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Socioeconomic Factors Dominate the Spatiotemporal Evolution of Urban Ecological Resilience in Environmentally Vulnerable Areas: A Case Study of the Loess Plateau

Weixin Wang [1], Huimin Chu [1], Qinmian Bai [1], Yehan Wu [1], Shaohong Wu [2], Xiaolan Li [3], Wei Wang [1] and Shanfeng He [1,*]

[1] School of Geography and Tourism, Qufu Normal University, Rizhao 276826, China; wxw020211@163.com (W.W.); huimchm@163.com (H.C.); baiqinmian@163.com (Q.B.); wuyehan1003@163.com (Y.W.); wangwei@qfnu.edu.cn (W.W.)
[2] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; wush@igsnrr.ac.cn
[3] School of Resources and Environment, Yili Normal University, Yining 835000, China; lixiaolan97@163.com
* Correspondence: hesf2020@qfnu.edu.cn; Tel.: +86-19862356365

Abstract

Under the background of the global "polycrisis", enhancing ecological resilience has become a key pathway for achieving sustainable urban development, particularly in ecologically fragile regions. This study takes the Loess Plateau as the study area and constructs an evaluation framework for urban ecological resilience based on three dimensions: resistance, adaptability, and recovery. By integrating multi-source data from 1990 to 2020, the spatiotemporal evolution of urban ecological resilience in the region is analyzed, and the Geodetector is employed to identify the impacts of natural, economic, and social factors on urban ecological resilience. The main findings are as follows: (1) The urban ecological resilience index on the Loess Plateau shows an overall trend of initial increase followed by decline. Cities in both the western and eastern parts exhibit similar evolutionary patterns, while cities in the central region demonstrate a continuous upward trend, with the resilience index increasing from 0.3658 in 1990 to 0.3838 in 2020. (2) Urban ecological resilience in the study area exhibits a spatial gradient pattern characterized by a decrease from core cities toward peripheral areas. Resilience levels gradually weaken outward from urban centers. The spatial agglomeration effect is relatively weak, with most regions showing insignificant clustering and lacking contiguous high-resilience clusters. (3) Urban ecological resilience on the Loess Plateau is jointly influenced by multiple factors, with the effects of key drivers displaying clear stage-specific characteristics. Socioeconomic factors—particularly population density, per capita GDP, and industrial structure—serve as the primary driving forces, while natural conditions provide basic constraints. Interactions among factors are dominated by bivariate interactions and nonlinear synergistic effects. These findings deepen the understanding of the evolution and driving mechanisms of urban ecological resilience in ecologically fragile regions and provide scientific support for enhancing urban resilience and promoting sustainable development in the Loess Plateau.

Keywords: driving forces; Geodetector; Loess Plateau; spatiotemporal pattern evolution; urban ecological resilience

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1. Introduction

The contemporary world confronts a "polycrisis"—a cascading interaction of interconnected environmental, economic, social, political, health, and technological crises where the combined effects far exceed the sum of their parts [1]. These complex and interdependent challenges span multiple domains, including the environment, society, economy, public health, geopolitics, governance, and technological development, reinforcing and amplifying one another to generate systemic risks [2]. In this context, both natural and human-made ecosystems must enhance their capacity to resist and adapt to risks, and to restore equilibrium following disruptions, thereby preserving their structural and functional stability. This capacity is defined as ecological resilience [3], characterized by an ecosystem's ability to recover, self-organize, and learn from disturbances [4]. The sustainable development of human society fundamentally relies on the sustainability of ecosystems and their services [5]. Enhancing ecological resilience is therefore a critical pathway to achieving sustainable development, as it provides a foundation for mitigating compounded risks, particularly climate change and natural disasters.

At present, social-ecological resilience has garnered extensive scholarly attention, prompting the development of diverse assessment frameworks and indicator systems. Within this framework, the conceptual scope of resilience can be expanded by adjusting system boundaries and integrating multiple dimensions [6]. This perspective facilitates the assessment of coupled social-economic-natural ecosystems, guiding them toward more sustainable development trajectories.

For example, Rafael Córdoba Hernández and Federico Camerin studied the Madrid Autonomous Community. Building on the EU MAES project, they utilized DPSIR, EUNIS, CICES, and SIOSE datasets to construct an urban planning assessment framework for ecological carrying capacity. This framework integrates ecological pressure identification, ecosystem service valuation, and spatial planning. Their study identified habitat conversion, pollution, and resource overexploitation as key stressors, demonstrating that the integration of spatial planning into ecological assessment can effectively enhance regional ecological resilience [7]. Similarly, Nemec et al. employed a streamlined framework to evaluate the social-ecological resilience of the Platte River system based on nine dimensions, ranging from ecological variability and modularity to social capital and multi-level governance [8]. Additionally, methodological frameworks such as the urban landscape quality index have been utilized to evaluate landscape quality and urban livability [9].

Furthermore, research methods across different spatial scales exhibit significant heterogeneity in data selection. Studies at watershed, regional, or municipal scales often integrate socioeconomic indicators from statistical yearbooks and complementary datasets to analyze spatial-temporal dynamics through key parameters like regulatory frameworks, industrial structure, and economic performance [10]. In contrast, finer-scale analyses—such as those focusing on subsidence areas—primarily employ land use datasets to assess the environmental impacts of land-cover change, emphasizing intra-regional spatial variability and differentiation patterns [11]. Comprehensive analysis reveals varied results across the study areas against a backdrop of overall ecological quality fluctuation, a pattern also observed in other regional studies that report pronounced spatiotemporal differentiation of urban ecological resilience [12]. Certain urban areas or smaller spatial units exhibit enhanced disturbance resistance, showcasing strong abilities to absorb impacts, adapt to changing conditions, and recover rapidly following the mitigation of stressors. Furthermore, these resilient systems can achieve new equilibrium states through adaptive learning and transformative processes [13]. This capacity can be quantified by measuring average recovery time and is significantly influenced by human social activities [14,15].

As an essential component of social–ecological resilience, urban ecological resilience emerges from the complex interplay between natural and human factors. Economic development, technological innovation, land use patterns, and climatic conditions all exert integrated and multifaceted influences on it [16]. Recognizing this, the 100 Resilient Cities initiative, launched by the Rockefeller Foundation, established resilience as a core objective for sustainable cities, emphasizing their capacity to absorb shocks, adapt, and recover amidst chronic stresses [17]. Building on this resilience-oriented framework, scholars have proposed diverse pathways to bolster urban ecological resilience, including promoting green trade, adopting clean technologies, optimizing intensive land use, and developing "sponge cities" and urban green infrastructure [18,19].

In China, three decades of rapid urbanization and intensive human activity have placed enormous pressure on urban ecosystems. The expansion of industrial and residential zones has systematically encroached upon natural habitats, precipitating a decline in ecosystem service capacity [20]. This spatiotemporal transformation has led to significant landscape fragmentation and increased impervious surface coverage [21], thereby exacerbating urban ecological vulnerabilities. The Loess Plateau serves as a distinct regional manifestation of a polycrisis. Its vulnerability is characterized by deeply interwoven contradictions across spatiotemporal scales—spanning environmental pressures, development constraints, social transformation, demographic shifts, land-use restructuring, and regional governance dilemmas. This has further elevated ecological risks for cities on the Loess Plateau. Therefore, improving the ecological resilience of cities in this region and strengthening their ability to resist risks and adapt to change has become crucial for achieving high-quality urban development [22].

