

Article

Analysis of the Environmental Benefits and Driving Forces of the Development of the “Production–Living–Ecological Space” Pattern Based on the ERI-ESV Geodetector

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Abstract: Based on five periods of Landsat remote sensing data from 1980 to 2020, this study constructs a landscape ecological risk-ecosystem service value evaluation model and integrates it with a geodetector model to analyse the environmental benefits of the development of the “production–living–ecological space” pattern and its driving factors in the Xuzhou planning area. The results of the study are as follows: (1) Over the past 40 years, the expansion of living spaces has significantly encroached upon adjacent agricultural production areas and ecological spaces, such as forests and grasslands. Specifically, the areas of agricultural land, forests, and grassland have been diminished by 277.39 km², 23.8 km² and 12.93 km², respectively; in contrast, urban and rural living spaces have increased by 238.62 km² and 58.92 km², alongside a rise in industrial production areas, water bodies, and other ecological spaces. (2) Throughout the 40-year period, both the landscape ecological risk (ERI) and ecosystem service value (ESV) in the study area have shown a decreasing trend. The proportion of high- and medium-high-risk areas of the ERI have decreased by 5.19% and 7.50%, respectively, while low, lower, and medium ecological risk areas have increased by 6.40%, 3.22% and 3.07%, respectively. In addition, low-ESV areas have increased by 14.22%, while the proportion of high- and medium-high-ESV areas have decreased by 1.16%. (3) There is a significant positive spatial correlation between the ERI and ESV. Regions with dense ecological spaces comprising forests, water bodies, and grasslands, particularly in the northeastern part of the Jiawang District and the southeastern part of the Tongshan District, demonstrate superior regional ecosystem service quality. The ERI and ESV are dominated by “high–high” and “low–high” aggregation. Conversely, in the southwestern part of the study area, the expansion of living space has led to the transformation of some agricultural land, forest land, and grassland into less risky construction land, resulting in a decline in the quality of regional ecosystem services. The local spatial correlation between the ERI and ESV changed from “high–high”, “low–low”, “low–high” agglomeration to “low–low” agglomeration. (4) Key factors influencing the spatial differentiation of the “production–living–ecological space” include the GDP, population density, soil type, and the distance to towns and roads. Among these, the interaction between population density and soil type has the most significant effect on the changes in the pattern of the “production–living–ecological space”.

Keywords: production–living–ecological space; pattern evolution; landscape ecological risk; ecological service quality; driving factor



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1. Introduction

The rapid development of urbanisation has led to significant changes in land use functions, with the continuous expansion of urban construction land encroaching upon

national land such as arable land, grassland, and forest land. This has exacerbated the conflict between living, production, and ecological land uses [1,2]. Such changes directly impact on the quality of regional ecosystem services and functions, threaten the regional ecological security pattern, and negatively affects the ecological environment [3]. At present, China's land use spatial pattern has shifted from being dominated by production spaces to the coordinated development of a "production–life–ecology" spatial framework [4], and the report of the 20th National Congress of 2022 stressed the importance of ecological priority development and proposed the construction of a regionally coordinated development system for national land space. In the context of "harmonious coexistence between humans and nature", using methods such as geographic detectors, this study evaluates the potential ecological impacts and driving factors of land use transformation in the "production–living–ecological space" from the perspectives of landscape ecological risk and ecosystem service value. It proposes spatial ecological restoration zoning for national territory to enhance the efficiency of land management and ecological restoration efforts, thereby promoting the rational allocation of the "production–living–ecological space" and regional coordinated development. This is of significant importance for improving the effectiveness of national land consolidation and ecological restoration, fostering sustainable regional development [5].

At present, scholars both domestically and internationally are concentrating their research on various aspects of the "production–living–ecological space." These include the functional transformation of land use and its ecological environmental effects [6,7], the evolution of land use and the value of ecosystem services in the "production–living–ecological space" [8,9], and the transformation of land use alongside the evolution of landscape ecological risks [10,11]. Landscape ecological risk assessment and ecosystem service value assessment are integral to ecological safety assessment, forming key components of ecological environment assessment [12,13]. Previous studies on landscape ecological risk [14,15] and ecosystem service value [16,17] have primarily focused on analysing the spatial and temporal evolution trend of an individual indicator, offering targeted restoration advice that provides some guidance. However, there is a scarcity of literature exploring the correlation between these two indicators. During the rapid urbanization process, the rapid transformation of the land use landscape pattern of the "production–living–ecological space" leads to changes in regional ecological risk, subsequently affecting the value of regional ecosystem services. This dynamic forms the ecological process of "landscape pattern–landscape ecological risk–ecosystem service quality" [18,19]. Therefore, characterising and assessing regional ecological security patterns and identifying ecological restoration areas from the perspectives of landscape ecological risk and ecosystem service value provide new perspectives for revealing the coupling and mutual feedback mechanisms between landscape patterns and ecological environmental change processes. An in-depth investigation of the mutual feedback mechanism between land use transformation and ecological and environmental benefits within the "production–living–ecological space" is crucial for conducting the ecological restoration zoning of national land space, thereby mitigating the conflicts between humans and land. Furthermore, exploring the drivers of spatial variability in ecosystem services and landscape ecological risks can aid decision-makers in understanding which factors can be adjusted to enhance ecological protection and management decision-making. Despite this, there are still relatively few studies that comprehensively analyse the relationship between ecosystem services and landscape ecological risks from both spatial and temporal perspectives, while simultaneously exploring the drivers of the spatial variability in this relationship. Understanding these drivers of spatial variability of ecosystem services and landscape ecological risks can facilitate the accurate analysis of regional ecological environment change processes, providing robust decision support for regional land use management and ecological environmental protection. This lays the theoretical foundation for the coordinated development of the "production–living–ecological space".

In view of this, this study utilizes land use data from 1980 to 2020 to investigate the spatial differentiation patterns of landscape ecological risk and ecosystem service value in the Xuzhou planning area, within the perspective of “production–living–ecological space”. We employ spatial correlation analysis, a Geoprobe, and other research techniques to explore the spatial correlation characteristics between landscape ecological risk and ecosystem service value, as well as their driving mechanisms, and propose optimization strategies. The findings of this study provide suggestions for preventing and controlling ecological risks and the enhancement of ecosystem functions in the Xuzhou planning area. These insights are instrumental in mitigating human–land conflicts and fostering the development of an ecological civilization.

2. Materials and Methods

2.1. Overview of the Research Area

The city of Xuzhou ($116^{\circ}22' \text{ E} \sim 118^{\circ}40' \text{ E}$, $33^{\circ}43' \text{ N} \sim 34^{\circ}58' \text{ N}$), located in the northeastern part of Jiangsu Province, encompasses an area of $11,765 \text{ km}^2$. The terrain slopes from northwest to southeast, with elevation ranging between 20 and 50 m. As a national old industrial base and resource-depleted city, Xuzhou faces a significantly damaged regional ecological environment and an urgent need for ecological restoration and socioeconomic innovation and transformation. It is necessary to prioritize ecological protection as the first priority, and to coordinate systematic reform and innovation. According to the development requirements of the urban master plan and the spatial distribution of land use functions, the study area is delineated as the Xuzhou planning area (Figure 1), including the administrative jurisdiction of the Xuzhou urban area and Shuanggou Town in Suining County.

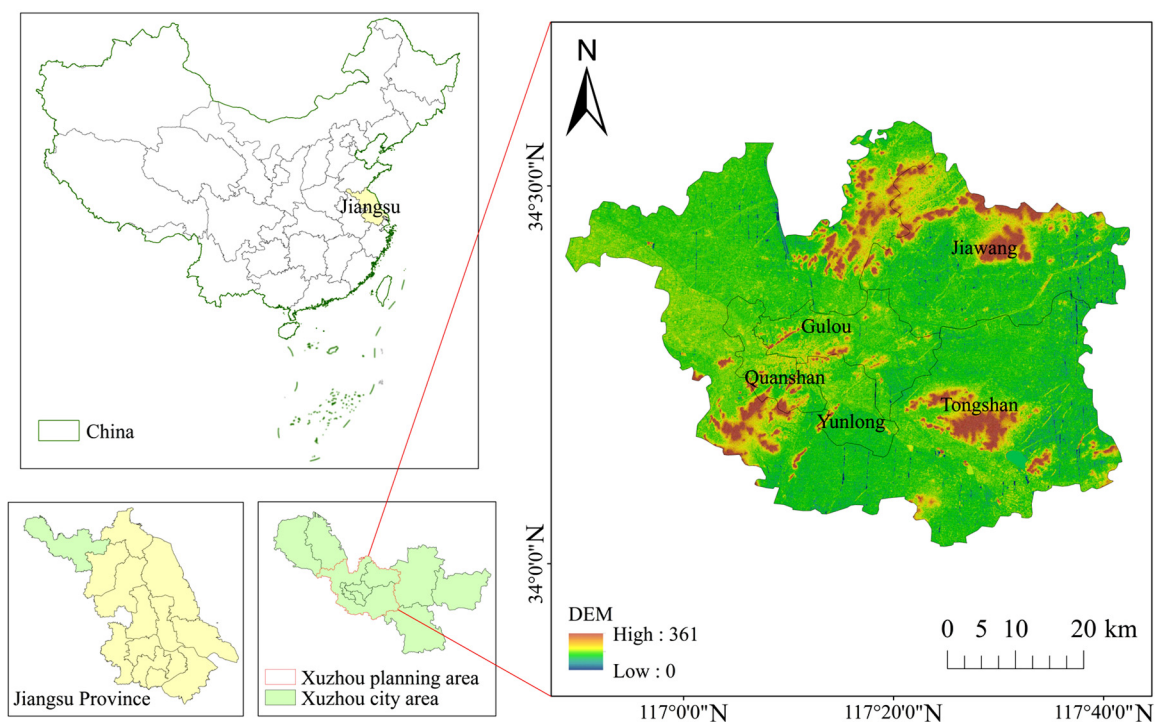


Figure 1. Scope of the research area.

