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Exploring the Coupling Coordination Relationship of Urban Resilience System in Ecologically Fragile Areas: Case Study of the Loess Plateau in China

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Abstract: Urban ecosystem health threats and natural disasters have a prominent influence under the rapid urbanization process, and high urban resilience (UR) is the key to response to human-natural disasters. This study attempts to construct a comprehensive index system of UR based on the DPSIR (Driving—Pressure—State—Impact—Response) framework to explore the coupling coordination relationship and driving factors of UR in ecologically fragile areas, using panel data of 39 cities in the Loess Plateau from 2010 to 2019. The empirical results have shown that most cities present low and medium levels of urban resilience, indicating that the UR of the Loess Plateau is not ideal, that there is a significant spatial difference between the urban resilience and coupling coordination degree (CCD), and the spatial characteristics are represented by "central depression". Additionally, there are significant discordant relationships among the five subsystems of UR, which means that the pressure subsystem has the highest score, while the driving force subsystem and state subsystem have the lowest score. Regarding the driving factors, institutional quality, scientific and technological expenditure, and industrial upgrading have a significant positive impact on UR, while gross industrial output, urban carbon emissions, and urban population density have a significant negative impact on UR. This study provides a new index system and information and decision-making reference for UR exploration, which is also conducive to the future urban sustainable development planning in ecologically sensitive areas.

Keywords: urban resilience; DPSIR framework; coupling coordination degree model; driving factors; Tobit model; the Loess Plateau

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1. Introduction

According to UN-Habitat's Sustainable Development Goals, increasing urban resilience to the impacts of natural and anthropogenic hazards is a key issue of the "Overview of Urban Resilience Scheme" launched by UN-Habitat. Since the issue of "urban resilience" was first proposed by the International Council for Local Environmental Issues (ICLEI) in 2002, urban resilience has been gradually expanded to multi-dimensional perspectives, including urban socio-economic and spatial analysis [1,2]. Cities account for about 75% of global carbon emissions and energy consumption [3]. A series of "urban diseases" have brought constraints to sustainable urban development with rapid industrialization and urbanization, such as air pollution [4], imbalance in the water-energy-food relationship [5], waste of land and water resources [6], and destruction of biodiversity [7]. With this background, international schemes such as the 100 Resilient Cities scheme, launched by the Rockefeller Foundation, the 2030 Agenda for Sustainable Development, and the World Cities Report (2020), published by UN-Habitat, are proposed to solve the sustainable problems for urban ecosystems.

Urban resilience is a new concept in sustainable urban planning, where cities and local governments need to enhance their ability to reduce losses and shorten recovery periods from any potential disaster [8]. Due to the ecological environmental deterioration and urban livable threats brought about by rapid industrialization and urbanization, how to assess urban resilience and identify driving factors have become the key issues to sustainable urban planning and design in the future [9]. Presently, existing studies have emphasized that the assessment of urban resilience should not only consider the dynamic changes in the social economy and urban ecosystem, but also pay attention to the inter-relationship between various subsystems of urban resilience [10,11]. The theoretical framework exploration of urban resilience mainly includes the PSR (pressure-state-response) framework [12], the DPSEEA (driving-pressure-state-exposure-effect-action) framework [13], the UGS-3CC (urban green space-concepts and competences and connections) framework [14], and the DPSIR (driving-pressure-state-impact-response) framework [15]; these frameworks are widely used to investigate the dynamic relationship between regional socio-economic systems and the ecosystem.

Based on the analysis of existing studies, the marginal contribution of this study includes the following two aspects. First, cities on the Loess Plateau in ecologically sensitive area and economically underdeveloped areas are selected to explore urban resilience and driving factors, aiming to provide a reference for urban transformation and upgrading and the improvement of disaster prevention and mitigation capacity in underdeveloped areas. Second, based on the DPSIR framework, the spatial-temporal evolution of urban resilience and the coupling coordination degree of five subsystems in underdeveloped regions are explored, which remedy the deficiency of the research on the coordinated development of multiple systems under the DPSIR framework.

2. Literature Review

Existing studies have found that landscape patterns are an effective medium for observation and intervention of urban resilience system [16,17]. Protecting the functions of local landscape systems can help maintain urban sustainability and increase the overall capacity of cities to respond to natural disasters [18]. Based on the theory of landscape ecology, some studies have explored the urban resilience of a single region by constructing an urban resilience analysis framework integrating scale, density, morphology, and function [19]. Some studies have demonstrated a service, connectivity, and environment (SCE) model to evaluate urban resilience from the perspective of landscape [20]. Regarding urban resilience from the perspective of nature-based solutions (NBS), the NBS concept has been widely used in disaster risk reduction and urban resilience assessment [21,22]. From a microscopic perspective, landscape plays an important role in improving community resilience, the alliances and the role of community in orienting landscape planning, and the role of community in micro-interventions for urban biodiversity and landscape functionality [23]. Some studies have adopted the prediction-adaptation-resilience (PAR) approach to analyze the future urban landscape resilience and sustainable development goals (SDGs), which is crucial for exploring sustainable urban planning and development models in the context of rapid urban proliferation [24].

The DPSIR framework was proposed by the European Environment Agency (EEA) in 1993 to reveal the casual chain between the origin and outcome of environmental problems, aiming to provide a technical framework for systematic exploration of the dynamic relationship between the social economy and natural environment [25]. The DPSIR framework covers multi-dimensional factors of economy, society, and ecological environment, which can comprehensively reflect the impact of various factors on the urban complex ecosystem and the interaction between various factors [26]. The DPSIR framework can be used to explore the relationships among the five subsystems, group the corresponding indicators, and systematically analyze the structural and functional evolution of the composite system. In essence, the complex human-natural relationship described by the DPSIR framework provides a technical basis for exploring the resilience

of urban ecosystems and the coordinated development of multiple systems [27]. Based on the DPSIR framework, existing studies have explored urban disaster resilience, urban ecological security resilience, and urban sustainable development ability from the perspective of multivariate systems [28–31]. The DPSIR framework provides technical support for sustainable urban management and planning and remedies the research deficiencies of the complex relationship between humans and nature in social sciences and ecology.

Urban resilience has become a frontier field and research hotspot in the field of urban ecological, socioeconomic, and cultural sustainable development. Existing studies have defined the conceptual connotation of urban resilience, and different disciplines have different priorities in defining urban resilience. It could be concluded that the systematic synthesis and factor diversification of urban resilience has become the consensus of academic research [32–34]. For one thing, urban resilience assessment includes a multi-layered framework for pre-disaster preparedness, post-disaster response, and post-disaster reconstruction; some studies have defined urban resilience from the perspective of the city's ability to cope with disasters, and it is believed that urban resilience refers to the urban ability to survive and adapt to development when it suffers from continuous and chronic pressure or sudden disaster impact [35,36]. Previous studies define urban resilience and construct a multi-dimensional assessment framework based on the perspective of the urban integrated system, including infrastructure resilience, institutional resilience, economic resilience, and social resilience; these multi-dimensional systems interact in complex relationships, which can cooperate with each other in coping with the urban adaptation and development capacity in the present and future periods [37,38].