In summary, current research on urban ecological resilience relies heavily on indicator frameworks built from single-dimensional or weighted multi-source data, often overlooking the integration of resilience's conceptual foundations and intrinsic attributes. There remains a lack of comprehensive analysis on how land use change, human activities, and economic development jointly shape urban ecological resilience, particularly at the scale of environmentally fragile regions such as Loess Plateau—a critical area for ecological restoration yet understudied in this regard. To address this gap, this study constructs a multidimensional assessment model based on resistance, adaptability, and recovery. By analyzing spatiotemporal changes in urban ecological resilience across the Loess Plateau from 1990 to 2020, and employing the Geodetector method to identify driving forces across natural, economic, and social dimensions, this research provides robust empirical evidence for building resilient cities and advancing sustainable development in the region.

2. Study Area

The Loess Plateau is located in the central and northern parts of China, spanning seven provincial-level regions: Qinghai, Gansu, Ningxia, Inner Mongolia, Shaanxi, Henan, and Shanxi. The region is predominantly characterized by arid and semi-arid climate zones (Figure 1). Based on provincial boundaries, it can be divided into three subregions—west, central, and east [23]. The Loess Plateau, recognized as the world's largest and most extensive loess deposit, is one of China's most ecologically fragile areas due to intense soil erosion, sparse vegetation cover, high population pressure, low land productivity, and severe sediment deposition in the Yellow River [24]. From the perspective of ecological resilience, these conditions contribute to inherently low levels of resistance, adaptability, and overall resilience. In recent years, the region has experienced rapid economic growth. By 2020, its GDP, industrial output, and per capita GDP had increased by factors of 14.35, 10.86, and 11.79, respectively, since 2000, exceeding the national average [25]. The urbanization rate rose from 34.9% to 63.8% during 2000–2020, driving substantial demographic

shifts and urban spatial expansion, often at the expense of natural ecosystems. This growth has triggered environmental challenges such as declining urban ecological quality, reduced ecosystem service values, and a heightened greenhouse effect, thereby posing significant constraints on sustainable urban development and ecological civilization construction in the Loess Plateau.

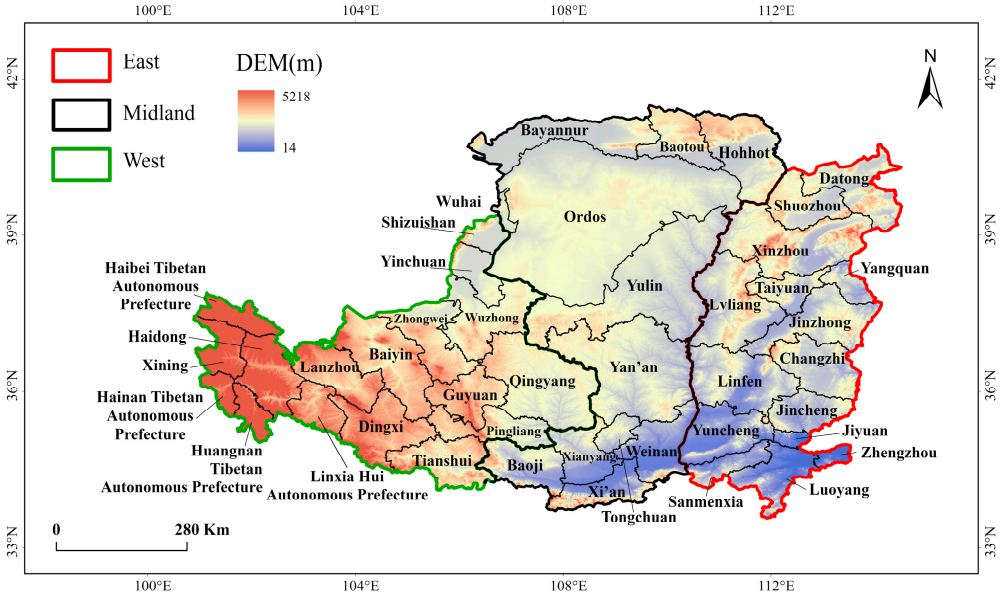

Figure 1. Overview of the study area.

3. Materials and Methods

3.1. Data Source

This study employed land use data for the Loess Plateau from the Chinese Academy of Sciences' Resource and Environment Science Data Center (https://www.resdc.cn). The dataset, with a 30 m resolution, covers the years 1990, 1995, 2000, 2005, 2010, 2015, and 2020. Following the primary classification standards of "Current land use classification" (GB/T21010-2017) [26] and considering the actual land use patterns and ecological context of the study area, we reclassified the land into six categories: farmland, forest land, grassland, water bodies, construction land, and unused land. Climate data (annual average precipitation and temperature) were obtained from NOAA's National Centers for Environmental Information (https://www.ncei.noaa.gov/). The average slope data was calculated and extracted from the DEM dataset available from the Geospatial Data Cloud (https://www.gscloud.cn). Socioeconomic indicators, including population density, per capita GDP, and total social retail sales for every five years from 1990 to 2020, were collected from the China City Statistical Yearbook [27].

3.2. Methods

3.2.1. Research Framework

Figure 2 presents the technical framework for analyzing the spatiotemporal evolution of urban ecological resilience and its driving factors in the Loess Plateau. An assessment model was developed based on three core dimensions of resilience—resistance, adaptability, and recovery. Subsequently, the Geodetector method was employed to examine both the individual and interactive effects of multiple factors on the spatial differentiation of ecological resilience across different periods. The findings provide a scientific basis for guiding ecological protection and restoration efforts, as well as for promoting the advancement of ecological civilization in the region.

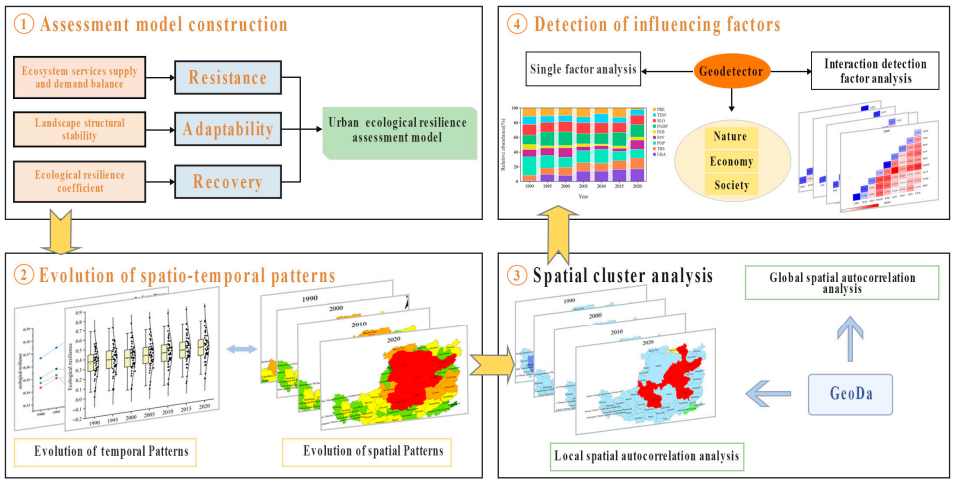

Figure 2. The overall framework of the study.