2.2. Data Source and Processing

The data sources are detailed in Table 1. The raw data were processed using ArcGIS 10.8 software, and during this process, all data were standardized to the WGS_1984_UTM_Zone_50N coordinate system. Following the classification method of Dong Jianhong et al. for “production–living–ecological space” [20], the land use data were classified based on the

functional principle. Consequently, a classification system of “production–living–ecological space” in the Xuzhou planning area was constructed (Table 2).

Table 1. Data sources.

Type of Data	Source of Data
Land use data, GDP and population density data	CAS Resource Environment Data Center: https://www.resdc.cn . (accessed on 12 December 2023)
Elevation and slope data	Geospatial data cloud: https://www.gscloud.cn . (accessed on 12 December 2023)
Climate data such as temperature and precipitation	National Earth System Science Data Center: http://www.geodata.cn . (accessed on 15 December 2023)
Data on distance from cities, railways, roads, rivers, etc.	National Geographic Information Resource Catalog Service System: https://www.webmap.cn . (accessed on 15 December 2023)
Socio-economic data	Xuzhou Statistical Yearbook

Table 2. The classification system of “production–living–ecological spaces”.

Classification System	Primary Classification	Secondary Classification
Production space	Agricultural production space (A) Industrial production space (B)	Paddy land, dry land Other building land
Living space	Urban living space (C) Rural living space (D)	Towns Rural settlements
Ecological space	Forest ecological space (E) Grassland ecological space (F) Water ecological space (G) Other ecological space (H)	Forest, scrubland, open forest, other forest land High-cover, medium-cover, low-cover grasslands Rivers, lakes, reservoirs, ponds, etc. Saline, sandy, bare ground, etc.

2.3. Research Method

2.3.1. Analysis of Land Use Change

(1) Dynamic attitude of land use

The attitude of land use dynamics reflects the change in the area of a land use type and its intensity in a given study period [21,22]. The formula is as follows:

$$K = \frac{U_j - U_i}{U_i} \times \frac{1}{T} \times 100\% \quad (1)$$

In Equation (1), K is the land use dynamic, U_i , U_j are the areas at the beginning and end of the study period for a given land class, and T is the time scale for a given study period [23].

(2) Land use transfer matrix

The land use transfer matrix reflects the mutual transformation information between various types of land use in a certain study period [24,25]. In ArcGIS 10.8, the land use data of the Xuzhou planning area from 1980 to 2020 were rasterized, and the acquired image metadata were processed by Excel to obtain the land use transfer matrix of “production–living–ecological space”. The specific formulas are as follows:

$$B_{ij} = \begin{bmatrix} B_{11} & B_{12} & \cdots & B_{1n} \\ B_{21} & B_{22} & \cdots & B_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ B_{n1} & B_{n2} & \cdots & B_{nn} \end{bmatrix} \quad (2)$$

In Equation (2), B_{ij} is the area converted from land category i to land category j at the beginning and end of the study period, and n is the total number of land types in the “production–living–ecological space”.

2.3.2. Eco-Environmental Benefit Analysis

(1) Landscape ecological risk assessment

According to the specific conditions of the study area and the objectives of the research, an equally spaced systematic sampling method was adopted. A 2 km × 2 km grid was selected to divide the Xuzhou planning area, resulting in a total of 848 evaluation units. The landscape ecological risk evaluation model was then utilized to calculate the landscape ecological risk index of each evaluation unit [26]. Drawing on to the findings of the related literature, the landscape disturbance index and the landscape vulnerability index were selected to calculate the landscape ecological risk index. The specific calculation formula and the meanings of the parameters are shown in Table 3.

Table 3. Calculation formula for the ecological risk index.

Index Name	Formulas	Meaning
Ecological risk index	$ERI_i = \sum_{k=1}^N \frac{A_{ki}}{A_k} R_i$ (3)	ERI_i is the ecological risk index; A_{ki} is the area of landscape type i in the k th risk area; A_k is the total area of the k th risk landscape; R_i is the landscape loss degree index.
Landscape loss degree	$R_i = E_i \times V_i$ (4)	E_i is the landscape disturbance index and V_i is the vulnerability index, which was obtained by assigning values 6, 5, 4, 3, 2, 1, 1, 1, 1, and 1 to eight types of land use functional spaces: other ecological space, water ecological space, agricultural production space, grassland ecological space, forest ecological space, urban living space, rural living space and industrial production space, and then normalized to obtain the landscape vulnerability index.
Landscape disturbance degree	$E_i = aC_i + bN_i + cF_i$ (5)	a , b , and c are the corresponding weights of each landscape index, which are assigned as 0.5, 0.3, and 0.2, respectively, with reference to related studies.
Landscape fragmentation degree	$C_i = \frac{n_i}{A_i}$ (6)	A_i is the area of landscape type i , and n_i is the number of patches in landscape i .
Landscape separation degree	$N_i = \frac{A}{2A_i} \sqrt{\frac{n_i}{A_i}}$ (7)	A_i is the area of landscape type i , A is the total area of the landscape, and n_i is the number of patches in landscape i .
Landscape fractal dimension	$F_i = 2 \ln(p_i/4) / \ln A_i$ (8)	A_i is the area of landscape type i , p_i is the perimeter of landscape type i .

(2) Valuation of ecosystem services

The study adopted the “Ecosystem Service Equivalent Value per Unit Area of Chinese Ecosystems” compiled by Xie Gao Di et al. and revised it according to the land use functions of the “production–living–ecological space” in the study area. The revision followed the guideline that the economic value of the ecosystem service equivalent factor is equal to 1/7 of the market value of the average grain yield of the current year [27]. The data from the China Agricultural Products Price Survey Yearbook for the period from 1980 to 2020 indicates that the average rice production in the study area was 5702.76 kg ha^{−1}, with an average market price of 1.48 RMB kg^{−1}. The calculated value of the ESV unit factor was 1205.73 RMB ha^{−1}. This value was then multiplied by the corresponding data in the study area to obtain the service value factor per unit area of ecosystem in the Xuzhou planning area (Table 4). The specific calculation formula is as follows:

$$V_{ES} = \sum_{j=1}^n \sum_{i=1}^n A_i E_{i,j} \quad (9)$$

In Equation (9), V_{ES} is the total ecosystem service value, RMB; $E_{i,j}$ refers to the coefficient of the ecosystem service value of the j th category of the i th land use type, RMB ha^{−1}; A_i is the area of the i th land use type, ha.

Table 4. The equivalent of the ecosystem service values per hectare in the Xuzhou planning area.

First-Order Type	Secondary Type	Unit Area Value Coefficient by Land Use Type/(Yuan · ha ^{−1})				
		Agricultural Production Space	Forest Ecological Space	Grassland Ecological Space	Water Ecological Space	Other Ecological Spaces
Supply service	Food production	1205.73	397.89	518.47	639.04	24.12
	Raw material production	470.23	3593.07	434.06	422.01	48.23
	Gas regulation	868.12	5208.74	1808.59	614.92	72.34
Regulating service	Climate regulation	1169.56	4907.32	1880.93	2483.80	156.74
	Decontaminate the environment	928.41	4931.42	1832.71	22,631.51	84.40
	Hydrological regulation	1675.96	2073.85	1591.56	17,905.06	313.49
Support services	Soil conservation	1772.42	4847.03	2700.83	494.35	204.98
	Maintain biodiversity	1229.85	5437.84	2254.71	413.64	482.30
Cultural service	Aesthetic landscape	204.98	2507.92	1048.99	5353.43	289.37

(3) Spatial correlation analysis

Global and local spatial autocorrelation analyses of the landscape ecological risk index and ecosystem service quality in the Xuzhou planning area were conducted using Geoda 1.20 software to explore the aggregation effect and spatial heterogeneity of these variables [28,29]. The global autocorrelation module calculates Moran's index (Moran's I) to reflect the spatial correlation between the landscape ecological risk value and ecosystem service quality in the study area. The value of Moran's index is in the interval of $[-1, 1]$. A positive Moran's $I > 0$ indicates that a given spatial unit is clustered with neighbouring spatial units in the form of the same high value or low value, while a negative Moran's $I < 0$, indicates that a given spatial unit is clustered with neighbouring spatial units in the form of high value–low value or low value–high value [30]. The local autocorrelation module was used to generate a spatial clustering LISA map, which visualizes the clustering of landscape ecological risk and ecosystem service quality in the study area. The clustering is categorized into high–high, high–low, low–low, low–high and non-significantly clustered areas. The specific formulae are as follows:

$$I_{vr} = \frac{n \sum_{k=1}^n \sum_{j=1}^n W_{ij} \left(\frac{x_{kv} - \bar{x}_v}{\delta_v} \right) \left(\frac{x_{kr} - \bar{x}_r}{\delta_r} \right)}{(n-1) \sum_{i=1}^n \sum_{j=1}^n w_{ij}} \quad (10)$$

In Equation (10), r and v represent the landscape ecological risk index and ecological service value per unit area, respectively; the term I_{vr} denotes the global correlation coefficient of r and v ; δ_v and δ_r are the variances of r and v ; x_{kv} and x_{kr} are the ecological service value per unit area and the landscape ecological risk index, respectively, in the evaluation unit k ; n is the total number of evaluation units; and W_{ij} is the spatial weighting between the evaluation units i and j .

