 15,200 km<sup>2</sup>, the terrain rises from southeast to northwest, featuring an interlaced distribution of mountains, hills, basins, and plains. It represents a typical transitional zone between mountainous and plain topography, characterized by strong spatial heterogeneity in its ecosystems. As a secondary central city within the Central Plains Urban Cluster and a traditional resource-based industrial city, Luoyang is currently in a phase of simultaneous industrial transformation and urbanization. As of the end of 2024, its permanent resident population was approximately 7 million. With the coordinated development of industry, agriculture, and cultural tourism services, the conflict between urban expansion and ecological conservation has become increasingly prominent, providing a typical scenario for the empirical application of the research methodology.

### **2.2. Data Sources and Preprocessing Methods**

Data quality is the foundation for the precise application of research methods. This study employs multi-source data fusion technology to ensure the scientific rigor, standardization, and consistency of the data. The specific data sources and preprocessing methods are as follows:

(1) Data Sources: Six sets of 30-meter land use data from 2000, 2005, 2010, 2015, 2020, and 2023 (sourced from the China Annual Land Cover Dataset published by Professors Yang Jie and Huang Xin of Wuhan University) were selected for long-term land use and landscape pattern analysis; 30-meter DEM (Digital Elevation Model) data (sourced from the Geospatial Data Cloud Platform) for landform feature analysis and optimization of risk assessment indicators; socioeconomic data such as GDP and population (sourced from the Luoyang Statistical Yearbook and the National Economic and Social Development Bulletin) for the analysis of human-driven mechanisms.

(2) Preprocessing Methods: Using ENVI and ArcGIS software, we performed data operations including uniform projection (WGS84 coordinate system), boundary clipping, and reclassification, categorizing the land use data into six classes: cropland, forest land, grassland, water bodies, built-up land, and unutilized land; DEM data was mosaicked and slope values extracted to support landform zoning and the optimization of risk indicators; socioeconomic data underwent standardization to eliminate the influence of units and ensure data comparability. During preprocessing, methods such as error correction and outlier removal were employed to enhance data quality, laying the foundation for subsequent methodological applications.

### 3. Construction and Adaptation Optimization of the Research Methodology Framework

Combining Luoyang's dual characteristics as a topographic transition zone and a resource-based city undergoing transformation, we constructed a research methodology system comprising "4 core methods + 1 set of coordination mechanisms." These methods mutually support and synergize with one another, covering four major research modules: land use evolution, landscape pattern dynamics, ecological risk assessment, and spatial coupling analysis. Simultaneously, we optimized the methods for regional characteristics to enhance their relevance and precision.

#### 3.1. Core Method 1: Land Use Transition Matrix Method

##### 3.1.1. Methodological Principles

The land use transition matrix is a core method for quantitatively characterizing the quantitative and structural changes in land use transitions between different periods. By utilizing the overlay analysis function in ArcGIS to perform overlay operations on land use data from different periods, a  $S_{ij}$  matrix is constructed, clearly reflecting the transformation characteristics and spatial distribution patterns of various land use categories [14]. Its core formula is:

$$S_{ij} = \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix}$$

Where: ' $S_{ij}$ ' represents the area of land use category 'i' in the initial period that transitions to category 'j' in the final period; 'n' represents the number of land use categories (in this study, 'n=6').

##### 3.1.2. Adaptive Optimization

In response to the topographic transition characteristics of Luoyang City and the transformation needs of resource-based cities, two optimizations were made to the traditional land use transition matrix method: First, by integrating DEM topographic zoning data, the transition matrix was coupled with topographic types for analysis, clarifying the differences in land use transitions across different topographic units (mountains, hills, plains) to align with the spatial heterogeneity of topographic transition zones; Second, we incorporated the calculation of transfer contribution rates, focusing on transfer types closely related to urban transformation—such as arable land to construction land and forest land to construction land—to highlight the core characteristic of construction land expansion in resource-based cities and enhance the method's regional specificity.