3.2.2. Urban Ecological Resilience Assessment Model

According to the International Association for Regional Sustainable Development, urban resilience refers to the capacity of urban systems and regions to effectively resist, absorb, adapt to, and respond to disturbances, while maintaining the stable functioning of public safety, social order, and economic systems [10]. These three attributes—resistance, adaptability, and recovery—also define urban ecological resilience, which constitutes a key component of overall urban resilience. Accordingly, this study develops an evaluation model based on these three dimensions.

Resistance refers to an urban ecosystem's ability to withstand external risks, which is closely linked to its ability to provide ecosystem services and to recover from disturbances [28]. Ecosystem services reflect the ecological foundation supporting human survival and development within specific spatiotemporal contexts [29]. The ecosystem service value (ESV), monetized using the equivalent factor method per unit area [30], quantifies this service provision capacity.

However, evaluations focused solely on the supply side fail to encapsulate human society's intrinsic dependence on ecosystems. As urban residents' demand for ecosystem services such as green spaces, parks, and aquatic environments continues to rise, such demand can, to some extent, drive the protection of ecological spaces through planning regulation and ecological conservation. This promotes coordination between ecosystem service supply and social demand and enhances the ability of urban ecosystems to resist external disturbances. Therefore, this study introduces ecosystem service demand on the basis of ecosystem service value and constructs an urban ecosystem resistance index from the perspective of supply–demand dynamics. Following Han Zenglin et al.'s research, we developed an index of ecosystem service demand (ESD) using three key indicators: land use intensity, population density, and GDP per land area [31]. Finally, the urban ecological resilience index (Rs) is derived by integrating ecosystem service supply (ESV) and demand (ESD). The formulas used are as follows:

$$ESV = \sum_{i=1}^{n} A_i \times VC_i \quad (1)$$

$$ESD = LDI \times lnP \times lnG \quad (2)$$

$$LDI = 100 \times \left(\sum_{i=1}^{n} P_i \times Q_i \right) \quad (3)$$

$$Rs = \sqrt{\frac{ESV \times ESD}{\left(\frac{ESV+ESD}{2}\right)^2}} \quad (4)$$

where Rs is the urban ecological resistance; ESV is the ecosystem service value of the study area; A_i is the total area of land use type i; VC_i is the ecosystem service value factor for land use type i (yuan/km^2); ESD is ecosystem service demand; P is the population density (persons/km^2); G is the land-averaged GDP (yuan/km^2); LDI is the combined land use intensity index; P_i is the intensity of land use at level i in the study area (i = 1, 2, 3, 4); Q_i is the percentage of area occupied by land use type i in the study area; n is the number of land use intensity tertiles in the study area.

Adaptability reflects an urban ecosystem's capacity to adjust to external environmental changes. Following the work of Xia Chuyu et al., this dimension of urban ecological resilience is measured using a landscape structure stability index (A) [32]. The structural stability of an ecosystem landscape is determined by the organizational stability of landscape patterns, which is closely related to spatial heterogeneity and landscape connectivity. These two factors represent distinct and complementary aspects of ecosystem landscape structure, so their weights can be assumed equal [33]. Based on actual land-use characteristics of the Loess Plateau, we selected patch density (PD) and the Shannon diversity index (SHDI) to represent landscape heterogeneity, while the patch cohesion index (COHESION) was used to measure landscape connectivity (Table 1). The calculation formula is as follows:

$$A = 0.25 \times PD + 0.25 \times SHDI + 0.5 \times COHESION \quad (5)$$

Table 1. Meaning of landscape structural stability index.

	Landscape Index	Descriptions
Landscape heterogeneity	Patch density (PD)	Reflecting the degree of landscape fragmentation, the larger the PD, the higher the degree of fragmentation
	Shannon diversity (SHDI)	Reflecting the diversity of patch types
Landscape connectedness	Patch cohesion (COHESION)	Reflecting the physical connectivity of the corresponding patch type

Recovery describes an urban ecosystem's capacity to restore its functions following external disturbances or pressures. This dimension of ecological resilience was quantified using an established ecological resilience model and its corresponding coefficients [33]. Specifically, the ecological resilience coefficients for different land-use types are assigned as follows: farmland = 0.3, orchard land = 0.6, forest land = 0.8, construction land = 0.2, water body = 0.8, tidal marsh = 0.7, and unused land = 1. These coefficients were set as spatially and temporally invariant during the study period (1990–2020), which is consistent with common practices in regional ecological resilience assessment. Such a coefficient system is applicable to the Loess Plateau because it reflects the basic biophysical properties and ecological stability of major land-use types in terrestrial ecosystems, which are highly consistent with the landscape composition and environmental background of the study area. The specific calculation formulas are provided below:

$$Rc = \sum A_k \times R_k \quad (6)$$

where *Rc* is the urban ecological recovery index, A_k is the area of land use type k, and R_k is the ecological resilience coefficient of land use type *k*.

In addition, to eliminate dimensional differences among indicators and ensure comparability across the time series, this study applies the min-max normalization method to remove the dimensions of the three dimensions—resistance, adaptability, and resilience. Each indicator is standardized to a [0, 1] range, using the global maximum and minimum values of all study units over the entire research period (1990–2020) as benchmarks. Given that resistance, adaptability, and recovery represent three distinct facets of urban ecological resilience, this study assigns equal weights to the three dimensions with reference to the research of Wang et al. [34]. The Urban Ecological Resilience Index (UERI) is calculated as follows:

$$UERI = \sqrt[3]{Rs \times A \times Rc} \tag{7}$$

where *Rs* is the urban ecological resistance index; *A* is the landscape structure stability index; *Rc* is the urban ecological recovery index. To further examine the robustness of the model, this study also tested the effects of different weighting schemes on the results. The results show that the spatial pattern of urban ecological resilience remains generally consistent under slight adjustments to the weighting scheme, indicating that the model exhibits strong robustness.

3.2.3. Spatial Autocorrelation Analysis

The Moran's I method was employed to evaluate spatial autocorrelation in urban ecological resilience across the Loess Plateau, identifying clustering patterns and spatial relationships among cities [35].

The global Moran's I index characterizes the spatial pattern and distribution status or clustering condition of metric attribute values throughout the entire study area. Formulae are given below:

$$Moran's\ I = \frac{n}{S_0} \times \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{8}$$

where n is the number of study units, x_i and x_j are the observed values of neighboring cells i and j, which is the average value of the ecological resilience index of cities, with w_{ij} taking the value of an element of the spatial weight matrix w, S_0 is the sum of all elements in the spatial weight matrix.

The Local Moran's I index is used to identify the spatial similarity or correlation between the attribute values of geographic units and their neighboring spatial units, and it can show how much each local unit aligns with the overall trend.

$$Local\ \text{Moran's I} = \frac{Z_i}{S^2}\sum_{j\neq i}^{n} w_{ij}Z_j \tag{9}$$

$$Z_i = x_i - \overline{x}\ ,\ Z_j = x_j - \overline{x}\ ,S^2 = \frac{1}{n}\sum(x_i - \overline{x})^2 \tag{10}$$

where w_{ij} is an element of the spatial weight matrix w taking the value, n is the total number of cities in the study area. x_i and x_j are the ecological resilience index of neighboring cities.