2.3.3. Geographic Detector

The environmental effects of the land transformation in the “production–living–ecological space” result from the spatial characterisation of natural, socio-economic and accessibility factors through a complex coupling process. Geoprobe is a statistical model for studying the drivers of the spatial differentiation of geographical elements [31,32]. In this study, elevation (X1), slope (X2), average annual temperature (X3), annual precipitation (X4), soil type (X5), gross domestic product (GDP) (X6), population density (X7), distance to town (X8), distance to road (X9), distance to railway (X10), and distance from river (X11) were selected from the three exploratory dimensions: the natural environment, economy and society and accessibility, for a total of 11 indicators. Using the factor de-

tection module of Geoprobe, the extent to which these variables affect the differentiation of the “production–living–ecological space” in the study area was identified. Interaction detection was also employed to analyse the extent to which these variables explain the enhancement or weakening of the ecological landscape risk and the quality of ecological services. This analysis reveals the formation mechanism and driving mechanism of the “production–living–ecological space” in the Xuzhou planning area. The specific formulas are as follows:

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

In Equation (11), N_h and N represent the number of samples in stratification h and the whole region, respectively; L is the categorization of the driving factor X ; $h = 1, \dots, L$; σ_h^2 and σ^2 are the variance of stratification h and the whole region, respectively; q is the explanatory power of a single driving factor, with values in the range of $[0, 1]$. A larger value of q indicates a greater impact of the driving factor on the land use change of the “production–living–ecological space”.

3. Results

3.1. Evolution of the Pattern of “Production–Living–Ecological Space” in the Xuzhou Planning Area

3.1.1. Changes in the Structure of the “Production–Living–Ecological Space”

From 1980 to 2020, the pattern of the “production–living–ecological space” in the Xuzhou planning area exhibited a notable divergence, with the largest proportion of agricultural production space, followed by urban and rural living space (Figure 2). Over the past 40 years, urban and rural living spaces continued to expand, increasing by 238.62 km² and 58.92 km², respectively. The area of industrial land and water also increased by 7.25 km² and 8.73 km², respectively. Conversely, the areas of agricultural land, forest land, and grassland declined by 277.39 km², 23.80 km², and 12.93 km², respectively. The areas of other ecological spaces remained relatively stable.

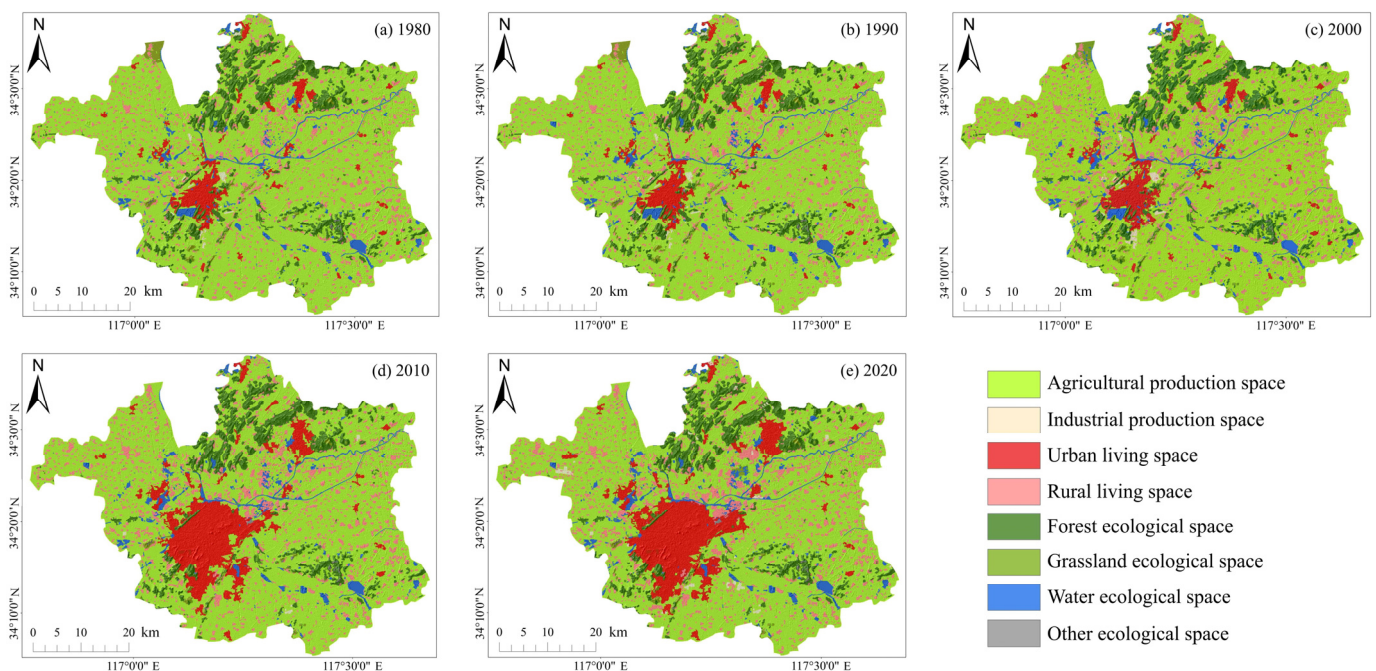


Figure 2. Changes in the pattern of the “production–living–ecological space”.

Combined with the analysis of the dynamics of land use (Table 5), it is evident that urban living space experienced the most drastic change over the 40-year period, with a dynamic of 4.13%, peaking at 14.22% during the period of 2000–2010. The industrial production land use motivation rate is 1.81%, which was the second highest. The trend in rural living space showed an “increase–decrease–increase” pattern, but all changes were positive overall. The dynamic rates for agricultural production land, woodland, grassland, and other ecological spaces peaked at 0.65%, −0.65%, −3.64%, and 1.65%, respectively, between 2000 and 2010. In summary, from 1980 to 2000, the land use of the “production–living–ecological space” changed slowly, and the relationship between the people and the land was relatively stable; from 2000 to 2010, the pattern of the “production–living–ecological space” underwent the most drastic changes, and the contradiction between the people and the land intensified. However, from 2010 to 2020, the attitude of the land use dynamics of the “production–living–ecological space” declined to a low level of change, and the contradiction between the people and the land was eased.

Table 5. Attitude of land use in the “production–living–ecological spaces” of the Xuzhou planning area.

Time	Production Space		Living Space		Ecological Space			
	Agriculture	Industry	Urban	Rural	Forest	Grassland	Water	Other
1980–1990	0.05	0.02	0.10	0.01	0.01	0.04	0.91	0.00
1990–2000	0.30	5.41	1.28	1.19	−0.12	−0.19	1.05	0.03
2000–2010	0.65	−7.71	14.22	0.01	−0.65	−3.64	−1.00	1.65
2010–2020	0.37	43.77	1.10	0.59	−0.08	1.16	0.10	0.00
1980–2020	−0.26	1.81	4.13	0.37	−0.17	−0.60	0.19	0.34

3.1.2. Changes in the Transfer of the “Production–Living–Ecological Space”

The transfer of land for the “production–living–ecological space” from 1980 to 2020 (Figures 3 and 4) is primarily characterized by the outflow of agricultural production space, forest and grassland ecological space, and the transfer-in of living space in towns and villages. Over the 40-year period, a significant portion of agricultural land was transferred to towns and villages, with an area of 169.78 km² and 102.56 km², respectively. These transfers accounted for 85.95% of the total area transferred out. The transfer in forest and grassland was primarily into urban and agricultural land. The expansion of industrial production space, water resources, and other ecological spaces primarily resulted from the transfer of agricultural land.