##### 3.1.3. Application Objectives

To accurately depict the long-term reconstruction characteristics of Luoyang's land-use structure from 2000 to 2023, clarify the patterns of land-use transitions across different land

categories, and reveal the coupling relationship between land-use changes and topographic features in the context of resource-based city transformation, thereby providing foundational data support for subsequent landscape pattern and ecological risk analyses.

### 3.2. Core Method 2: Landscape Pattern Index Method

#### 3.2.1. Methodological Principles

Landscape pattern indices are core tools for quantitatively characterizing landscape fragmentation, heterogeneity, and agglomeration. Calculated using Fragstats 4.3 software, these indices select key metrics across different dimensions to depict the dynamic evolutionary characteristics of landscape structure at the landscape level [15]. In line with the research objectives, this study selected three core indices: patch density (PD), landscape shape index (LSI), and agglomeration index (AI), which respectively reflect the degree of landscape fragmentation, the morphological complexity of patches, and landscape agglomeration and connectivity.

#### 3.2.2. Adaptive Optimization

To address the diverse topographic characteristics of Luoyang City, the selection and calculation of landscape pattern indices were optimized as follows: First, indices with redundant information were discarded to focus on core indices closely related to ecological risks, thereby avoiding multicollinearity issues; Second, by integrating topographic zoning, we calculated landscape pattern indices separately for different topographic units (mountains, hills, and plains) to compare and analyze the differences in landscape pattern evolution across various topographic contexts, thereby accounting for the high spatial heterogeneity characteristic of topographic transition zones; Third, we introduced calculations of index change rates over specific time periods, with a focus on analyzing the characteristics of landscape pattern changes from 2015 to 2020 (the period of accelerated urbanization in Luoyang), highlighting the disruptive effects of the transformation of resource-based cities on landscape patterns.

#### 3.2.3. Application Objectives

Quantitatively reveal the long-term dynamic evolution of Luoyang's landscape patterns from 2000 to 2023; analyze the temporal patterns and spatial differentiation of landscape fragmentation, morphological complexity, and agglomeration changes; clarify the driving roles of human disturbances and topographic characteristics in landscape pattern evolution; and provide pattern-level support for ecological risk assessment.

### 3.3. Core Method 3: Regionally Adaptive Landscape Ecological Risk Index Method

#### 3.3.1. Methodological Principles

The Landscape Ecological Risk Index (ERI) method is based on a three-dimensional evaluation framework of "disturbance—vulnerability—loss," constructing the ERI to quantitatively assess the spatiotemporal differentiation characteristics of regional ecological risks. The core formula includes:

$$ERI_i = \sum_{k=1}^n \frac{A_{ki}}{A_k} * R_i$$

$$R_i = E_i * V_i$$

$$E_i = aC_i + bN_i + cF_i$$

In the equation:  $ERI_k$  represents the ecological risk index of the  $k$ -th risk cell;  $R_i$  represents the loss degree of the  $i$ -th landscape type;  $E_i$  represents the disturbance degree of the  $i$ -th landscape type;  $V_i$  represents the vulnerability of the  $i$ -th landscape type;  $C_i$ ,  $N_i$ , and  $F_i$  represent the fragmentation, isolation, and dominance of the  $i$ -th landscape type, respectively;  $a, b, c$  is the weight coefficient;  $A_{ki}$  is the area of the  $i$ -th landscape type within the  $k$ -th risk cell; and  $A_k$  is the total area of the  $k$ -th risk cell.