3.2.4. Geodetector

The Geodetector is a set of statistical methods designed to detect spatial heterogeneity and identify its underlying driving factors [36]. By applying the factor detector and interaction detector, the driving factors influencing the spatial distribution characteristics of urban ecological resilience on the Loess Plateau can be uncovered. Since the Geodetector

requires the discretization of continuous variables, and different discretization methods may affect the result stability, this study adopts the quartile method for explanatory variable discretization in the baseline analysis. To reduce uncertainty arising from the discretization process, the K-means clustering method is also employed as an alternative discretization approach for robustness testing. Furthermore, ordinary least squares (OLS) regression is applied to cross-validate the identification results of driving factors. The model is specified as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} \quad (11)$$

where q has a value range of [0, 1] and measures the extent to which the driver explains the spatial divergence in urban ecological resilience. A larger value of q indicates that the independent variable has a stronger explanatory power for the dependent variables and vice versa; h is the stratification of the variant; The N_h and N are the numbers of units in layer h and the whole region, respectively; and the variance of stratum h and the whole area, respectively.

4. Urban Ecological Resilience Evaluation in Loess Plateau

4.1. Temporal Evolution of Urban Ecological Resilience in Loess Plateau

Overall, urban ecological resilience on the Loess Plateau exhibited a trajectory characterized by an initial increase followed by a subsequent decline, peaking in 1995 and then entering a fluctuating downward trend (Figure 3). This evolution can be divided into two distinct phases: (1) Ascending phase (1990–1995): The average urban ecological resilience in the Loess Plateau increased from 0.35 to 0.3557, representing a growth of 1.62%. Growth was observed across the eastern, central, and western regions, with increases of 1.2%, 1.7%, and 1.75%, respectively. The regional disparities in the index were relatively small (0.007–0.01), which can be attributed to the widespread implementation of afforestation programs across the Loess Plateau. As a result, ecological resilience in the region remained relatively coordinated and stable, progressing steadily toward high-quality development. (2) Descending phase (1995–2020): The average urban ecological resilience index on the Loess Plateau decreased from 0.3556 to 0.3481. This decline was mainly due to ongoing urban expansion, as construction land has increasingly encroached on ecological land, and grasslands have been converted into cultivated land. These changes have led to a simplification of ecosystem structure and a gradual reduction in functional complexity. Consequently, the capacity of ecosystems to withstand external risks and recover from disturbances has been progressively weakened. Declines were most pronounced in the eastern region (−5.8%) and were also observed in the western region (−2.7%). In contrast, the index for central region increased steadily from 0.3723 in 1995 to 0.3838 in 2020. The primary improvement is attributed to a series of major ecological projects implemented since the 1980s, including the Grain for Green Program, the Grazing-for-Grass Program, and small watershed comprehensive management initiatives, which have enhanced the region's ecological conditions. As a result, ecological resistance and adaptability in the central area have improved more consistently compared to other regions. During this period, high-anomaly values increased markedly, peaking in 2020, while low-anomaly values exhibited only modest growth. This pattern indicates increasing polarization of ecological resilience among cities on the Loess Plateau and suggests that regional disparities are widening. Addressing these spatial imbalances will be crucial for promoting coordinated development of ecological resilience across the Loess Plateau.

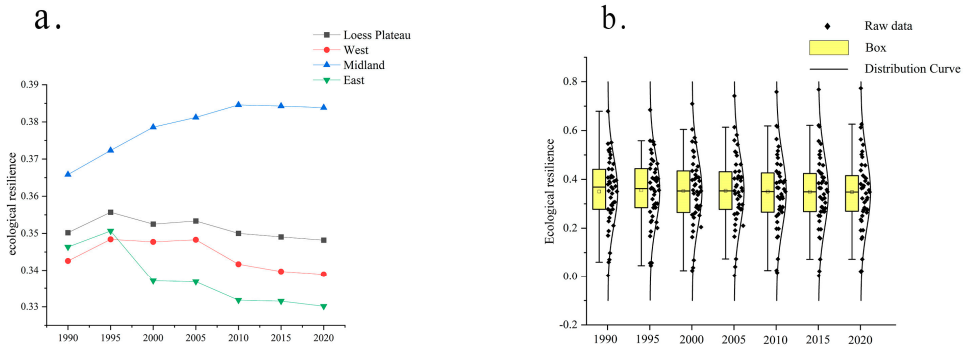

Figure 3. Time-series trend of urban ecological resilience in the Loess Plateau: (**a**) Temporal trends of average ecological resilience across different regions (Midland, Loess Plateau, West, and East); (**b**) Distribution characteristics and density evolution of ecological resilience for all study units, illustrated by combined boxplots, jittered points, and kernel density curves.

4.2. Spatial Patterns of Urban Ecological Resilience in the Loess Plateau

To thoroughly analyze the spatial changes in urban ecological resilience across the Loess Plateau, we used the natural breaks method to categorize urban ecological resilience into five levels: low-level resilience, medium–low resilience, medium-level resilience, medium–high resilience, and high-level resilience. The spatial distribution map of urban ecological resilience levels across the Loess Plateau was then generated (Figure 4).

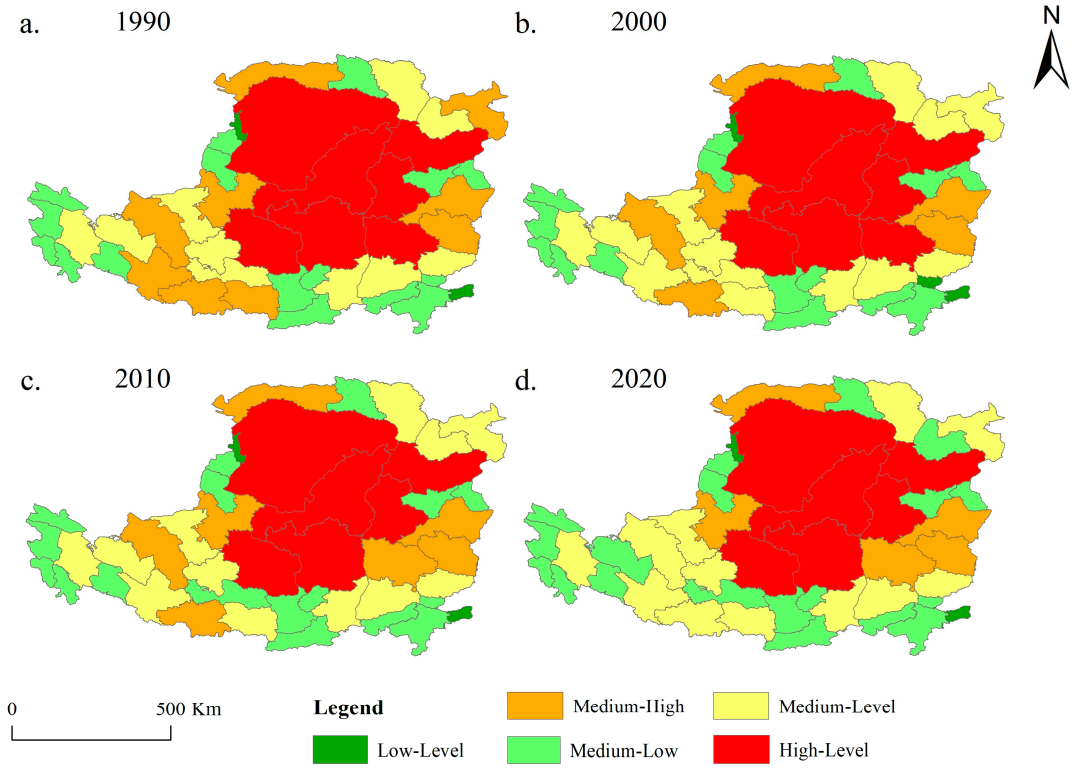

Figure 4. Distribution of Spatial Patterns of Urban Ecological Resilience in the Loess Plateau: (**a**) 1990; (**b**) 2000; (**c**) 2010; (**d**) 2020.