In terms of time periods, during the 1980–1990 period, land use changes were primarily characterized by transformations between agricultural land and water bodies. From 1990–2010, the predominant trend was the conversion of agricultural production spaces into rural and urban land. The 2000–2010 period witnessed the most significant encroachment of living spaces into agricultural production and ecological spaces, with 112.17 km² and 41.28 km² of agricultural land being converted to urban and rural living spaces, respectively. Additionally, this period saw a rapid urban expansion in the southwest centre of the city, leading to urban spaces encroaching on some of the ecological spaces such as forests, grasslands, and watersheds. From 2010 to 2020, the primary trend in land use transformation within the “production–living–ecological space” was the continued conversion of agricultural production spaces into urban and rural living spaces. During this period, significant emphasis was placed on ecological restoration. Notably, some agricultural production spaces in the northeastern part of Jawang District, near Pan’an Lake and Dugong Lake, were converted into water spaces, resulting in a slight increase in the area of water.

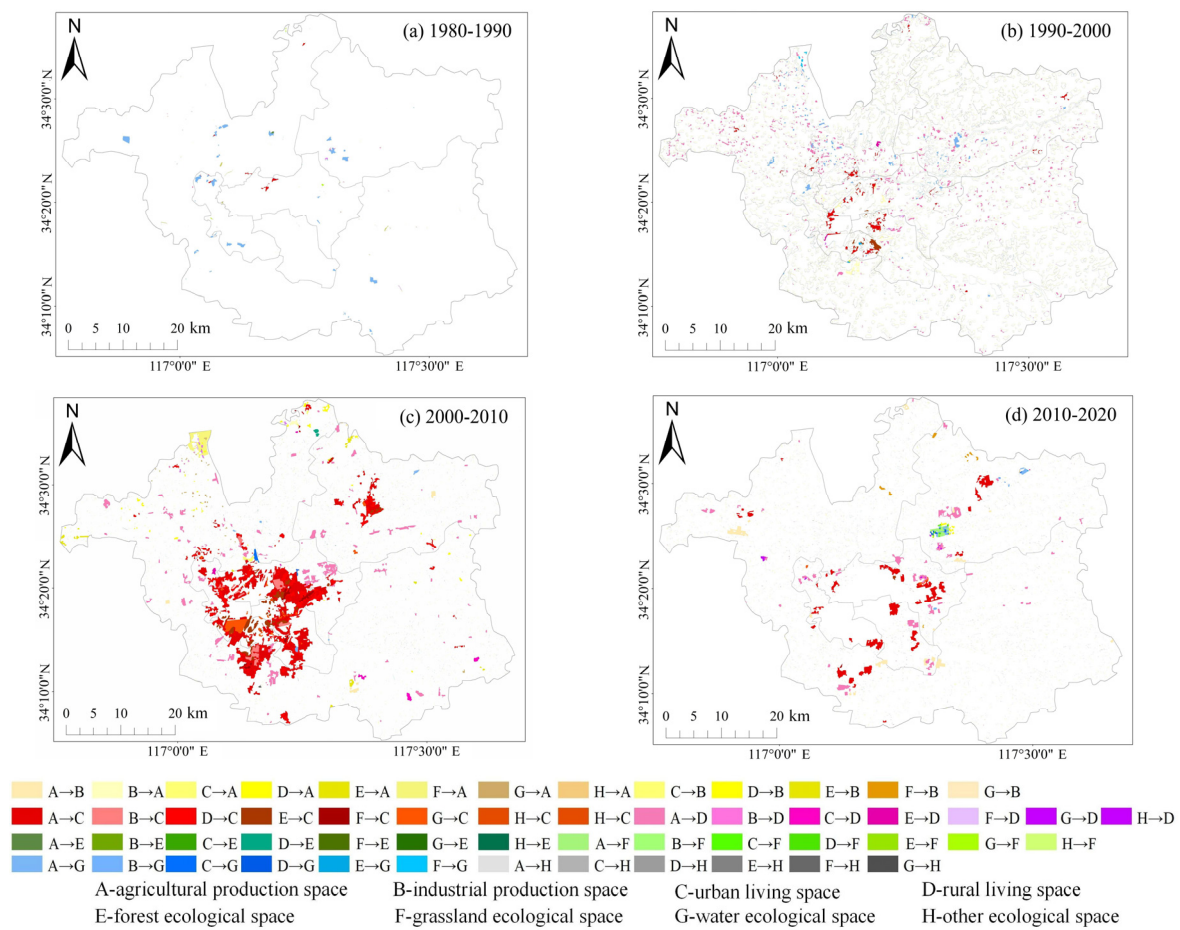


Figure 3. The spatial distribution of land transfers in the “production–living–ecological spaces” of the Xuzhou planning area.

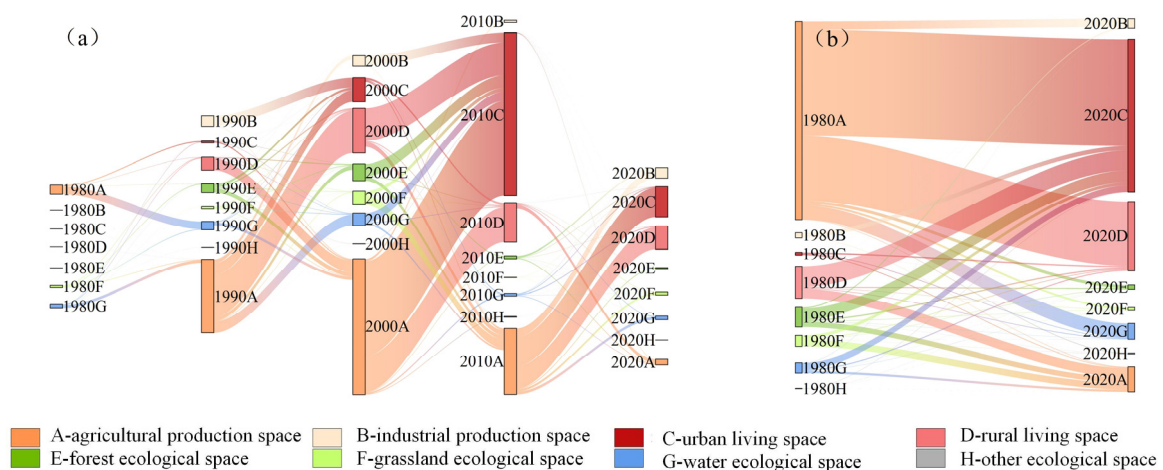


Figure 4. (a) Sankey diagram of changes in “production–living–ecological space” transfer by time period, 1980–2020; (b) dazzle diagram of changes in “production–living–ecological space” transfer, 1980–2020.

3.2. Analysis of Landscape Ecological Risk and the Evolution of the Ecological Service Value of the “Production–Living–Ecological Space” in the Xuzhou Planning Area

3.2.1. The Spatial and Temporal Evolution of Landscape Ecological Risk

Using the natural breakpoint method combined with the actual conditions of the study area, the ecological risk level of the Xuzhou planning area is divided into five categories

of low- ($ERI \leq 0.052$), medium-low- ($0.052 < ERI \leq 0.072$), medium- ($0.072 < ERI \leq 0.086$), medium-high- ($0.086 < ERI \leq 0.098$), and high ($ERI > 0.098$)-risk zones (Figure 5). From 1980 to 2020, the spatial distribution of the ERI in the Xuzhou planning area exhibited significant variation, and the average value of the ERI decreased. The ERI high- and medium-high-risk areas cover a large and shrinking area, shrinking by 5.19% and 7.50%, respectively, over the 40-year period. These zones were characterized by a complex distribution, encompassing a wide range of agricultural land, forest land, and watersheds, with a high degree of landscape fragmentation and segregation. In contrast, the medium, medium-low and low-risk areas accounted for a relatively small proportion, and were predominantly located in the southwestern part of the study area and the northeastern part of Jawang District. The area of medium-, medium-low-, and low-risk areas tended to increase over the 40-year period, increasing by 6.40%, 3.22%, and 3.02%, respectively.