Regarding the measurement index system of urban resilience, there is still no unified measurement index system for urban resilience in existing studies. However, it could be found from previous research that the construction of an urban resilience index system follows the principle of urban sustainable development and the regional characteristics of cities. For instance, determining the resilience index of cities and communities is the basis for assessing the pre-disaster preparedness and post-disaster response measures, which is of great significance for regional disaster vulnerability assessment, disaster prevention, and mitigation decisions [39]. The index system of urban resilience includes the elements of urban disaster management, urban disaster prevention and mitigation measures, and disaster prevention policies for cities in disaster-prone regions; the key to the index system construction is to reflect the city's comprehensive response-ability and adaptability to human-natural disasters [40,41]. Additionally, based on sustainable theories in ecology and sociology, urban resilience is based on the multi-dimensional perspective of urban sustainable development goals (SDGs) in order to evaluate the interaction between urban ecosystem resilience and its subsystems [42,43]. Some studies have pointed out that the urban resilience measurement reflects the evolution of the structure and function of the urban ecosystem, that the key to improving urban resilience lies in urban ecosystem service capacity, and that the resilience of urban ecosystem service capacity depends on the quantity, quality, and structural elements of green infrastructure [44,45].

From what has been discussed above, it could be found that the index system of urban resilience measurement has not been unified. Uran resilience not only emphasizes the stability of multiple system dimensions of nature, economy, and society, but also considers the dynamic complex relationship among the components of the urban resilience system. Additionally, existing studies are still insufficient to assess urban resilience in ecologically fragile areas, especially the dynamic studies on the identification of key factors of urban resilience. How to assess urban resilience in ecologically fragile areas and identify key factors is an important part of achieving sustainable urban development goals. Therefore, the entropy weight TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) model, coupling the coordination degree model and the Tobit model, were combined to explore the urban resilience and driving factors in underdevelopment areas based on the DPSIR framework. Thirty-nine cities on the Loess Plateau from 2010 to 2019

were adopted for investigation, aiming to provide a comprehensive analysis framework for urban resilience and urban planning and design in underdeveloped areas.

3. Study Area and Data Source

3.1. Study Area

The Loess Plateau is the most concentrated and largest loess accumulation area in the world, with an area of about 640,000 square kilometers. It is one of the areas with the most concentrated contradiction between population, resources, and ecological environment in China. The Loess Plateau is a semi-humid and semi-arid region with diverse vegetation types and the largest proportion of grassland area, with an average altitude of 500–2000 m. The region spans seven provinces (autonomous regions), including Henan, Qinghai, Ningxia, Gansu, Shaanxi, Shanxi, and Inner Mongolia. Since the reform and opening-up, the continuous increase of population in the Loess Plateau has stressed the sustainability of regional resources and environment along with the rapid industrialization and urbanization development. Presently, the sustainable development of the Loess Plateau has been restricted by such problems as sparse vegetation, serious soil erosion, high population pressure, lagging industrial development, and landslide disasters. The geographical location of the Loess Plateau in China is shown in Figure 1.

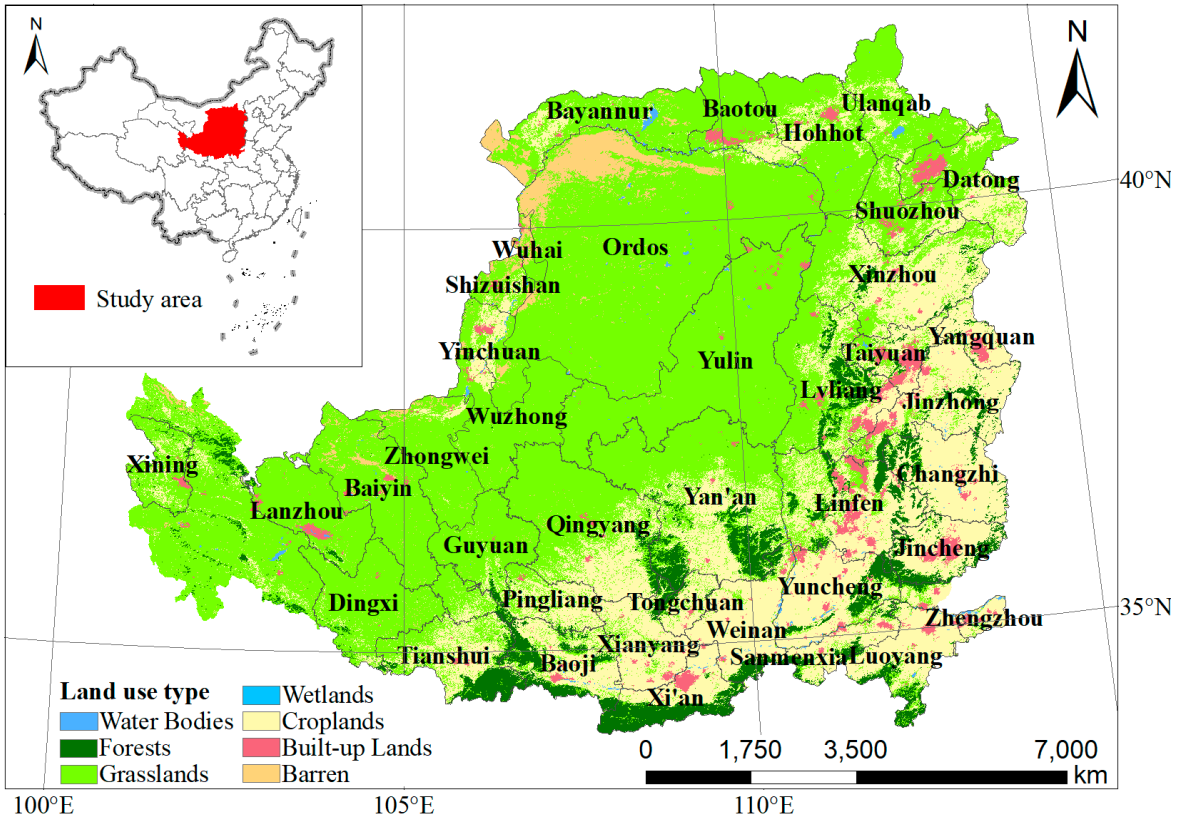


Figure 1. The geographical location of the Loess Plateau, China.

3.2. Data Source

The data sources of urban resilience index system construction and driving factors in this study include "China Urban Statistical Yearbook (2011–2020)", "Shanxi Statistical Yearbook of Shanxi Province (2011–2020)", "Statistical Yearbook of Shaanxi Province (2011–2020)", "Statistical Yearbook of Gansu Province (2011–2020)", "Statistical Yearbook of Henan Province (2011–2020)", "Statistical Yearbook of Qinghai Province (2011–2020)", "Statistical Yearbook of Inner Mongolia Autonomous Region (2011–2020)", and the "Statistical Yearbook of Ningxia Autonomous Region (2011–2020)". Some missing data were filled by the interpolation method.

4. Methodology

In this study, the entropy weight TOPSIS model has been used to measure urban resilience in the Loess Plateau region, and the objective weights of various indicators in the index system have been calculated based on the entropy weight method. TOPSIS model has been used to evaluate the comprehensive index of urban resilience in 39 regions of the Loess Plateau. Additionally, based on the DPSIR framework, the coupling coordination model is used to explore the coordinated evolution of the five sub-systems of urban resilience. Finally, the TOBIT model is used to investigate the driving factors and obstacle factors of urban resilience in ecologically fragile areas. The theoretical framework of this study is shown in Figure 2.