Urban ecological resilience on the Loess Plateau exhibits a spatial gradient decline from central cities to peripheral and edge cities. From a static perspective, high-resilience zones are mainly concentrated in the eastern and central regions of the Loess Plateau—such as Ordos, Yulin, Yan'an, Xinzhou, Luliang, Linfen, and Qingyang–where extensive forest and grassland coverage provides strong ecosystem services and ecological support.

Medium–high and medium-level resilience zones are widely distributed, often surrounding or interspersed with the high-level resilience zones. In contrast, the low-level and medium–low resilience regions are mainly distributed along the periphery of the Loess Plateau, including: (1) The eastern plains and mountainous areas such as Taiyuan, Yangquan, Jiyuan, Zhengzhou, and Luoyang where high population density and extensive construction land have led to reduced vegetation cover and weakened ecological resilience. (2) The western plateau and mountainous areas of Haibei Tibetan Autonomous Prefecture, Hainan Tibetan Autonomous Prefecture, Huangnan Tibetan Autonomous Prefecture, Xining, and Shizuishan, which exhibit relatively higher but constrained resilience due to homogeneous land-use structures, resulting in limited adaptability, reduced ecosystem service diversity, and overall weaker resistance. From a dynamic perspective, the number of cities in the low and medium–low resilience areas rose from 18 in 1990 to 21 in 2020, indicating a notable expansion of low-resilience areas. Concurrently, the number of medium–high-resilience cities declined significantly from 9 in 1990 to 5 in 2020, further indicating an overall downward trend in urban ecological resilience across the Loess Plateau during the study period.

5. Spatial Aggregation of Urban Ecological Resilience in Loess Plateau

5.1. Global Spatial Autocorrelation Analysis

The global spatial autocorrelation Moran's I index was calculated to examine the spatial correlation of urban ecological resilience across the Loess Plateau (Table 2). From 1990 to 2020, the global Moran's I index remained positive, fluctuating slightly around 0.18 (±0.03). With the exception of 2020, all years passed the significance test at the 0.05 level, while the *p*-value in 2020 was 0.06, approaching the significance level. Overall, urban ecological resilience on the Loess Plateau exhibited a tendency towards stable positive spatial correlation. Specifically, there was a certain degree of spatial dependence between the ecological resilience of a region and that of its neighbors, resulting in a relatively stable spatial agglomeration pattern overall.

Table 2. Global spatial autocorrelation analysis of urban ecological resilience in the Loess Plateau.

Year	1990	1995	2000	2005	2010	2015	2020
Moran'I index	0.181	0.204	0.197	0.18	0.181	0.178	0.178
Z score	1.9214	2.0952	2.0309	1.8335	1.8812	1.8645	1.8647
P	0.03	0.02	0.03	0.04	0.05	0.04	0.06

5.2. Local Spatial Autocorrelation Analysis

To examine the spatial clustering and correlation patterns of urban ecological resilience in the Loess Plateau from 1990 to 2020, we analyzed the Local Moran's I index (Figure 5). The "High-High" agglomeration area—mainly distributed in cities such as Wuzhong, Yulin, Xinzhou, Luliang, and Linfen—exhibited a block-like clustering pattern. This indicates that these cities possess synergistic advantages in ecological conditions, ecosystem service provision, and landscape structure. Within the region, ecological conditions are relatively homogeneous, development is comparatively coordinated, and ecological resilience exhibits positive spatial spillover effects with relatively small spatial disparities. The number of such cities increased from 5 in 1990 to 7 in 2010 before declining to 6 in 2020.

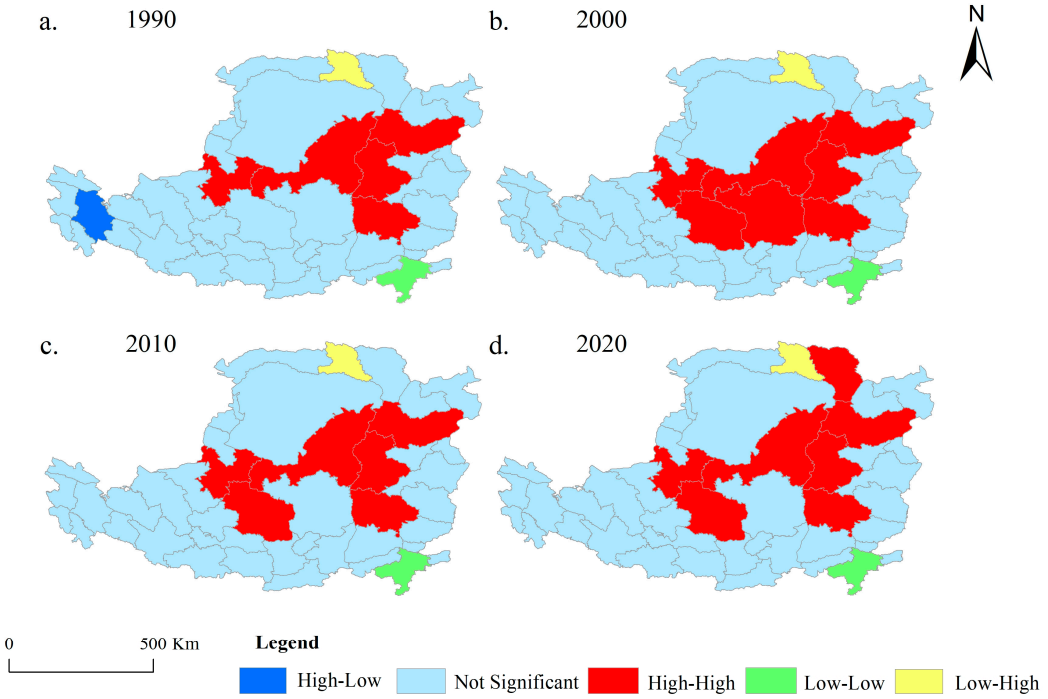

Figure 5. LISA cluster diagram of urban ecological resilience index in the Loess Plateau: (**a**) 1990; (**b**) 2000; (**c**) 2010; (**d**) 2020.