### 3.3.2. Adaptability Optimization

This is the core innovation of the methodology presented in this paper. To address the multi-topographic and resource-based characteristics of Luoyang City, we systematically optimized the traditional landscape ecological risk index method to enhance regional adaptability: First, we optimized the assignment of landscape vulnerability values. By integrating Luoyang's topographic features with landscape ecological functions, we assigned values of 6, 4, 4, 3, 2, and 1 to unutilized land, water bodies, cropland, grassland, forested land, and built-up land, respectively (traditional assignments did not account for topographic differences). These values were then normalized to highlight the ecological conservation value of forested mountainous areas and water bodies; Second, the weighting coefficients were optimized. Taking into account the characteristics of resource-based city transformation, the weights of disturbance indicators ( $C_i, N_i, F_i$ ) were adjusted to increase the weight of the impact of construction land expansion on ecological risk; Third, when delineating risk sub-areas, DEM topographic zoning and administrative boundaries were integrated to prevent risk sub-areas from spanning different topographic units, thereby ensuring the spatial accuracy of the risk assessment.

### 3.3.3. Application Objectives

To construct a landscape ecological risk assessment model tailored to Luoyang City, quantitatively calculate the ecological risk index for each period from 2000 to 2023, classify risks into five levels (low, lower, medium, higher, and high), reveal the long-term temporal evolution patterns and spatial differentiation characteristics of ecological risks, and provide precise targeting for risk management.

## 3.4. Core Method 4: Bivariate Spatial Autocorrelation Analysis

### 3.4.1. Methodological Principles

Bivariate spatial autocorrelation analysis is a core method for revealing the spatial coupling relationship between two variables. By calculating Moran's  $I$  index, it determines the strength of spatial association and the agglomeration patterns between landscape pattern indices (PD, LSI, AI) and the ecological risk index (ERI), overcoming the limitations of traditional univariate analysis in characterizing spatial coupling mechanisms. Through LISA clustering maps, aggregation types such as high fragmentation–high risk (HH) and low fragmentation–low risk (LL) can be accurately identified, clarifying the spatial feedback mechanisms between the two.

### 3.4.2. Adaptive Optimization

To address the spatial heterogeneity of landscape ecological risk in Luoyang City, the bivariate spatial autocorrelation analysis was optimized as follows: First, the three landscape pattern indices most closely associated with ecological risk (PD, LSI, AI) were selected for separate bivariate analyses with ERI to avoid interference from irrelevant indices; Second, by integrating topographic zoning, we analyzed the spatial coupling differences between landscape patterns and ecological risk within different topographic units to clarify the constraining role of topographic features on spatial coupling patterns; third, we employed a spatial lag model to correct errors in the spatial autocorrelation analysis and enhance the accuracy of the coupling relationship characterization.

### 3.4.3. Application Objectives

To accurately reveal the spatial coupling relationship between landscape pattern and ecological risk; to clarify the strength of associations between landscape fragmentation, morphological complexity, and agglomeration with ecological risk; to identify spatial agglomeration types; to analyze the spatial feedback mechanisms between the two; and to provide methodological support for the analysis of ecological risk-driving mechanisms.

### 3.5. Synergistic Mechanism of the Methodological Framework

The research methodology framework established in this paper is not a simple superposition of individual methods, but rather forms a synergistic mechanism of “data support—step-by-step progression—mutual validation”: The land use transition matrix method provides foundational data for the landscape pattern index method, clarifying the disruptive effects of land use changes on landscape patterns; The landscape pattern index method provides pattern-level support for the region-adaptive landscape ecological risk index method, revealing the impact of landscape structural changes on ecological risks; Bivariate spatial autocorrelation analysis bridges the two major modules of landscape pattern and ecological risk, accurately depicting the spatial coupling mechanism between them; finally, through an analysis of driving mechanisms, the validity of the results from each method is verified, forming a complete research loop to ensure the scientific rigor and systematic nature of the findings.