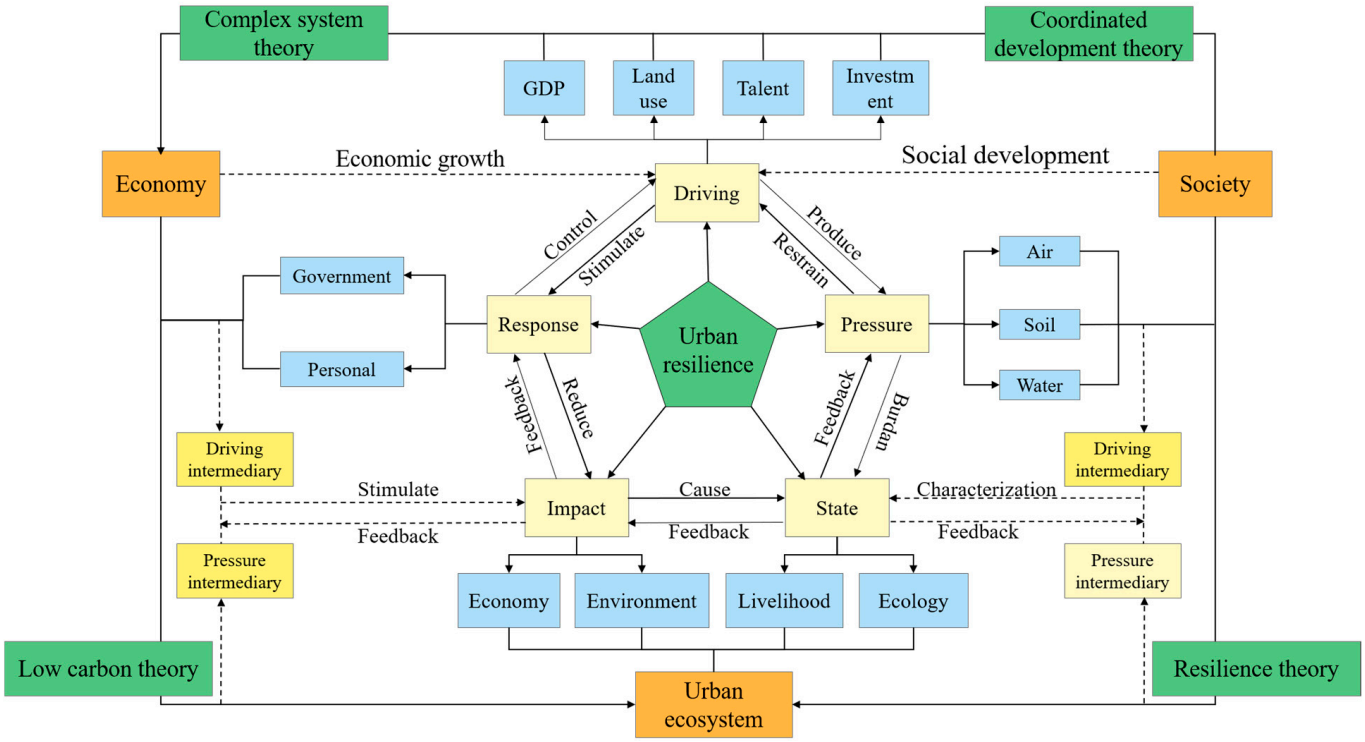


Figure 2. The theoretical framework of this study.

4.1. Entropy Weight TOPSIS Model

The entropy weight calculation is a method to determine the weight according to the rating index value. The advantage is that it can objectively reflect the information implied by the data, which can avoid the measurement result deviation caused by the difference of selected indicators. According to the variation degree of each index, the weight of the index can be calculated objectively. The calculation procedure is as follows:

$$\omega_i = \frac{N_i}{\sum_{i=1}^{m} N_i} \tag{1}$$

where w_i is the weight results of index i, $i = 1, 2, 3, \ldots, m$. There are twenty-five indicators in the evaluation index system, $m = 25$. N_i represents the discrete degree of the index i, and the calculation formula is as follows:

$$N_i = 1 - H_i \tag{2}$$

$$H_i = -k \sum_{j=1}^{n} \sum_{t=1}^{r} f_{ij} \ln f_{ij} \tag{3}$$

$$f_{ij} = \frac{r_{ij}}{\sum_{t=1}^{r} r_{ij}} \tag{4}$$

where H_i denotes the entropy of the index i, k is the Boltzmann constant. $j = 1, 2, 3, \ldots, n$, j represents the evaluation number of the study area. t denotes the time of this study. f_{ij} is the proportion of the standardized value of index i in the entire evaluation matrix. Before the entropy measurement, the range standardization method was used to standardize the original data. The positive index was calculated by Equation (5), and the negative index was calculated by Equation (6).

$$r_{ij} = \frac{v_{ij} - \min(v_{ij})}{\max(v_{ij}) - \min(v_{ij})} \tag{5}$$

$$r_{ij} = \frac{\max(v_{ij}) - v_{ij}}{\max(v_{ij}) - \min(v_{ij})} \tag{6}$$

The entropy weight is combined with the TOPSIS model based on the results of the index weight calculation. The TOPSIS model (Technique for Order Preference by Similarity to an Ideal Solution) is a common decision technology in systems engineering, and is widely used in solving multi-objective decision problems with finite solutions [46,47]. Compared with other comprehensive evaluation methods, the advantage of the TOPSIS model is that it can comprehensively consider indicators of multiple dimensions, can be combined with an objective weight-solving method for comprehensive evaluation, and can intuitively determine the optimal solution or optimal choice. In addition, compared with multi-dimensional index system solving, this method does not involve complicated mathematical calculations and models, and can be easily understood and applied. This method uses distance as an evaluation criterion; the urban resilience and the integrated level of its subsystems are evaluated based on the degree of the calculation target that is close to or deviates from the positive and negative ideal solution, which can objectively reflect the dynamic change trend of urban resilience. The equation is as follows:

$$T_j = \frac{D_j^-}{D_j^+ + D_j^-} \tag{7}$$

$$D_j^+ = \sqrt{\sum_{i=1}^{m} \left(\mathrm{u}_i^+ - \mathrm{u}_{ij}\right)^2} \tag{8}$$

$$D_j^- = \sqrt{\sum_{i=1}^{m} \left(\mathrm{u}_i^- - \mathrm{u}_{ij}\right)^2} \tag{9}$$

where T_j denotes the measurement results of urban resilience and its subsystems, $0 \leq T_j \leq 1$. D_j^+ and D_j^- denotes the distance of the measurement vector to the positive and negative ideal solution, respectively.

$$Q^+ = \left\{ \max_{1 \leq i \leq m} q_{ij} | i = 1, 2, \cdots, m \right\} = \left\{ q_1^+, q_2^+, \cdots, q_m^+ \right\} \tag{10}$$

$$Q^- = \left\{ \min_{1 \leq i \leq m} q_{ij} | i = 1, 2, \cdots, m \right\} = \left\{ q_1^-, q_2^-, \cdots, q_m^- \right\} \tag{11}$$

where Q^+ is the maximum value of the index i in the evaluation data in the year j, which represents the positive ideal solution. Q^- is the minimum value of the index i in the

evaluation data in the year j, which represents the negative ideal solution. The weighted normalized matrix Q constructed based on entropy weight is as follows.

$$Q = \begin{bmatrix} q_{11} & q_{12} & \cdots & q_{1n} \\ q_{21} & q_{22} & \cdots & q_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ q_{m1} & q_{m2} & \cdots & q_{mn} \end{bmatrix} = \begin{bmatrix} \mathrm{r}_{11} \times w_1 & \mathrm{r}_{12} \times w_1 & \cdots & \mathrm{r}_{1n} \times w_1 \\ \mathrm{r}_{21} \times w_2 & \mathrm{r}_{22} \times w_2 & \cdots & \mathrm{r}_{2n} \times w_2 \\ \vdots & \vdots & \vdots & \vdots \\ \mathrm{r}_{m1} \times w_m & \mathrm{r}_{m2} \times w_m & \cdots & \mathrm{r}_{mn} \times w_m \end{bmatrix} \quad (12)$$