In 1990, the "High-Low" type was observed only in the Haidong Tibetan Autonomous Prefecture, indicating a high-resilience core surrounded by low-resilience neighboring areas. This pattern can be primarily attributed to favorable environmental conditions of Haidong, which is situated in the Hehuang Valley and benefits from a diverse mosaic of forest, grassland, cultivated land, and water resources. This landscape configuration enhances ecosystem stability and self-regulation. However, the region's fully dominated topography constrains the spatial diffusion of ecological elements, thereby limiting positive spillover effects. Additionally, inter-provincial administrative boundaries, regional development imbalances, and insufficient cross-jurisdictional coordination in ecological governance have collectively led to an isolated spatial pattern—often termed a "resilience island"—where higher resilience in the core area contrasts with lower resilience in surrounding regions. For such regions, a coordinated development strategy is essential to promote resource sharing and functional complementarity with adjacent low-resilience cities. Throughout the study period, Baotou consistently exhibited a "Low–High" clustering pattern, indicating relatively low local resilience compared with higher resilience in surrounding areas. This outcome is primarily due to persistent anthropogenic pressures, including intensive heavy industrial development, continual expansion of urban and industrial-mining land, and fragmentation of ecological spaces, which together have contributed to its sustained low ecological resilience. Luoyang, located in the eastern plains of the Loess Plateau, was characterized by a relatively developed economy, extensive construction land, high population density, and strong demand for ecosystem services. Its limited ecological land–farmland, forest, and grassland—was insufficient to meet the existing demand for ecosystem services, resulting in persistently low ecological resilience and classification as a "Low-Low" type area during the study period. Overall, urban ecological resilience in the Loess Plateau exhibited a relatively weak spatial clustering effect, with limited clustered areas. Most regions showed insignificant local autocorrelation, failing to form a contiguous resilience pattern.

6. Driving Forces of Urban Ecological Resilience in the Loess Plateau

6.1. Selection of Driving Forces

Urban ecological resilience is influenced by multiple factors. Reflecting its conceptual basis and drawing on prior research, we selected nine detection variables, which are grouped into three dimensions—natural, economic, and social—for analysis using the Geodetector (Table 3).

Table 3. Indicator system for driving factors of urban ecological resilience in the Loess Plateau.

	Variable Name	Indicator Meaning	Unit	Variable Representation
Nature	Average annual precipitation	Precipitation intensity	mm	PRE
	Average annual temperature	Temperature state	°C	TEM
	Average slope	Topography	°	SLO
Economy	Real GDP per capita	The level of economic development	yuan/person	PGDP
	The share of the secondary industry's value added in GDP	Industrial structure	%	IND
	The share of gross industrial output value of foreign-invested enterprises in GDP	The level of openness	%	IOV
Society	Population density	Population cluster	Persons/km^2	POP
	Total Retail Sales of Consumer Goods	Consumption level	ten thousand yuan	TRS
	The urban road area per capita	Infrastructure construction	M^2	URA

6.2. Factor Detection Analysis

The results of the Geodetector analysis indicate that population agglomeration and the level of economic development are the primary drivers shaping the spatial pattern of urban ecological resilience. However, the influence of each driving factor on urban ecological resilience exhibited clear stage-specific characteristics over the study period (Figure 6). From 1990 to 2010, population density (POP) and per capita GDP (PGDP) served as the dominant long-term driving factors, while natural factors—including average annual precipitation (PRE), average annual temperature (TEM), and average slope (SLO)—acted as important constraints. After 2010, as urban ecosystems gradually matured, the influence of POP declined. In contrast, the quality of economic development represented by PGDP, together with green investment and ecological governance capacity, maintained the strongest explanatory power and became the core driver of resilience evolution. Meanwhile, the driving effects of a series of socioeconomic factors—including the share of industrial output value of foreign-invested enterprises in GDP (IOV), total retail sales of consumer goods (TRS), and per capita road area (URA)—continued to strengthen. In comparison, the constraining role of natural factors such as PRE, TEM, and SLO gradually weakened. This shift suggests that, in the early stage, the expansion of population and economic scale provided the fundamental impetus for ecosystem resilience; as urban ecosystems matured, the driving mechanism transitioned from scale-driven growth to quality-oriented development, with the endogenous momentum of economic development promoting the evolution of the system toward a more resilient state characterized by greater adaptability and stronger restorative capacity.

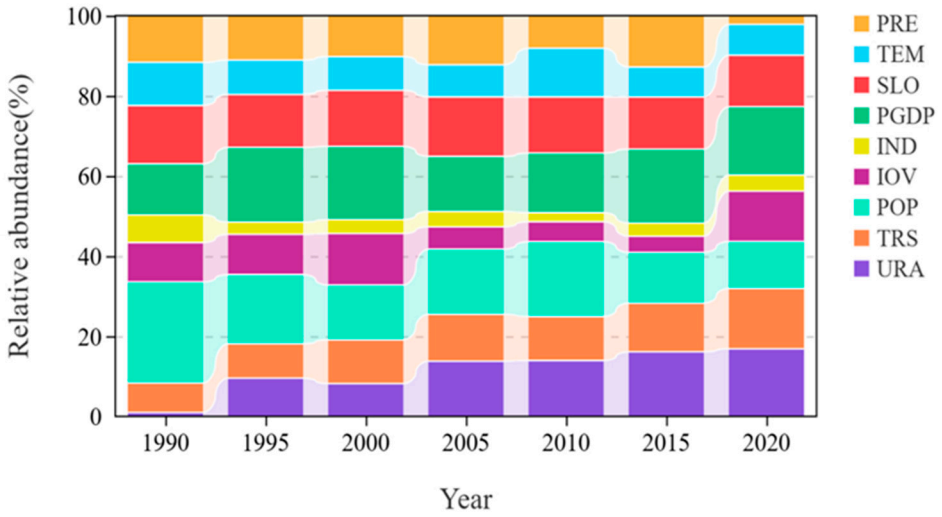

Figure 6. Driving forces percentage stacked bar chart.

Furthermore, to assess the influence of discretization methods on the Geodetector results, this study also applied the K-means clustering method as an alternative discretization approach. The results show that the ranking of key driving factors remains largely consistent across different discretization methods, confirming the robustness of the findings.

6.3. Interaction Detection Factor Analysis

We generated a heatmap to visualize the interactions among driving factors and to quantify their combined effects on urban ecological resilience (Figure 7). The results indicate that these factors do not act independently but exhibit either nonlinear or bivariate enhancement effects. This pattern reflects a typical "polycrisis" dynamic, in which multiple environmental, economic, and social factors interact and reinforce one another, generating systemic effects that exceed the sum of individual influences. Natural, economic, and social factors jointly shape the spatial distribution of urban ecological resilience, with interactions generally demonstrating stronger explanatory power than individual factors. This highlights that the evolution of urban ecological resilience is not driven by isolated variables, but by coupled and cascading processes across multiple subsystems.

According to the interaction detection results for 1990, the spatial differentiation of urban ecological resilience in the study area was primarily driven by industrialization, dominated by the secondary sector. This process interacted with terrain, precipitation, population agglomeration, and other factors, forming a synergistic multi-driver pattern. Among these interactions, the combination of the proportion of secondary industry value-added in GDP (IND) and SLO showed the strongest explanatory power (q = 0.778), indicating that industrial activities tended to concentrate in low-slope areas, turning them into core zones of ecological stress. Under this interaction, industrial expansion not only altered land use patterns but also triggered cascading ecological impacts, including vegetation degradation, hydrological disruption, and landscape fragmentation, exemplifying the amplification effects emphasized in polycrisis theory. The interaction between IND and PRE (q = 0.622) further reveals a coupling mechanism of "water resource availability—industrial distribution—urban expansion." Such coupling reflects how resource constraints and economic activities co-evolve, reinforcing pressures on ecological systems through feedback loops. Similarly, the interaction between SLO and POP (q = 0.596) demonstrates a pathway in which topographic constraints shape population distribution, which in turn restructures urban spatial patterns.