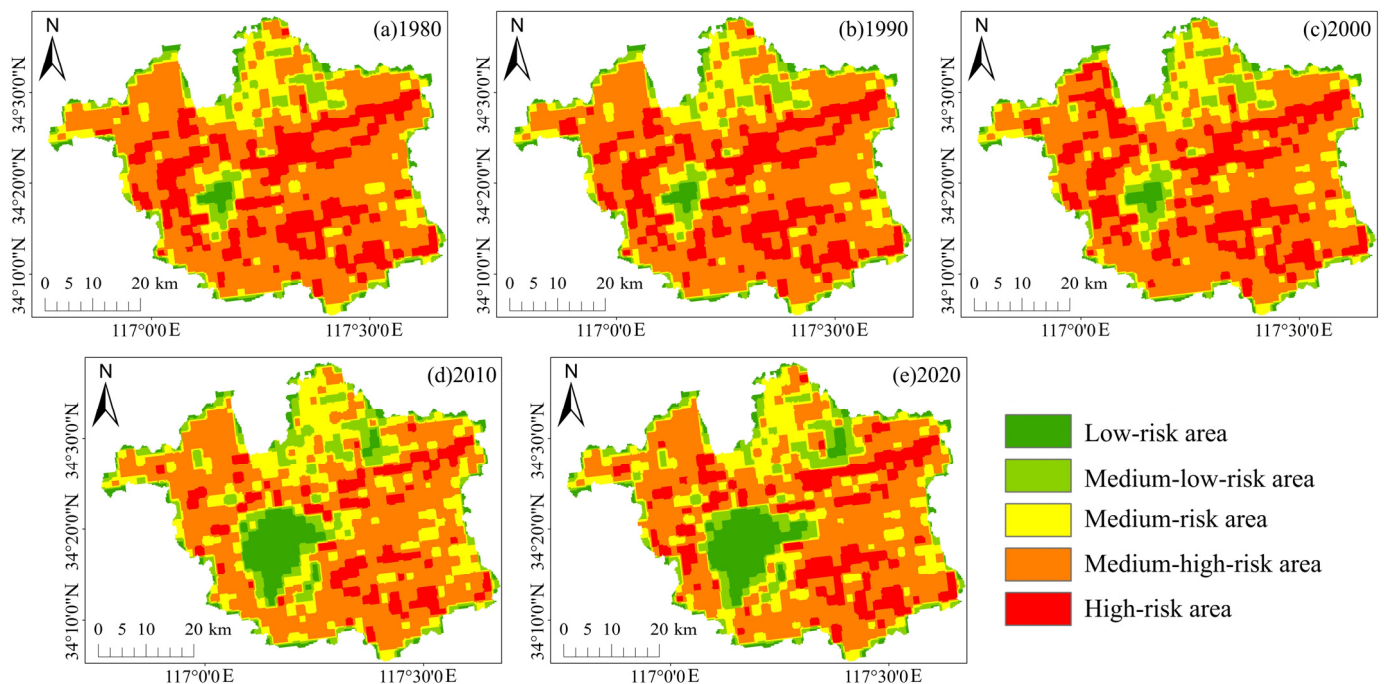


Figure 5. Spatial distributions of landscape ecological service quality in the Xuzhou planning area, 1980–2020.

Changes in the ecological risk levels from 1980 to 2020 are depicted in Figure 6. High- and medium-high-ERI-risk areas predominantly experienced transfers out, characterized by the transformation of high-risk areas into medium-high-risk areas and medium-high-risk areas into medium-low-risk areas. Specifically, the area of high- and medium-high-risk areas has decreased by 155.14 km² and 224.16 km², respectively. These land transfers were primarily concentrated at the periphery of the southwestern central urban area, which is geographically advantageous. During urbanization, portions of cultivated land, forest land, and water resources were converted into urban living land with low landscape vulnerability. Conversely, the area of the ERI low-, medium-low-, and medium-risk zones has increased by 191.31 km², 96.33 km², and 91.67 km², respectively. This increase mainly stemmed from high- and medium-high-risk areas. In the northeastern part of the study area, the landscape primarily consists of forest land and cultivated land with high ecological benefits, whereas the southwestern part is a hub of human activities. During urbanization, extensive land in the southwestern central city and the northeastern part of Jiawang District was developed and utilized. Consequently, urban living space continuously encroached on the surrounding agricultural production space and ecological space. Urban construction land proved to be more stable and less susceptible to environmental changes and human activities, thus reducing the regional landscape vulnerability and ecological risk. The

urbanisation rate was the fastest from 2000 to 2010, during which the landscape ecological risk in the southwestern central urban area and the northeastern part of Jiawang District was most significantly reduced.

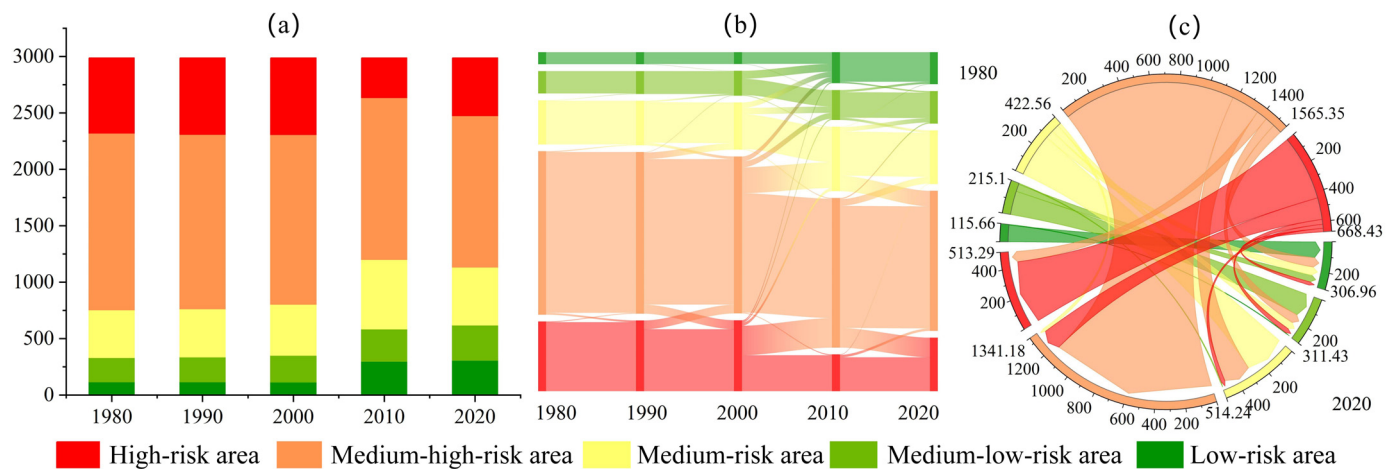


Figure 6. (a) Shares of ecological risk in the landscape at all levels, 1980–2020; (b) sankey diagrams of ecological risk transfer in the landscape at all levels for all periods, 1980–2020; (c) dazzle diagrams of ecological risk transfer in the landscape at all levels, 1980–2020.

3.2.2. The Spatial and Temporal Evolution of the Quality of Ecosystem Services

From 1980 to 2020, the total ecosystem service value of the Xuzhou planning area exhibited a trend of initially increasing and then decreasing. Overall, the ESV tended to decrease, dropping from 350,605,640,000 yuan to 318,753,800 yuan, representing a rate of change of about 10.03%. The most significant fluctuations occurred between 2000 to 2010 (Table 6). The hierarchical relationship of the total ecosystem service value supply of each functional space was other < grassland < water < forest land < agricultural land.

Table 6. Ecosystem service value (ESV) of the “production–living–ecological space” in the Xuzhou planning area, 1980–2020.

ESV (RMB 10,000)	Agricultural Production Space	Woodland Ecological Space	Grassland Ecological Space	Watershed Ecological Space	Other Ecological Spaces	Grand Total
1980	202,654.67	95,812.37	6040.62	46,040.34	57.65	350,605.64
1990	201,677.38	95,866.61	6065.94	50,249.45	57.65	353,917.04
2000	195,692.66	94,673.15	5947.75	55,523.58	57.82	351,894.96
2010	182,920.24	88,482.09	3780.84	49,984.47	67.37	325,235.00
2020	176,232.55	87,742.96	4221.26	50,488.95	67.37	318,753.08

The ecosystem service quality of the Xuzhou planning area was classified into five categories using the natural breakpoint method: low ($ESV \leq 6960$), medium-low ($6960 < ESV \leq 10,882$), medium ($10,882 < ESV \leq 16,160$), medium-high ($16,160 < ESV \leq 23,249$), and high ($ESV > 23,249$) (RMB 10,000) (Figure 7). The southwest and northeast regions exhibited more pronounced rank changes in ESV, indicating an increasing significance of spatial differentiation in the ESV. In the southwest, low-ESV areas gradually expanded and became contiguous. High- and medium-high-ESV areas were primarily located in the northeastern part of Jiawang District and the southeastern part of Tongshan District, regions rich in woodlands and watersheds. Over the past 40 years, the continuous encroachment of living spaces into agricultural production and ecological spaces led to a 14.22% increase in the area share of low-ESV regions. Conversely, the area share of high- and medium-high-ESV regions decreased by 1.16%, resulting in a certain degree of degradation in the quality of

ecosystem services in the region. This encroachment has compromised the overall quality of regional ecosystem services.