4.2. Coupling Coordination Degree Model

Based on the measurement results of five subsystems of urban resilience, this study uses the coupling coordination degree model (CCDM) to investigate the spatial-temporal evolution characteristics of the coupling and coordination level of the five subsystems under the DPSIR framework. The coupling degree refers to the dynamic correlation relationship between two or more systems, and the coordination degree denotes the level of coordinated development between these systems. The coupling coordination degree model is widely used in the dynamic relationship evolution of urban multivariate systems [48–50]. The specific equation is as follows:

$$C = \sqrt[n]{(D \times P \times S \times I \times R) / \left(\frac{D + P + S + I + R}{n}\right)^n} \quad (13)$$

$$T = \alpha \times D + \beta \times P + \chi \times S + \delta \times I + \phi \times R (\alpha + \beta + \chi + \delta + \phi = 1) \quad (14)$$

$$D = \sqrt{C \times T} \quad (15)$$

where D is the coupling coordination degree of urban resilience based on the DPSIR framework, with a value range of [0, 1]. C denotes the coupling degree of five subsystems, T and refers to the comprehensive measurement score of subsystems. D, P, S, I, R represents the five subsystems, and $n = 5$ in this study. Generally, existing research considers all subsystems to be equally important, therefore, $\alpha = \beta = \chi = \delta = \phi = 0.2$. According to the coupling coordination degree (CCD) classification standards in the existing literature, the CCD classification standards of urban resilience based on the DPSIR framework in this study are shown in Table 1.

Table 1. Grade classification of coupling coordination degree.

CCD	$0.700 \leq D \leq 1.000$	$0.500 \leq D < 0.700$	$0.400 \leq D < 0.500$
Grades	High coordination	Moderate coordination	Primary coordination
CCD	$0.300 \leq D < 0.400$	$0.200 \leq D < 0.300$	$D \leq 0.200$
Grades	Mild dissonance	Moderate dissonance	Severe dissonance

4.3. Tobit Model

To explore the key factors of urban resilience in an underdeveloped area, the Tobit model has been adopted to investigate the driving and obstacle factors of urban resilience in the Loess Plateau from 2010 to 2019. The primary model is as follows:

$$Y_i = \alpha_i + \sum_{i=1}^{n} \beta_i X_{it} + \varepsilon_{it} \quad (16)$$

where Y_i denotes the measurement results of urban resilience in the Loess Plateau. α_i is the intercepted item, β_i refers to the parameters of the item i, and X_{it} denotes the explanatory variables of this study. ε_{it} refers to the random error term. Based on analysis

of existing studies, it could be found that there are multi-dimensional driving factors for urban resilience. The final model is established as follows.

$$Y_{it} = \alpha_i + \beta_1 \ln(GIO_{it}) + \beta_2 \ln(PFR_{it}) + \beta_3 \ln(RD_{it}) + \beta_4 \ln(LIB_{it}) + \beta_5 \ln(CE_{it}) + \beta_6 \ln(PD_{it}) + \beta_7 \ln(TI_{it}) + \varepsilon_{it} \quad (17)$$

where GIO represents the gross industrial output, PFR denotes the per capita public finance revenue, RD is the expenditure on science and technology, LIB refers to the public library books per 100 persons, CE represents urban carbon emissions, PD denotes urban population density, and TI refers to the proportion of tertiary industry.

5. Index System

Since the DPSIR framework was proposed by the OECD in 1993, it has been widely used in the field of regional and urban eco-environment-based sustainable development [51,52]. The DPSIR framework covers four major elements: economy, society, resources, and environment. It not only reveals the impact of socioeconomic development and human behavior on resource consumption and ecological environment, but also illustrates the feedback mechanism of human behavior on society. This study constructs the evaluation index system of urban resilience in underdeveloped areas based on this framework, as shown in Table 2.

Table 2. Index system of urban resilience based on DPSIR framework.

Framework	Indicators	Unit	Weight	Attribute
Driving	Total retail sales of consumer goods	Yuan	0.175	+
	Number of university students per 10,000	People	0.221	+
	Per capita total import and export trade	Yuan	0.275	+
	Investment in fixed assets	Yuan	0.142	+
	Proportion of urban construction land	%	0.187	+
Pressure	Industrial wastewater discharge	Tons	0.191	−
	Industrial SO_2 discharge	Tons	0.238	−
	Industrial smoke (dust) discharge	Tons	0.204	−
	PM2.5 concentrations	mg/m^3	0.24	−
	Household water consumption	Tons	0.128	−
State	Per capita roads area	m^2	0.224	+
	Per capita green area	m^2	0.271	+
	Per capita living area	m^2	0.216	+
	Number of buses per 10,000 people	Cars	0.148	+
	Number of doctors per 10,000 people	People	0.141	+
	Green coverage rate of built-up area	%	0.078	+
Impact	Natural population growth rate	%	0.132	+
	Per capita GDP	Yuan	0.263	+
	Per capita household savings balance	Yuan	0.262	+
	The proportion of education workers	%	0.265	+
Response	Centralized sewage treatment rate	%	0.141	+
	Harmless disposal rate of household garbage	%	0.132	+
	Utilization rate of industrial solid waste	%	0.235	+
	Regional GDP growth rate	%	0.189	+
	Average employee wage	Yuan	0.303	+

Driving force denotes the potential factors causing environmental change and mainly refers to the urban socioeconomic activities and industrial development trends. The indicators "Total retail sales of consumer goods", "Number of university students per 10,000", "Per capita total import and export trade", "Investment in fixed assets", and "Proportion of urban construction land" were selected to reveal the driving force of urban resilience. Pressure refers to the negative impact of human activities on the ecological environment and

resource environment, which is mainly manifested as pollutant emission and resource consumption. The indicators "Industrial wastewater discharge", "Industrial SO_2 discharge", "Industrial smoke (dust) discharge", "PM2.5 concentrations", and "Household water consumption" were adopted to represent the pressure state of urban resilience. State refers to the urban comprehensive development status, including urban construction and social development. The indicators "Per capita roads area", "Per capita green area", "Per capita living area", "Number of buses per 10,000 people", and "Number of doctors per 10,000 people" were chosen for explain the state of urban resilience. Impact is the impact of the state of the system on the social economy and living conditions. The indicators "Green coverage rate of built-up area", "Natural population growth rate", "Per capita GDP", "Per capita household savings balance", and "The proportion of education workers" were adopted to reveal the impact subsystem of urban resilience. Response denotes the countermeasures against resource and environmental changes and the feedback of socio-economic growth in the process of urban sustainable development. The indicators "Centralized sewage treatment rate", "Harmless disposal rate of household garbage", "Utilization rate of industrial solid waste", "Regional GDP growth rate", and "Average employee wage" were selected to reflect the impact subsystem of urban resilience.

6. Results

6.1. Measurement Results of the Urban Resilience

Regarding the measurement results of the urban resilience of the Loess Plateau from 2010 to 2019 (Table 3), it could be concluded that most cities have low level and medium levels of urban resilience, indicating that the urban resilience of the Loess Plateau is not ideal. Six cities had an average higher than 0.5, including Ordos (0.562), Hohhot (0.504), Taiyuan (0.539), Xi'an (0.536), Yinchuan (0.521), and Zhengzhou (0.502), with a proportion of 15.38%. The reason for the high-level urban resilience is that these cities are regional economic centers or resource-based cities, with relatively developed socioeconomic levels, and the government has a high ability to manage the ecological environment and improve the carrying capacity of urban ecosystems. In terms of temporal evolution characteristics, the urban resilience of most regions showed a trend of fluctuation evolution, and some cities presented a declining trend from 2010 to 2019. Twelve cities presented an increasing trend of urban resilience from 2010 to 2019, including Baiyin, Dingxi, Jinzhong, Lanzhou, Luoyang, Sanmenxia, Taiyuan, Wuhai, Xi'an, Xining, Zhengzhou, and Zhongwei, with a proportion of 30.77%.