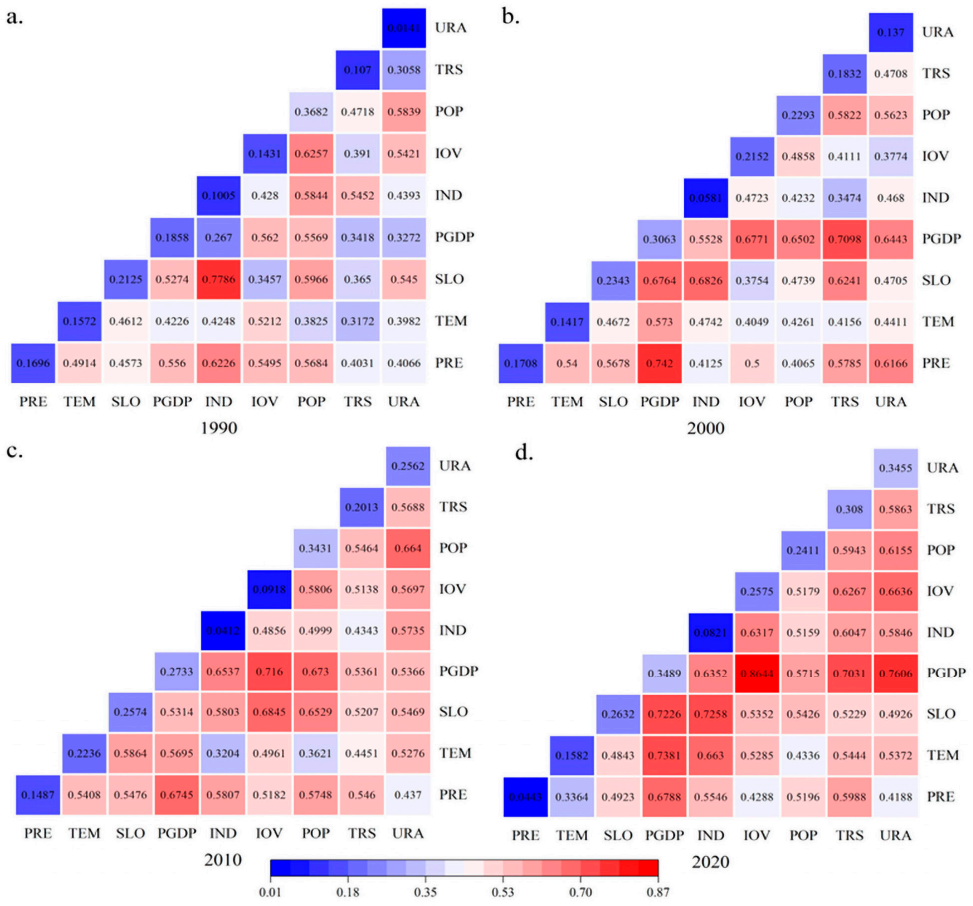

Figure 7. Interaction detection results of urban ecological resilience drivers in the Loess Plateau: (**a**) 1990; (**b**) 2000; (**c**) 2010; (**d**) 2020.

By 2000, the interaction between PGDP and PRE exhibited the strongest explanatory power, reaching approximately 67%. This suggests that regions with higher levels of economic development are more dependent on adequate precipitation to meet their water demands for production, domestic use, and ecological functions. The spatial distribution of water resources thus plays a critical role in shaping economic agglomeration, forming a characteristic pattern of "favorable precipitation conditions—enhanced economic carrying capacity—relatively stable urban and ecological spatial structures". Subsequently, the interaction between PGDP and TRS, as well as that between IND and SLO, ranked next in explanatory strength. The former indicates that areas with higher economic and consumption levels exhibit greater demand for ecosystem services—such as green spaces, parks, and aquatic environments—which in turn encourages the protection and optimization of ecological spaces. The latter continues to reflect the topographically constrained industrial layout observed in 1990, although its explanatory power has gradually weakened. This shift signals that industrialization-driven growth has been progressively replaced by broader, quality-oriented economic development as the dominant driving force, marking the city's entry into a new stage of structural transition.

After 2000, PGDP consistently emerged as a key factor in interaction effects, highlighting the increasing role of economic development in shaping urban ecological resilience. Natural and socio-economic factors exhibit strong and dynamic interactions, forming a network of interdependent drivers whose combined impacts intensify systemic pressures on urban ecosystems. Key factors—including PGDP, TRS, IND, SLO, PRE, and POP—jointly drive the spatiotemporal differentiation of urban ecological resilience in the Loess Plateau.

To examine the robustness of the drivers identified by the Geodetector, this study supplements the analysis with ordinary least squares (OLS) regression. The results indicate that PGDP, POP, and TRS all show significant effects in the regression model, and the direction of their impacts is generally consistent with the main drivers identified by the Geodetector, confirming the robustness of the findings.

7. Discussion

7.1. The Impact of Land Use Change on Urban Ecological Resilience

The transition from natural to human-dominated landscapes reflects changes in land use structure as well as transformations in human land management and governance practices [37]. Land use conversions varied considerably over the study period.

From 1990 to 2000, the magnitude of land use conversion was relatively modest, primarily characterized by the transformation of grassland into farmland and unused land into grassland. This reflects that reclamation activities induced by population growth have exerted a certain influence on urban ecological resilience. During 2000–2010, farmland was largely converted to grassland, construction land, and forest, resulting in the most substantial loss of farmland during the study period. From 2010 to 2020, farmland, unused land, and grassland continued to decline, while construction land expanded considerably (Figure 8). Farmland experienced the largest reduction (11,484.35 km^2), followed by unused land (2676.12 km^2). Construction land increased the most (12,652.95 km^2), with 63% of this expansion originating from farmland. Overall, since 2000, with rapid economic development, increasing openness, rising consumption, and accelerating urbanization across the Loess Plateau, socioeconomic factors driven by development needs have become the dominant drivers of urban ecological resilience in the region.

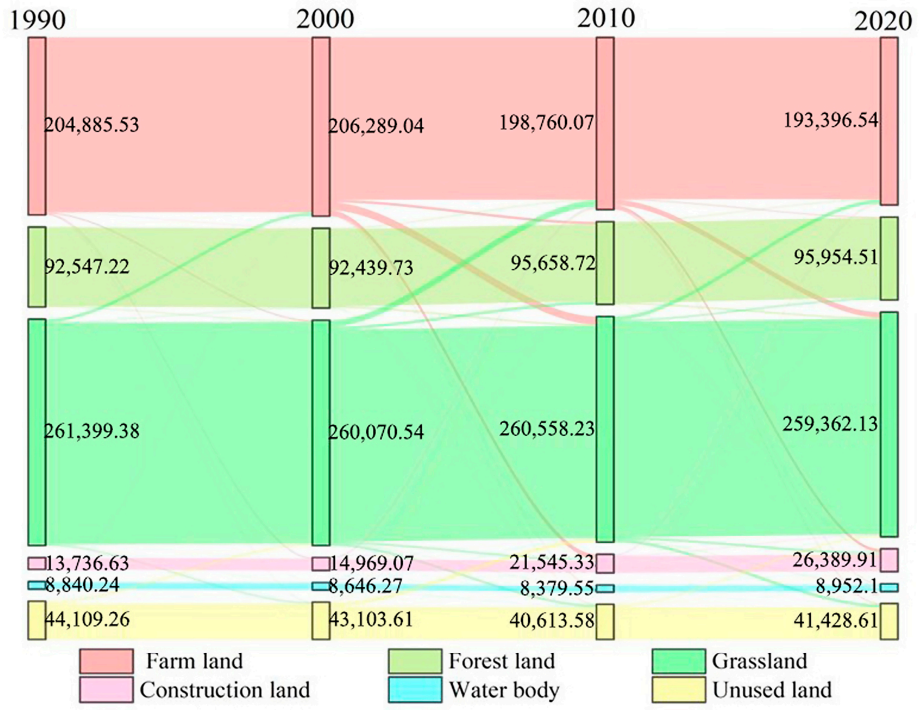

Figure 8. Land use change in the Loess Plateau.