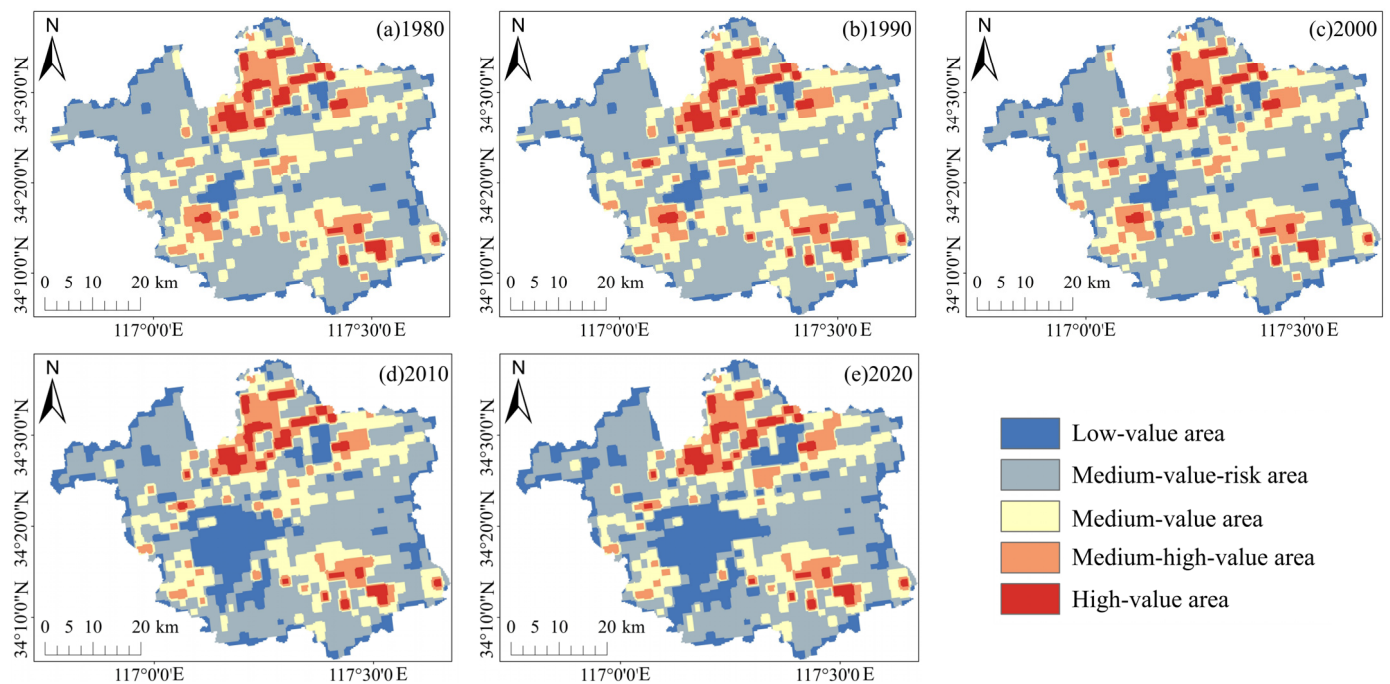


Figure 7. Spatial distribution of landscape ecosystem service quality in the Xuzhou planning area, 1980–2020.

In conjunction with the alteration of the ESV area and its rank transfer (Figure 8), it was determined that a significant portion of ESV medium-low- and medium-value areas in the southwest and central part of the study area underwent a transition to low-value areas over the 40-year period. This region, being the main area of urbanization and construction within the Xuzhou planning area, experienced a decline in the value of regional ecological services due to the progress of economic development. The dense forested areas in the northeastern part of Jiawang District and the southwestern Tongshan District are the concentrated areas of high and medium-high ESV, indicating a relatively strong regional ecological background. These areas should be regarded as key logistic support areas for ecosystem service provision. Over the 40-year period, high- and medium-high-ESV areas exhibited a fluctuating trend, with periods of increasing, decreasing, and subsequently increasing. During the period from 1980 to 2000, the ratio of high- and medium-high-ESV areas in the study area increased by 0.19% and 0.63%, respectively. This increase was primarily due to the conversion of portions of agricultural land into water bodies. Between 2000 and 2010, rapid urbanization led to a significant reduction in agricultural production space and ecological areas comprising waters and woodlands in the southwestern part of the study area. This reduction contributed to a decline in the quality of regional ecosystem services. From 2010 to 2020, environmental protection and ecological restoration efforts resulted in the conversion of some agricultural land in Pan'an Lake and Dugong Lake in the northeastern part of Jiawang District into watersheds. This conversion led to a slight improvement in the quality of regional ecosystem services. This analysis underscores the dynamic changes in ecosystem service values in the Xuzhou planning area, highlighting the impacts of urbanization and ecological restoration on regional ecological service quality.

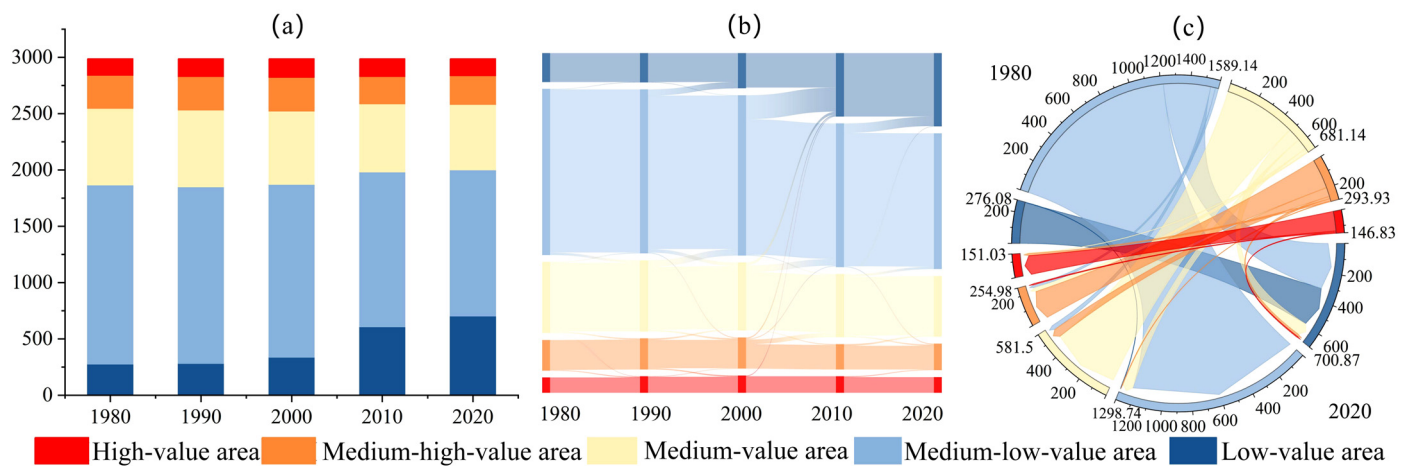


Figure 8. (a) Shares of ecosystem service quality at different levels, 1980–2020; (b) sankey diagram of ecosystem service quality transfer at different levels for each time period, 1980–2020; (c) dazzle diagram of ecosystem service quality transfer at different levels, 1980–2020.

3.2.3. Correlation Analysis of Landscape Ecological Risk Values (ERI) and Ecosystem Service Values (ESVs)

Global spatial correlation analyses of landscape ecological risk (ERI) and ecosystem service value (ESV) in the Xuzhou planning area (Figure 9) yielded global Moran's I values of 0.210, 0.209, 0.221, 0.267, and 0.286 for the years of 1980–2020, respectively. Using a 999 permutation test ($p = 0.001$), Moran's I values were consistently greater than 0, indicating a significant positive spatial correlation between the ERI and ESV over time. The increasing trend of Moran's I over the 40-year period reflects an intensifying spatial clustering of landscape ecological risk and ecosystem service quality associated with land use changes in the “production–living–ecological space”.

The results of local spatial correlation analyses of the ERI and ESV (Figure 10) revealed three predominant types of aggregation zones: “high–high”, “low–low”, and “low–high” aggregation zones, while “high–low” aggregation areas were sparse and isolated. In the northeastern part of the study area, specifically in Jiawang District, and the southeastern part of Tongshan District, the distribution of forest, water, and grassland ecological space supports relatively high ecosystem service quality. These areas are characterized by “high–high” and “low–high” aggregation of the ERI and ESV. The south-western part of the study area, characterized by complex landscape types and high landscape fragmentation, is particularly susceptible to human activities. Urbanization has led to the expansion of living spaces in towns and cities, encroaching on agricultural production land and ecological spaces. Consequently, some arable land, forest land, grassland, and water bodies have been converted into high-stability construction land. The local spatial correlation of the ERI and ESV in this southwestern part of the study area has changed from a “high–high”, “low–low”, and “low–high” agglomeration to a predominantly “low–low” agglomeration. In addition, some “low–low” agglomerations have emerged at the border of the study area. These regions, primarily comprising contiguous agricultural and rural areas, exhibit low landscape fragmentation and are distant from urban centres, making them less susceptible to human activities. Consequently, they possess low landscape ecological risk and lower ecosystem service quality.