Table 3. Urban resilience results of the Loess Plateau from 2010 to 2019.

City	2010	2019	City	2010	2019	City	2010	2019
Bayannur	0.379	0.384	Luoyang	0.321	0.393	Wuzhong	0.381	0.409
Baiyin	0.334	0.406	Lvliang	0.375	0.308	Xi'an	0.482	0.572
Baotou	0.505	0.434	Pingliang	0.380	0.418	Xining	0.423	0.471
Baoji	0.344	0.346	Qingyang	0.415	0.424	Xianyang	0.368	0.369
Datong	0.365	0.376	Sanmenxia	0.331	0.377	Xinzhou	0.382	0.355
Dingxi	0.373	0.418	Shizuishan	0.434	0.407	Yan'an	0.422	0.390
Ordos	0.550	0.556	Shuozhou	0.366	0.379	Yangquan	0.389	0.362
Guyuan	0.430	0.445	Taiyuan	0.511	0.548	Yinchuan	0.477	0.510
Hohhot	0.493	0.491	Tianshui	0.381	0.393	Yulin	0.425	0.358
Jincheng	0.397	0.379	Tongchuan	0.399	0.399	Yuncheng	0.315	0.302
Jinzhong	0.359	0.431	Weinan	0.289	0.321	Changzhi	0.346	0.333
Lanzhou	0.441	0.516	Wuhai	0.453	0.506	Zhengzhou	0.413	0.578
Linfen	0.334	0.320	Ulanqab	0.401	0.418	Zhongwei	0.359	0.442

From the perspective of a single city (Figure 3), Xi'an and Zhengzhou showed a significant growth trend from 2010 to 2019; the urban resilience of Xi'an increased from 0.482 in 2010 to 0.572 in 2019, with a growth rate of 18.67%. The urban resilience of

Zhengzhou increased from 0.413 in 2010 to 0.578 in 2019, with a growth rate of 39.95%. Lvliang and Yulin presented a significant decline trend in urban resilience from 2010 to 2019; the measurement results of urban resilience in Lvliang decreased from 0.375 in 2010 to 0.349 in 2019, with a reduction rate of 17.87%. The urban resilience of Yulin decreased from 0.425 in 2010 to 0.398 in 2019, with a reduction rate of 15.76%. Regarding the temporal trends of urban resilience in single city, twelve cities showed a declining trend of urban resilience from 2010 to 2019, indicating these cities have insufficient capital and technology investment in urban disaster management and ecological governance and protection. In addition, twelve cities showed a growth rate of more than 10%, with a proportion of 30.77%, including Baiyin (21.56%), Dingxi (12.06%), Jinzhong (20.06%), Lanzhou (17.01%), Luoyang (22.43%), Sanmenxia (13.90%), Weinan (11.07%), Wuhai (11.70%), Xi'an (18.67%), Xining (11.35%), Zhengzhou (39.95%), and Zhongwei (23.12%).

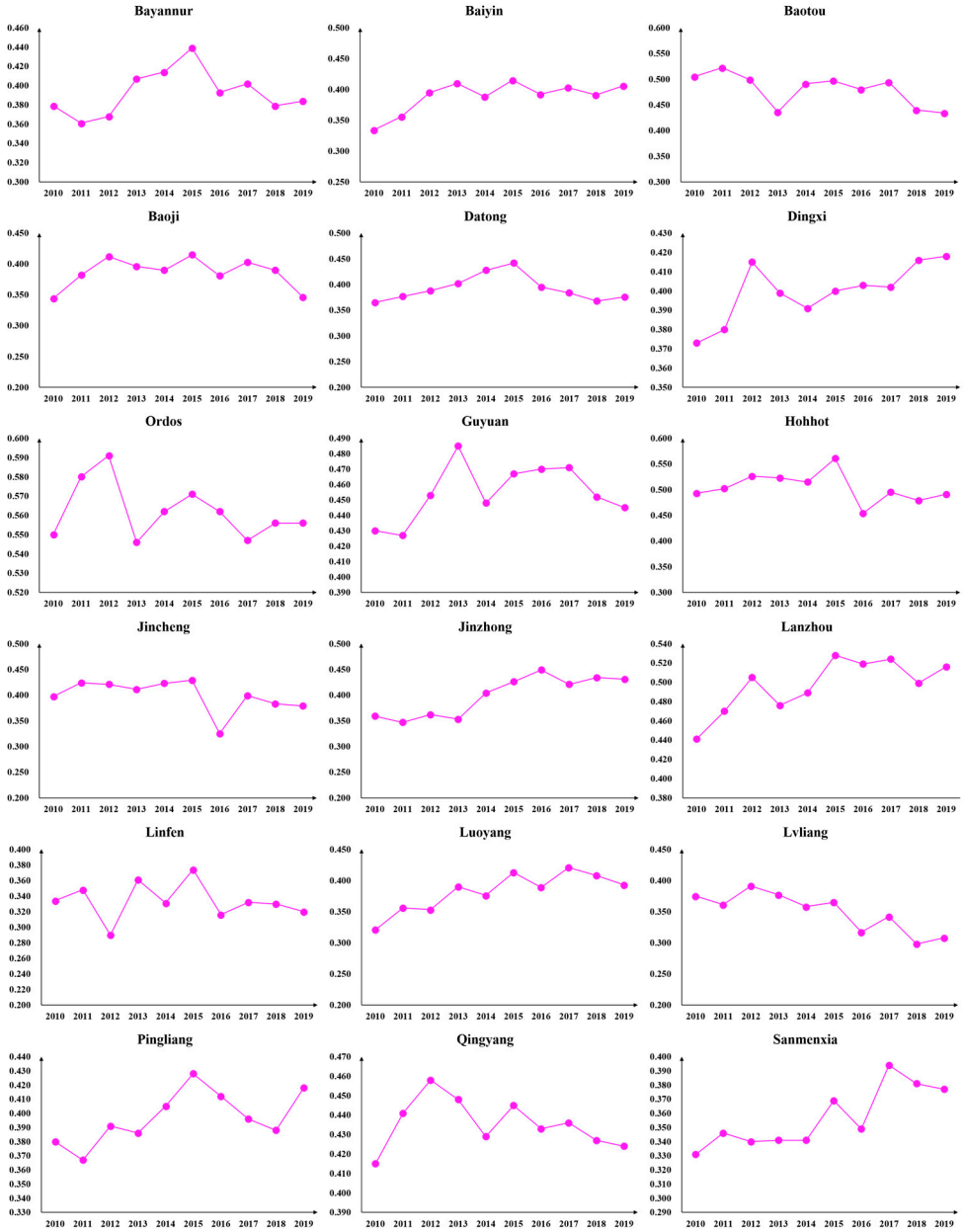


Figure 3. *Cont.*



Figure 3. Evolution characteristics of urban resilience in 39 cities on the Loess Plateau (Note: In the evolution results of each city in Figure 3, the abscissas represent the year and the ordinates refer to the level of urban resilience).