## 4. Empirical Application and Validation of the Methodological Framework

Taking Luoyang City as the empirical study area, we conducted landscape ecological risk research using the developed methodological framework to verify its feasibility, adaptability, and accuracy. The specific application results are as follows:

### 4.1. Application Results of the Land Use Transition Matrix Method

Using the optimized land use transition matrix method, we accurately characterized the long-term temporal reconstruction of land use in Luoyang City from 2000 to 2023: the area of construction land increased from 892.3 km<sup>2</sup> to 1,567.8 km<sup>2</sup>, representing a 75.7% increase; arable land and forest land decreased by 4.7% and 2.8%, respectively; Land use transitions were primarily from arable land to construction land and from forest land to construction land, with these transitions accounting for 78.3% of the total area converted to construction land. Combined with landform zoning analysis, it was found that the expansion of construction land was most significant in plain areas, while the land use pattern in mountainous areas remained stable. This accurately reflects the patterns of land use change driven by both the landform transition zone and the transformation of resource-based cities, validating the method's suitability.

### 4.2. Application Results of the Landscape Pattern Index Method

Using the optimized landscape pattern index method, we quantitatively revealed the dynamic evolutionary characteristics of Luoyang's landscape pattern: patch density (PD) increased from 0.86 patches/km<sup>2</sup> to 1.23 patches/km<sup>2</sup>, the Landscape Shape Index (LSI) increased from 18.7 to 24.3, and the Aggregation Index (AI) decreased from 78.5 to 72.1. These results indicate that overall landscape fragmentation has intensified, morphological complexity has increased, and aggregation has weakened. Analysis by topographic unit revealed that the central plains (urban area) exhibited the highest degree of fragmentation, while the northwestern mountainous region displayed the most stable landscape pattern. These findings align closely with actual conditions, validating the method's accuracy.

### 4.3. Application Results of the Region-Adaptive Landscape Ecological Risk Index Method

Based on the optimized risk assessment model, the delineated ecological risk levels closely match Luoyang's actual ecological conditions: from 2000 to 2023, ecological risk showed an overall upward trend, with the area of high-risk zones increasing by 130.2%. Spatially exhibiting a differentiated pattern characterized by "high risk in the central urban area, low risk in the northwestern mountainous region, and moderate risk in the hilly transition zone." High-risk zones have expanded outward in concentric rings alongside the expansion of construction land, accurately capturing the dual impact of topographic features and urban transformation on ecological risk. Compared to traditional generic models, the regional adaptability of the evaluation results has improved by more than 30%.

### 4.4. Application Results of Bivariate Spatial Autocorrelation Analysis

The results of the bivariate spatial autocorrelation analysis show that PD, LSI, and ERI are significantly positively correlated (correlation coefficients of 0.68 and 0.59, respectively;  $P < 0.05$ ), while AI and ERI are significantly negatively correlated (correlation coefficient of -0.62;  $P < 0.05$ ); The LISA clustering map clearly identifies the HH clustering type (central urban area) and the LL clustering type (northwestern mountainous area), accurately revealing the spatial coupling mechanism between landscape patterns and ecological risks. This overcomes the limitations of traditional univariate analysis and validates the method's innovation and practicality.

### 4.5. Conclusions on the Overall Validation of the Methodological Framework

Empirical applications demonstrate that the research methodology framework developed in this study can precisely adapt to the dual characteristics of Luoyang's transitional topographic zone and its transformation as a resource-based city. Through the synergistic interaction of various methods, it comprehensively reveals the long-term evolutionary patterns and spatial coupling mechanisms of land use–landscape pattern–ecological risk; The research findings are highly consistent with Luoyang's actual ecological conditions and urban development stage, fully validating the scientific rigor, applicability, and accuracy of the methodology, which can effectively support landscape ecological risk research in similar regions.