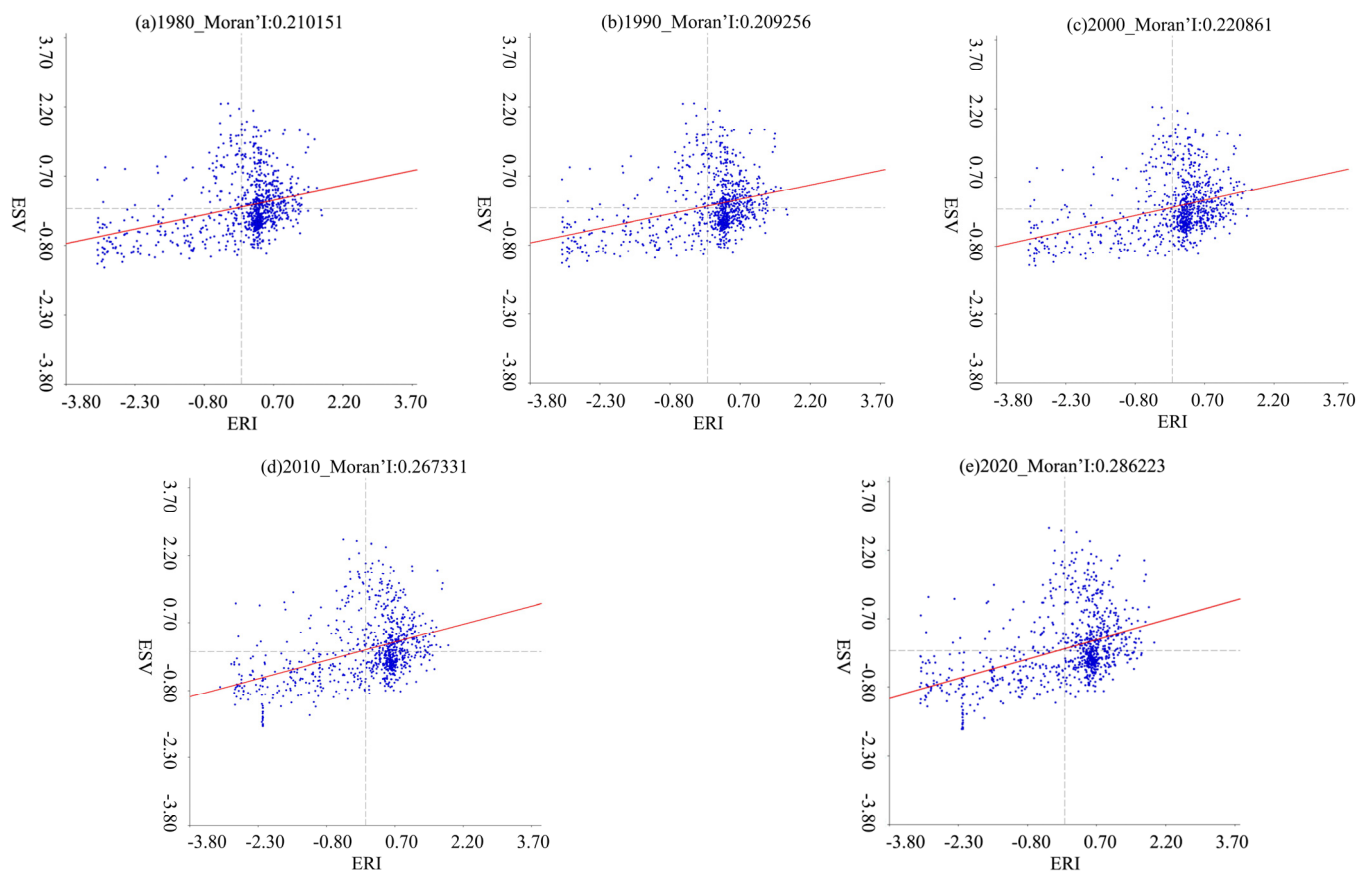


Figure 9. Global Moran's I Scatterplot of the ERI and ESV in the Xuzhou Planning Area, 1990–2020.

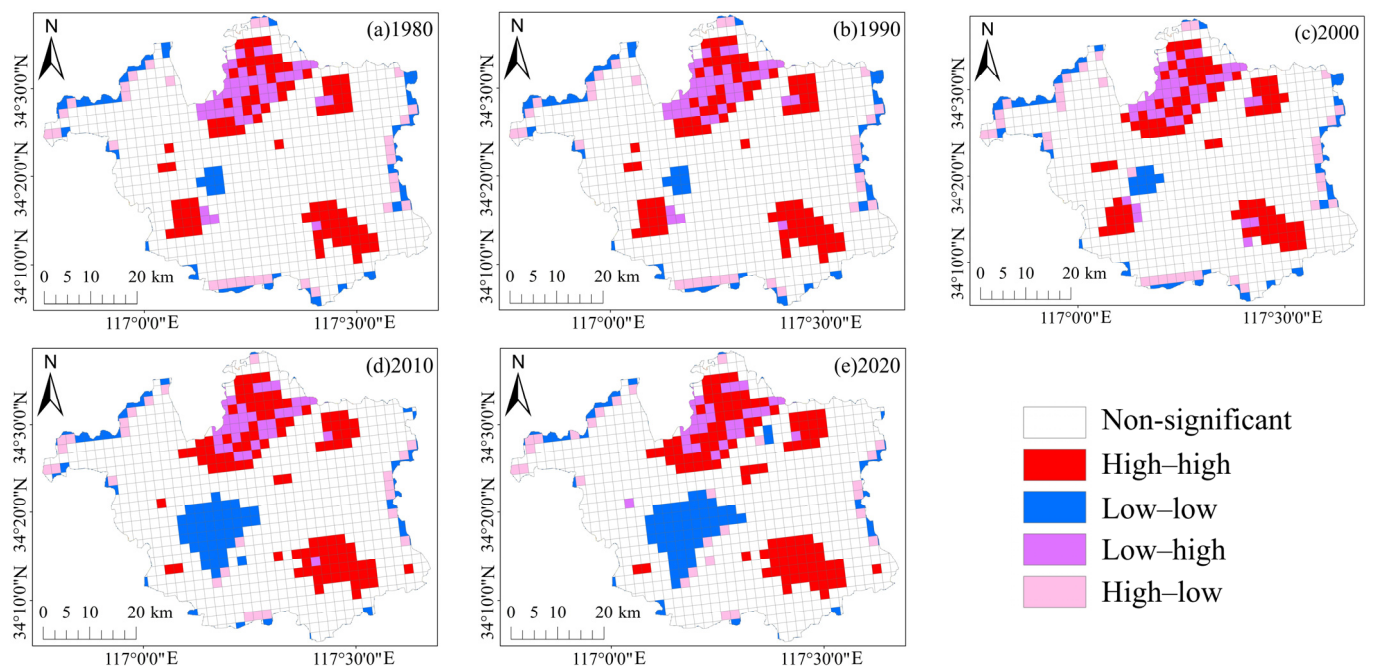


Figure 10. Local spatial correlations between the ERI and ESV in the Xuzhou planning area, 1990–2020.

3.3. Driving Force Analysis

3.3.1. Analysis of the Results of Single-Factor Probes

The results (Table 7) indicate that population density and GDP are the primary drivers of the evolution of the “production–living–ecological space”, with the q-values of both increasing from 0.0967 and 0.0957 in 2000 to 0.2792 and 0.2414 in 2020, respectively. This increase in population density and GDP since 2000 has led to an increased demand for food, housing, and public facilities. Among natural factors, the influence of soil type and altitude on the evolution of the “production–living–ecological space” is more significant. In terms of time series, while the influence of precipitation on the evolution of land use functions within the “production–living–ecological space” shows an increasing trend, the influence of other natural factors on the “production–living–ecological space” of the Xuzhou planning area decreases to different degrees. Among the accessibility factors, distance from town has a significant impact on the pattern of the “production–living–ecological space”, with the q-value increasing from 0.0868 in 2000 to 0.1493 in 2020. Additionally, the influence of the distance from roads and railways on the evolution of the production–living–ecological space increases. As the “first officer of economic development”, the improvement of road and transport systems further expands agricultural production and rural living space, and promotes regional economic and social development.

Table 7. Factor detection results for 2000–2020.

Factor Category	Driving Factor	2000		2010		2020	
		Q-Value	Contribution %	Q-Value	Contribution %	Q-Value	Contribution %
Natural factor	Elevation (X1)	0.0851	13.08	0.0913	10.78	0.0697	5.88
	Slope (X2)	0.0248	3.81	0.0226	2.67	0.0173	1.46
	Average annual temperature (X3)	0.0120	1.84	0.0118	1.39	0.0151	1.27
	Annual precipitation (X4)	0.0052	0.80	0.0164	1.94	0.0345	2.91
	Soil type (X5)	0.1752	26.93	0.1590	18.78	0.1302	10.99
Socio-economic factors	GDP (X6)	0.0957	14.71	0.1296	15.31	0.2414	20.37
	Population density (X7)	0.0967	14.87	0.1431	16.90	0.2792	23.56
	Distance to town (X8)	0.0868	13.34	0.1200	14.17	0.1493	12.60
Accessibility factor	Distance to road (X9)	0.0402	6.18	0.0952	11.24	0.1402	11.83
	Distance to railroad (X10)	0.0232	3.57	0.0505	5.96	0.1006	8.49
	Distance from river (X11)	0.0056	0.86	0.0072	0.85	0.0075	0.63

3.3.2. Interaction Detection Results and Analysis

The results of the driving factor interactions from 2000 to 2020 (Figure 11) indicate that the factor interactions in each year are all characterised by two-factor enhancement or non-linear enhancement. This suggests that the evolution of the “production–living–ecological space” pattern in the Xuzhou planning area is the result of the joint action of multiple factors. The interactions of socio-economic factors with natural factors and accessibility factors are generally stronger than the interactions within them. Population density (X7) and soil type (X5) exhibit the strongest interactions, with interactive explanatory powers of 0.290, 0.318, and 0.422 in 2000, 2010, and 2020, respectively. The interaction of GDP (X6) and soil type factor (X5) also shows significant explanatory power increasing from 0.284 in 2000 to 0.367 in 2020. Additionally, the explanatory power of the interaction of distance to town (X8), distance to road (X9), and population density (X7) shows a notable increase in explanatory power, rising from 0.167 and 0.149 to 0.342 and 0.352, respectively. These findings reflect how population growth, economic development, and improvements in the transportation system have led to increased demands for food, infrastructure, and housing. Consequently, there is a heightened demand for agricultural production space and urban living space, driving the evolution of the “production–living–ecological space” pattern in the Xuzhou planning area.