In terms of spatial evolution characteristics, it could be found that urban resilience in the Loess Plateau presented a significant spatial difference from 2010 to 2019, and cities with low-level urban resilience are mainly located in the southeast region of the Loess Plateau (Figure 4). Cluster analysis was conducted based on ArcGIS10.8, and the urban resilience measurement results were divided into high-level, medium-level, and low-level. The number of high-level cities increased from six in 2010 to eight in 2019, medium-level cities decreased from fifteen in 2010 to ten in 2019, and low-level cities increased from

eighteen in 2010 to twenty-one in 2019. The urban resilience of the Loess Plateau shows gradual improvement with the socio-economic growth, which is closely related to the construction of urban green infrastructure, the improvement of the social security system, and the protection of the ecological environment. Most cities with a high-level of urban resilience are located at the edge of the Loess Plateau; these cities have relatively high levels of socioeconomic development, relatively complete urban infrastructure, and a high level of ability to cope with human-natural disasters and environmental pollution control. Most cities with a low level of urban resilience are located in Shanxi Province; these cities rely on extractive industries to promote urban economic development. Resource-based cities have relatively single industrial structures, and the loss of a young labor force is not conducive to sustainable urban socioeconomic development. Additionally, the mountainous terrain limits the construction of transportation infrastructure, which leads to the slow-speed socioeconomic development and green infrastructure construction in Shanxi Province.

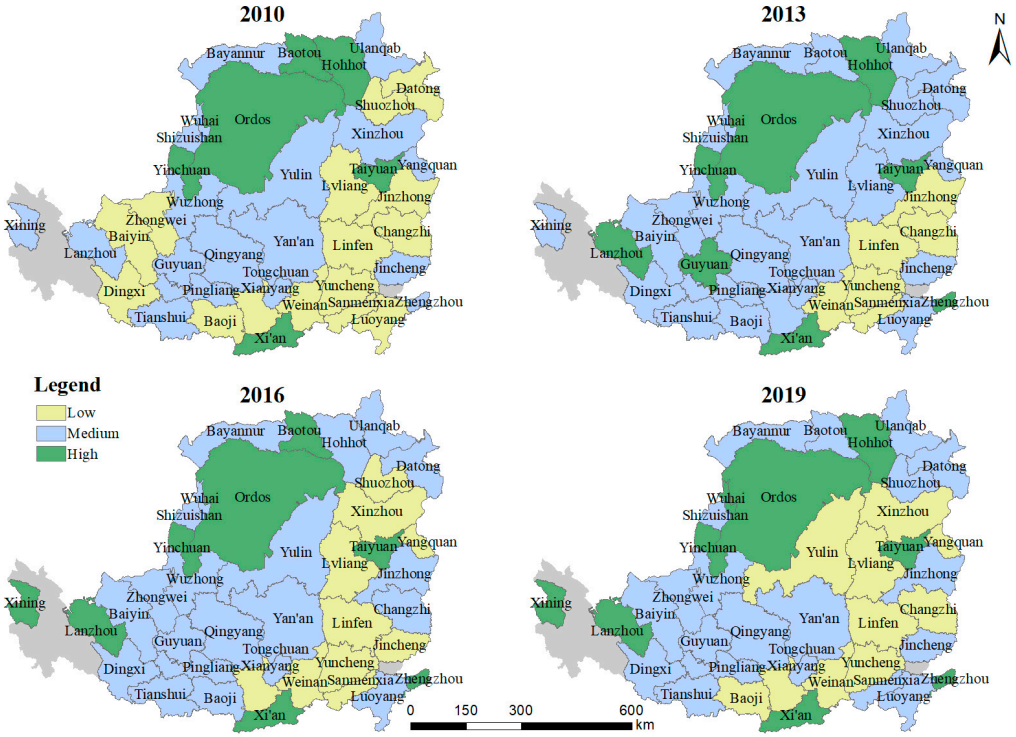


Figure 4. Spatial variation of urban resilience on the Loess Plateau in 2010, 2013, 2016, and 2019.

6.2. Analysis of the Coupling Coordination Degree

Based on the deconstruction of the DPSIR framework and the analysis of the coupling coordination degree of five subsystems, the coupling degree and coordination degree of five subsystems are measured by the CCD model; the measurement results are shown in Table 4. It could be found that most cities showed a low level of CCD and the average value of CCD in most cities was less than 0.3, indicating that there is a significant incongruous relationship between driving-pressure-state-impact-response of urban resilience in these areas. In terms of the average CCD, eight cities presented relatively high-level of CCD more than 0.3, with a proportion of 20.51%, including Baoji (0.304), Hohhot (0.302), Lanzhou (0.414), Taiyuan (0.445), Xi'an (0.576), Xining (0.324), Yinchuan (0.362), and Zhengzhou (0.643). These cities are provincial capitals or resource-based cities with high levels of socioeconomic development and industrial development; sufficient investment in urban ecosystem construction and ecological environment protection contributes to improving urban ability to respond to human-nature disasters, especially the construction project of urban green infrastructure and disaster prevention and mitigation. Zhengzhou and Yangquan had the largest group difference of 0.524 in coupling coordination degree. The coupling coordination degree of urban resilience in Zhengzhou is 0.643, the highest average

score on the Loess Plateau, while the coupling coordination degree of urban resilience in Yangquan is 0.119, the lowest average score on the Loess Plateau.

Table 4. Measurement Results of CCD based on the DPSIR framework.

City	2010	2019	City	2010	2019	City	2010	2019
Bayannur	0.102	0.191	Luoyang	0.230	0.244	Wuzhong	0.170	0.129
Baiyin	0.089	0.135	Lvliang	0.165	0.101	Xi'an	0.518	0.616
Baotou	0.391	0.218	Pingliang	0.124	0.144	Xining	0.252	0.323
Baoji	0.128	0.094	Qingyang	0.127	0.149	Xianyang	0.220	0.208
Datong	0.160	0.120	Sanmenxia	0.156	0.127	Xinzhou	0.139	0.082
Dingxi	0.073	0.128	Shizuishan	0.200	0.130	Yan'an	0.200	0.120
Ordos	0.373	0.191	Shuozhou	0.124	0.101	Yangquan	0.163	0.067
Guyuan	0.136	0.154	Taiyuan	0.431	0.408	Yinchuan	0.313	0.260
Hohhot	0.326	0.273	Tianshui	0.109	0.108	Yulin	0.269	0.132
Jincheng	0.304	0.181	Tongchuan	0.139	0.130	Yuncheng	0.144	0.104
Jinzhong	0.159	0.216	Weinan	0.101	0.156	Changzhi	0.212	0.100
Lanzhou	0.308	0.429	Wuhai	0.211	0.198	Zhengzhou	0.425	0.793
Linfen	0.123	0.109	Ulanqab	0.193	0.143	Zhongwei	0.088	0.178

From the measurement results of the evolution characteristics of CCD and five subsystems from 2010 to 2019 (Figure 5), the pressure subsystem of urban resilience in the Loess Plateau has the highest score from 2010 to 2019, while the driving force subsystem and state subsystem have the lowest score, resulting in a low coupling coordination level of urban resilience. The main reason is the feeble social and economic driving forces of urban resilience, which is closely related to the backward infrastructure construction, the relatively slow urban economic growth, and the incomplete social and public security system. The reason for the relatively high score of the response subsystem is that many cities actively implement environmental protection policies, and the government has increased the capital input in urban environmental protection and governance, facilitating residents' living security and employment. In terms of coupling coordination degree of five subsystems, the key to improving urban resilience CCD in underdeveloped areas lies in the urban economic driving force, social development driving force, and urban ecosystem driving force. Specifically, it includes the government's countermeasures for urban ecological protection and governance, optimization of urban industrial structure, improvement of scientific and technological efficiency, and urban disaster prevention and mitigation projects.