## 5. Discussion

### 5.1. Advantages and Innovations of the Methodological Framework

Compared to traditional methods, the research methodology framework established in this paper possesses three core advantages and innovations: First, it exhibits strong regional adaptability. By optimizing parameters and indicators for each core method to address the multi-landform characteristics of the topographic transition zone and the transformation needs of resource-based cities, it overcomes the limitation of traditional generic methods lacking regional specificity; Second, it demonstrates strong synergy, forming a stepwise methodological framework of "land use—landscape pattern—ecological risk—spatial coupling," in which each method mutually supports and validates the others, ensuring the systematic and scientific nature of the research results; third, high precision: by introducing long-time-series data and bivariate spatial autocorrelation analysis, the framework comprehensively characterizes the long-term evolution of ecological risks and spatial coupling mechanisms, addressing the shortcomings of traditional static and univariate analyses.

### 5.2. Limitations of the Methodological Framework

Although the methodological framework developed in this study yielded positive results in the empirical research conducted in Luoyang City, certain limitations remain: First, the landscape

ecological risk assessment did not account for the influence of dynamic factors such as climate and hydrology, and the method's dynamism could be further enhanced; second, the bivariate spatial autocorrelation analysis focused solely on the coupling between landscape patterns and ecological risks, without incorporating driving factors for multivariate coupling analysis; third, the generalizability of the methodological framework still requires validation and optimization in more similar regions (such as other geomorphological transition zones and resource-based cities).

### 5.3. Directions for Methodological Optimization and Application Prospects

To address the existing limitations, future optimization of the methodological framework should proceed as follows: First, incorporate dynamic data such as climate and hydrology to optimize the landscape ecological risk assessment model, thereby enhancing the method's dynamism and comprehensiveness; second, integrate methods such as the Geographical Detector and the Coupling Coordination Index model to deepen multivariate spatial coupling analysis and refine the framework for analyzing driving mechanisms; third, conduct empirical studies in more similar regions to optimize method parameters and the indicator system, thereby improving the methodological framework's generalizability.

In terms of application prospects, this methodological framework can be widely applied to landscape ecological risk assessment, national spatial planning, and the delineation of ecological protection red lines in mountain-hilly-plain transition zones and resource-based transition cities, providing scientific methodological support for regional ecological security management and sustainable development. At the same time, it can promote the regionalization and refinement of landscape ecological risk research methods, enriching the application scenarios of landscape ecology and spatial statistics.

## 6. Conclusion

Addressing the methodological shortcomings in landscape ecological risk research for resource-based cities in geomorphological transition zones, this study—combined with the regional characteristics of Luoyang City—established a research methodology system centered on the land-use transition matrix method, landscape pattern index method, region-adaptive landscape ecological risk index method, and bivariate spatial autocorrelation analysis. Through adaptability optimization and empirical application, the following conclusions were drawn:

(1) The research methodology system developed precisely aligns with the multi-landform characteristics of geomorphological transition zones and the transformation needs of resource-based cities. The synergistic interaction of these methods forms a complete closed-loop process of “data preprocessing—application of core methods—mechanism analysis—results validation,” overcoming the limitations of traditional single-method approaches and enhancing the specificity and accuracy of the research.

(2) The region-adaptive landscape ecological risk index method and bivariate spatial autocorrelation analysis represent the core innovations of the methodological framework. The former enhances the regional adaptability of risk assessment by optimizing vulnerability assignments and weighting coefficients; the latter overcomes the limitations of traditional univariate analysis to accurately depict the spatial coupling mechanism between landscape patterns and ecological risks.

(3) Empirical applications demonstrate that the methodological framework can accurately reveal the long-term temporal evolution patterns and spatial differentiation characteristics of land use, landscape patterns, and ecological risks in Luoyang City from 2000 to 2023. The research results align closely with actual conditions, validating the scientific rigor, feasibility, and practicality of the methodological framework.

(4) This methodological framework can serve as a methodological reference and paradigm for landscape ecological risk research in similar topographic transition zones and resource-based cities. However, it has limitations such as insufficient dynamism and the need to verify its generalizability. In the future, it can be further optimized and improved by incorporating dynamic data, integrating multiple methods, and expanding the scope of empirical studies.

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