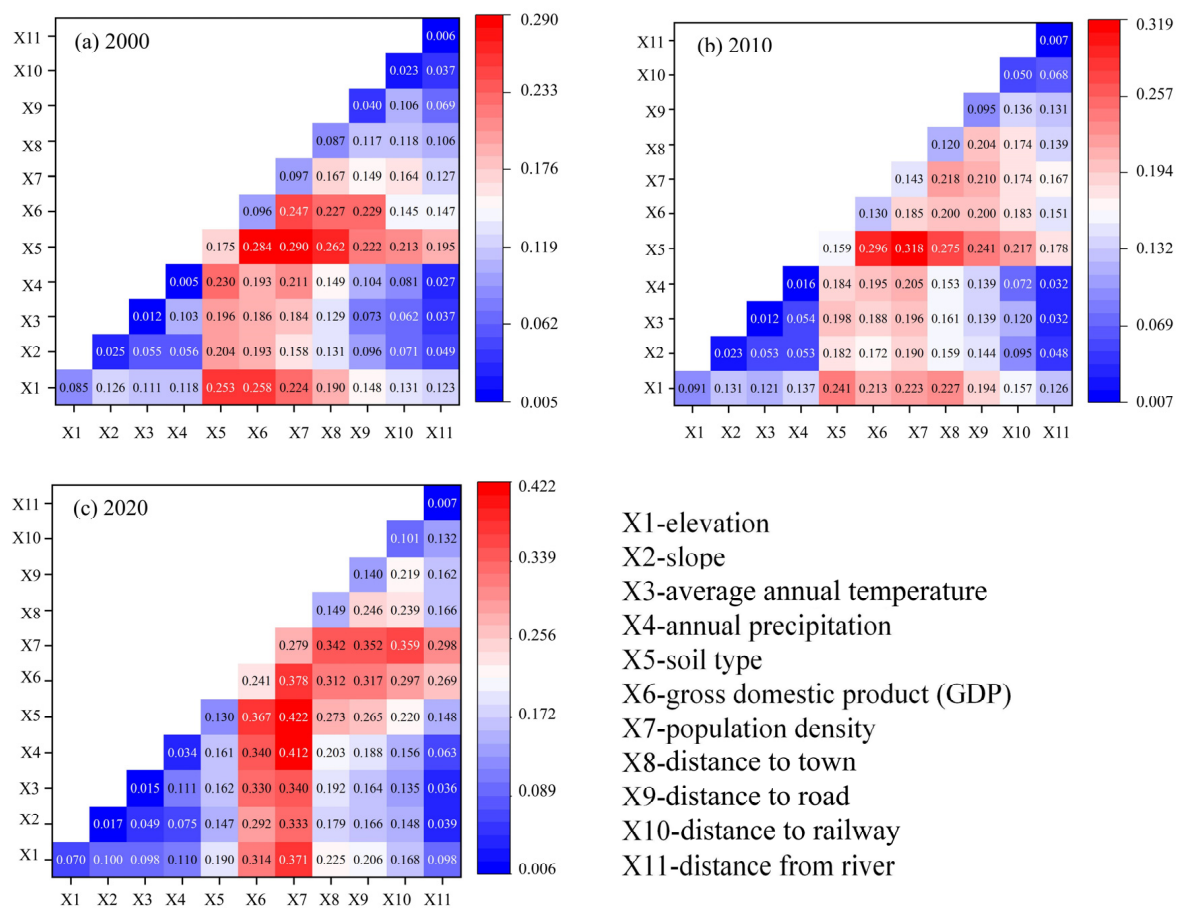


Figure 11. Driver interaction results, 2000–2020.

4. Conclusions and Recommendations

4.1. Conclusions

- (1) From 1980 to 2020, agricultural production space was predominant in the planning area of Xuzhou, followed by urban and rural living spaces. Over this 40-year period, significant changes occurred in the pattern of the “three living spaces”, with the rapid expansion of living spaces in the southwestern central city and the northeastern part of Jiawang District. This expansion continuously encroached upon the surrounding agricultural production spaces and the ecological spaces of forests and grasslands. The most drastic development of the “production–living–ecological space” occurred between 2000 and 2010, during which the conflict between human activities and land use was particularly pronounced.
- (2) Both the landscape ecological risk and the ecosystem service quality in the Xuzhou planning area gradually declined from 1980 to 2020. The northeastern part of Jiawang District and the southeastern part of Tongshan District, with their dense distributions of woodlands, watersheds, and grassland ecological spaces, maintained better regional ecosystem service quality. These areas were characterized by “high–high” and “low–high” aggregations of the ERI and ESV. Conversely, the southwestern part of the region, as the main site of urbanization, experienced significant landscape changes and a reduction in the value of regional ecosystem services. In this area, the local spatial correlation between the ERI and ESV shifted from “high–high”, “low–low”, and “low–high” aggregations to predominantly “low–low” aggregations.
- (3) Geoprobe analysis revealed that GDP, population density, soil type, distance to towns, and distance to roads are the main drivers of the evolution of the “production–living–ecological space”. The interactions between these factors were consistently strengthened, with the interaction between population density (X7) and soil type (X5) being

particularly significant for the spatial differentiation of landscape ecological risk and ecosystem service value.

4.2. Recommendations

The results of the study indicate that the central urban area in the southwestern part of the Xuzhou planning area is significantly influenced by socio-economic development and accessibility factors. Conversely, the watersheds, forests and grasslands in Jiawang District in the northeastern part of the study area and the southeastern part of Tongshan District provide substantial ecosystem service values while being less affected by socio-economic disturbances. Based on these findings, the following three recommendations are made:

- (1) The study area of the northeastern part of Jiawang District and the southeastern part of Tongshan District, characterized by dense regional distributions of forest and watershed ecological spaces, are high-risk-high-value areas. It is essential to adhere to principles of protection priority, strict management, systematic governance, scientific restoration, and rational use for the protection and construction of regional ecological land. Compliance with the Red Line of ecological protection is crucial, as is rectifying unauthorized anthropogenic activities encroaching on nature reserves. Regulating the intensity of human activities, connecting ecological spaces of forests, waters, grasslands, and important ecological functional zones, maintaining the integrity of ecological land, and preventing further fragmentation due to anthropogenic disturbances are imperative.
- (2) The northwestern part of the study area, identified as a low-risk-high-value zone, possesses strong regional ecological stability and well-functioning ecosystems. It is vital to strictly limit the expansion of construction land, promoting centralized construction and scaled-down development. Encouraging the natural renewal of woodlands and grasslands will enhance climate regulation and water conservation services. Developing a regional eco-economic model and establishing an exemplary leading role in ecological sustainability is recommended.
- (3) The central urban area in the southwestern part of the Xuzhou planning area, classified as a low-risk-low-value zone, has experienced a decline in regional ecosystem service value and landscape ecological risk primarily due to the conversion of ecological land into construction land. This area is heavily influenced by socio-economic development, with significant conflicts between human activities and land use. Adhering to the principles of the orderly expansion and moderate development of living space is necessary. Defining urban development boundaries scientifically and rationally, controlling the total amount of construction land, and making efficient use of land resources will help avoid the rapid expansion of urban living spaces at the expense of agricultural production and ecological spaces. This approach will promote the coordinated development of the “production-living-ecological space”.

The study constructed a landscape ecological risk–ecosystem service value assessment model, combined with a geographic detector, to analyse the environmental benefits and driving factors behind the evolution of the “production–living–ecological space” pattern in the Xuzhou planning area. This analysis provides a scientific basis for the coordinated development of ecological environmental protection and the “production–living–ecological space” in the Xuzhou planning area. However, there are still the following shortcomings: (1) The evolution of the “production–living–ecological space” is the result of the interaction between human beings and nature, and is affected by a combination of natural, social, cultural and policy factors. In order to understand this concept more comprehensively, future research needs to incorporate more cultural and policy factors in order to deepen the understanding of this complex phenomenon. (2) Due to limitations in data acquisition during 1980–2000 period, this study was unable to analyse the driving factors in this period. It is recommended that future research includes this timeframe to provide a more comprehensive analysis. By encompassing the 1980–2000 period, future studies can provide

more targeted strategic recommendations for the optimization of the “production–living–ecological space” and the sustainable development of the Xuzhou planning area.

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