Regarding the spatial variation of CCD on the Loess Plateau from 2010 to 2019, it could be found that the coupling coordination degree showed a significant imbalance in spatial difference, and the overall spatial characteristics are characterized by "central depression" with the temporal evolution (Figure 6). Indicating that there is an unbalanced development problem among the driving, pressure, state, impact, and response subsystem of urban resilience in the central region of the Loess Plateau, the possible reason is that some cities pay more attention to economic development while neglecting ecological environment protection and pollution control. The increase in the number of severe dissonance cities indicates that ecological protection and disaster prevention and control in the Loess Plateau region still needs to be improved, and that some cities still face tremendous pressure to cope with ecological and environmental protection and disaster prevention and mitigation.

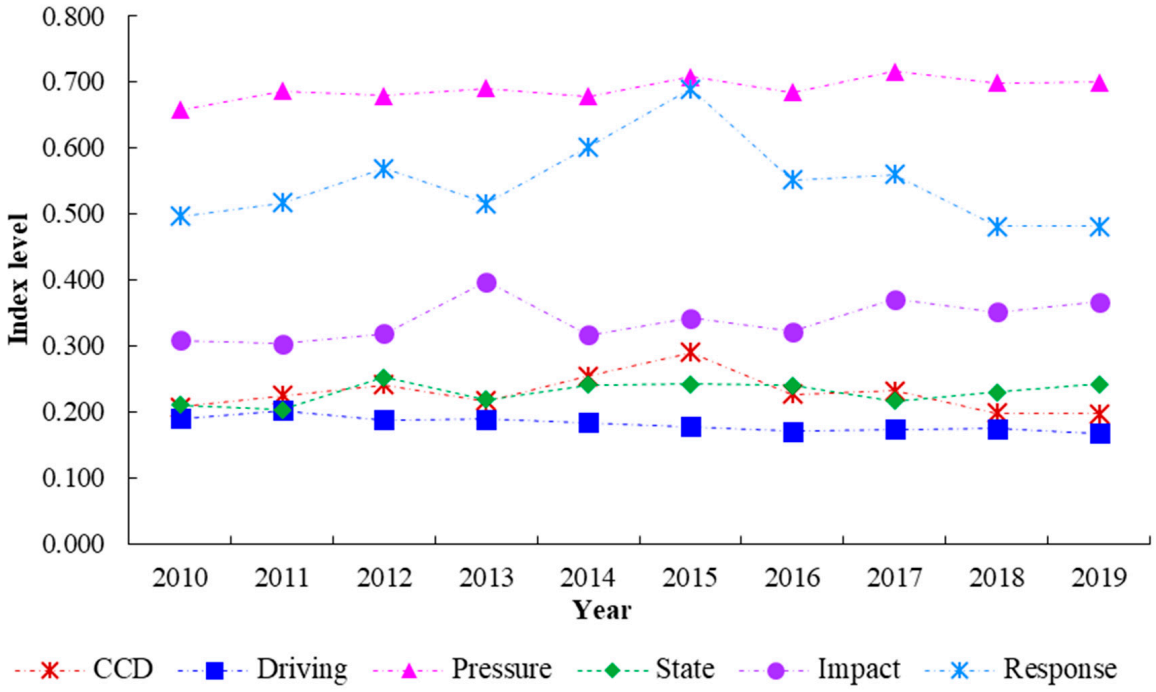


Figure 5. Evolution characteristics of CCD and five subsystems from 2010 to 2019.

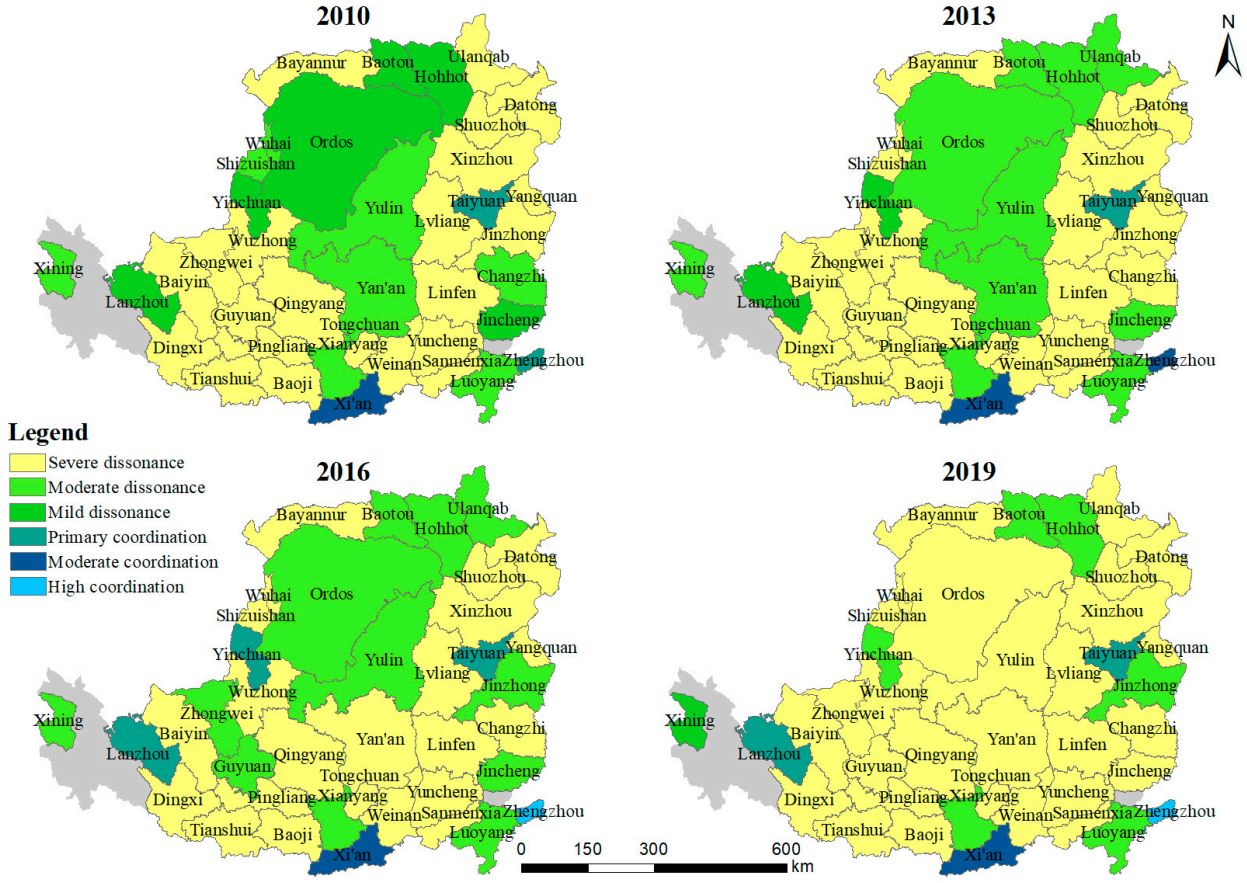


Figure 6. Spatial variation of CCD on the Loess Plateau in 2010, 2013, 2016, and 2019.

6.3. Analysius of the Driving Factors

Based on an analysis of existing studies on urban resilience, four dimensions variables were selected to explore the driving factors of urban resilience in the Loess Plateau from 2010 to 2019; these included urban economy, public service, environmental pressure, and industrial upgrading. The variables "Gross industrial output" and "Per capita public finance revenue" were adopted to reflect the urban economic development impact on urban resilience. The variables "Expenditure on science and technology" and "Public library books per 100 persons" were chosen to represent the urban public service construction impact on urban resilience. The variables "Urban carbon emissions" and "Urban population density" were selected to explain the urban environmental pressure effect on urban resilience. The variable "Proportion of tertiary industry" was adopted to reflect the driving force of urban resilience brought by industrial upgrading. Stata 15.0 was adopted for empirical analysis in this study. The empirical results showed that seven variables passed the significance level test. The definition and descriptive statistical results of variables are shown in Tables 5 and 6.