On the whole, the loss of farmland and grassland has diminished ecosystem services including climate regulation, biodiversity conservation, and water retention [38]. Urbanization has fragmented ecological land, decreasing the quality and efficiency of ecosystem services, thereby reducing urban ecosystem adaptive capacity [16,39]. The large-scale loss of

unused land further constrains urban ecological recovery, undermining urban sustainable development.

7.2. Comparison with Other Urban Ecological Resilience-Related Studies

Rapid urbanization has profoundly reshaped urban ecological resilience in the Loess Plateau. This study finds that urban ecological resilience exhibits an overall trend of initial increase followed by subsequent decline. Similar stage-wise patterns have been observed in other regions of China, such as Hangzhou, Dalian, and the Beijing–Tianjin–Hebei region [32,40,41]. However, the underlying mechanisms differ across regions. In areas with stronger ecological endowments and higher economic development, early-stage urbanization combined with environmental governance enhanced resilience, whereas later high-intensity development exceeded ecological carrying capacity and led to resilience decline. In contrast, the evolution of ecological resilience in the Loess Plateau is shaped by the combined effects of a fragile ecological background, large-scale ecological restoration policies, and rapid urban expansion. The region is characterized by severe soil erosion and weak ecosystem recovery capacity. Since the 1980s, ecological restoration programs, such as small watershed management and the Grain-for-Green Program, have improved ecosystem conditions and enhanced ecosystem service supply, contributing to the early increase in resilience [42]. However, since the mid-1990s, accelerated urbanization has led to the expansion of industrial land and construction areas, encroaching on ecological space [43]. Although cultivated land balance policies have been implemented, the lower quality of newly added land has not compensated for ecological losses. Meanwhile, the long recovery cycle and limited resistance of local ecosystems have constrained their capacity to offset increasing human pressures, resulting in a shift from resilience growth to decline. In addition, resilience exhibits a core–periphery gradient, decreasing from central urban areas to peripheral zones, with low-resilience areas expanding outward. Compared with other regions, the evolution of resilience in the Loess Plateau depends more strongly on the dynamic balance between policy interventions and natural constraints.

This pattern differs from previous studies reporting an initial decline followed by recovery in landscape ecological quality in the northern Loess Plateau [44]. The discrepancy mainly arises from differences in assessment frameworks. Existing studies often rely on supply-side indicators, such as ecosystem service value (ESV), NDVI, and land use, implicitly assuming that higher supply corresponds to stronger resilience [32,45,46]. However, this approach neglects the spatial heterogeneity of human demand and may introduce systematic bias. In urban core areas, high population density and development intensity lead to significantly higher demand for ecosystem services. As a result, supply-based assessments may overestimate actual resistance capacity. To address this limitation, this study incorporates ecosystem service demand into the assessment framework and redefines resistance from a supply–demand perspective. Rapid economic growth, population increase, and intensified land use jointly drive rising demand for ecosystem services, thereby increasing ecological pressure. For instance, in urban cores, although ecosystem service supply may be limited, concentrated demand leads to lower actual resistance capacity. Therefore, urban ecological resistance depends not only on supply but on the degree of matching between supply and demand. This perspective helps explain the differences between this study and previous findings.

Geodetector results further reveal that both socioeconomic and natural factors significantly influence the spatial distribution of urban ecological resilience, with factor interactions exhibiting stronger explanatory power than individual factors. The enhanced explanatory power of socioeconomic–natural interactions indicates that the evolution of urban ecological resilience is not driven by a single factor but by the combined and synergistic

effects of natural baseline conditions and socioeconomic disturbances. This corroborates the core findings of Zhu and Ling regarding urban open spaces in Shanghai, cementing multi-factor synergy as the dominant force in spatial morphological evolution [47]. It is also consistent with the conclusions of Wu et al. [16], further confirming that urban ecological resilience evolves under the joint influence of multiple interacting drivers.

From a social–ecological system (SES) perspective, the "increase–decrease" trajectory reflects a phased adaptive cycle. In the early stage, ecological restoration and economic development enhanced system adaptability. However, continuous urban expansion and environmental pressures gradually pushed the system toward its resilience threshold, leading to decline. The increasing influence of socio-economic factors highlights the growing role of human activities, while strong interaction effects indicate that resilience evolution depends on the coupling between natural and human systems. This process reflects an ongoing structural transformation of the regional SES [48].

Compared with previous studies focusing mainly on ecosystem service supply or landscape structure [44,49,50], this study develops a framework that integrates ecosystem service supply and demand. By explicitly incorporating human demand, the approach shifts from supply-based assessment to supply–demand matching, providing a more accurate representation of human–environment interactions and avoiding overestimation in high-demand areas. This contributes to improving the methodological framework of urban ecological resilience assessment. The findings provide important implications for ecological risk management in fragile regions. Policy measures should balance natural constraints and socio-economic development, implement region-specific strategies, and optimize land use and population distribution to enhance resilience.

Nevertheless, this study has several limitations. First, the indicator system for resilience assessment is not sufficiently refined, and abrupt factors such as extreme climate and major policies are not considered. Second, the analysis is limited to historical evolution and driving forces, lacking multi-scenario simulations and regional comparisons. Future research can improve the assessment framework, combine scenario simulations for prediction and pathway optimization, and strengthen the practical applicability of the conclusions.

8. Conclusions

Focusing on the Loess Plateau, this study applies spatial autocorrelation analysis and the Geodetector method to examine the spatiotemporal evolution and driving factors of urban ecological resilience from 1990 to 2020. The main conclusions are as follows:

(1) Urban ecological resilience in the Loess Plateau showed an overall trend of initial increase followed by a subsequent decline, which can be divided into an ascending phase (1990–1995) and a descending phase (1995–2020). While the western and eastern regions experienced declines, the central region exhibited sustained growth in urban ecological resilience.

(2) Urban ecological resilience exhibits a core–periphery spatial gradient, with resilience levels gradually decreasing from central urban areas to suburban and peripheral zones. Although the overall spatial agglomeration effect remains weak and spatial continuity is limited across most regions, significant local spatial clustering is still observed.

(3) The dominant drivers of urban ecological resilience varied over time. In the long term, population density (POP) and GDP per capita (PGDP) were the key driving factors. Factor interactions exhibited bivariate or nonlinear enhancement effects. Economic development level, population density, and industrial structure consistently acted

as the primary controlling factors influencing the spatial differentiation of urban ecological resilience.

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