Table 5. Definition of variables.

Variables	Definition	Symbol
Urban economy	Gross industrial output	*GIO*
	Per capita public finance revenue	*PFR*
Public service	Expenditure on science and technology	*RD*
	Public library books per 100 persons	*LIB*
Environmental pressure	Urban carbon emissions	*CE*
	Urban population density	*PD*
Industrial upgrading	Proportion of tertiary industry	*TI*

Table 6. Descriptive statistical results of driving factors.

Variables	Observations	Average	S. D.	Minimum	Maximum
GIO	390	16,433,731.37	18,619,594.24	152,775	144,656,312
PFR	390	4173.743	4474.093	112.867	30,549.732
RD	390	0.01	0.008	0.001	0.05
LIB	390	100.192	64.975	8.68	1736.541
CE	390	6367.189	16,267.794	18.379	111,036
PD	390	248.373	224.364	17.53	1440.37
TI	390	42.214	11.916	18.81	75.26

The Regression results based on the Tobit model were shown in Table 7. Urban economic development is the foundation of urban resilience, while economic resilience is key to urban sustainable development. It could be found that gross industrial output has a significant negative impact on urban resilience, and passes the 0.05 significance level test, indicating that the economic development of the secondary industry has a limiting effect on urban resilience on the Loess Plateau. The reason for this is that most cities have a high proportion of secondary industries (especially resource-based cities), and that industrialization has brought more industrial pollution while promoting urban economic growth, including air pollution, water pollution, and soil pollution. Additionally, per capita public finance revenue has a significant positive impact on urban resilience, and passed the 0.01 significance level test. The increase in government public finance revenue is a key measure of institutional quality. The increase in local fiscal revenue is conducive to the increase of the government's investment in ecological environmental protection and pollution control; it can improve the government's comprehensive green infrastructure construction, ecological protection, and natural disaster prevention and mitigation.

Table 7. Regression results based on the Tobit model.

Variables	Coefficient	S. D.	*p* Value
GIO	−0.017 **	0.014	0.043
PFR	0.165 ***	0.033	0.002
RD	0.218 ***	0.048	0.009
LIB	0.003	0.052	0.174
CE	−0.124 ***	0.011	0.000
PD	−0.132 **	0.013	0.011
TI	0.209 ***	0.056	0.000

Note: "**", and "***" indicate that the variables pass the significance level test of 0.05, and 0.01, respectively.

The improvement of public service capacity is an important driving force for urban social resilience. Regarding the empirical results, the expenditure on science and technology has a significant positive impact on urban resilience and passed the significance test of 0.01. The increased investment in urban science and technology funds is conducive to attracting scientific and technological talents to carry out innovative and entrepreneurial activities; it can enhance the vitality of urban economic development, and the increase of science and technology funds is conducive to improving the production efficiency of enterprises and reducing pollutants emission caused by industrial production. Public library books per 100 persons have a positive impact on urban resilience, but failed the significant test, indicating that library holdings have a positive effect on urban resilience, but the promoting effect needs to be improved in the process of urbanization. Additionally, industrial upgrading has a significant positive impact on urban resilience, passing the significance test of 0.01. Industrial upgrading is an important method to coordinate the resilience of urban economic development, and tertiary industry development has brought vitality to the sustainable growth of the urban economy. Especially for resource-based cities, industrial upgrading is conducive to optimizing the urban ecosystem health and reducing pollutants emissions, and the technological change brought by industrial upgrading becomes the driving force for the sustainable growth of the urban economy, which is conducive to promoting the positive interaction between urban socioeconomic resilience and ecosystem resilience.

Urban carbon emissions have a significant negative impact on urban resilience, passing the significance test of 0.01. Most resource-based cities in the Loess Plateau are faced with the problem of sustainable development, including high industrial proportion, unreasonable energy consumption structure, and backward production technology. These problems will lead to the increase of energy consumption and carbon emissions, while the deterioration of urban ecological environment limits the improvement of urban ecosystem resilience. In addition, urban population density has a significant negative impact on urban resilience, passing the significance test of 0.05; this indicates that the increase of urban population density on the Loess Plateau is not conducive to the improvement of urban resilience. Due to the Loess Plateau being an economically underdeveloped and ecologically sensitive area, several sustainable development problems, such as soil erosion, vegetation destruction, and frequent natural disasters, are prominent in most cities. As such, the local governments need to focus on urban planning and design based on local conditions. The unreasonable population density can cause resource consumption growth and unreasonable land expansion, which limits the optimization of urban socio-economic resilience and ecosystem resilience.

To verify the reliability of the empirical analysis results, the alternative variable method was used to test the robustness of the regression results of the Tobit model; the results are shown in Table 8. By replacing the variable "Proportion of tertiary industry" with the variable "Industrial upgrading index", it could be found from the robustness test results that the positive and negative direction of regression coefficients of all variables did not change, indicating that the test conclusions of influencing factors were reliable.

Table 8. Robustness test results of alternative variable method.

Variables	Coefficient	S. D.	*p* Value
GIO	−0.021 ***	0.012	0.008
PFR	0.131 ***	0.024	0.006
RD	0.175 **	0.009	0.032
LIB	0.018	0.036	0.256
CE	−0.047 ***	0.003	0.000
PD	−0.051 *	0.032	0.061
IU	0.322 **	0.025	0.043

Note: "*", "**", and "***" indicate that the variables pass the significance level test of 0.1, 0.05, and 0.01, respectively.

7. Discussion

Based on the empirical analysis, it could be found that the comprehensive level of urban resilience in the Loess Plateau region is relatively low, and that there were significant spatial disequilibrium characteristics. From the sub-system measurement results, the driving sub-system and the state sub-system had a relatively obvious inhibitory effect on the comprehensive level of urban resilience, which indicated that ecologically fragile areas should focus on the coordinated development of economic growth and urban expansion in the process of urbanization, and gradually improve the comprehensive strength of urban economic development to cope with the environmental instability caused by human activities and natural factors [53,54]. This is of great practical significance for realizing the sustainable development goal of cities in ecologically fragile areas.

Regarding the key factors of urban resilience in the Loess Plateau, governance, technological innovation, and industrial upgrading have significant positive effects on urban resilience, which is consistent with the conclusions of existing studies [55,56]. The improvement in governance capacity is mainly reflected in the increase in financial funds available for urban infrastructure development, which is essential to cope with natural disasters and environmental risks [57,58]. Technological innovation and industrial upgrading are important driving forces to improve the ability of urban sustainable development, and they are of great significance for enterprises to achieve sustainable clean production and sustainable economic growth [59,60]. In terms of obstacle factors, industrialization development, environmental pollution, and population density have significant negative effects on urban toughness in the Loess Plateau, which is consistent with the existing research conclusions. For ecologically fragile areas, despite increasing land use, irrational urban expansion caused by urbanization will bring unstable factors to the local ecological environment, such as frequent geological disasters and soil erosion [47]. In the case of relatively limited resource and environmental carrying capacity, irrational industrialization and urbanization will have a higher negative impact on ecologically fragile areas than other regions [61]. Compared with previous studies, this study attempted to construct an index system for measuring urban resilience in ecologically fragile areas and explored the driving factors and obstacles of urban resilience, aiming to provide decision-making information reference for urban sustainable development and urbanization construction in ecologically fragile areas.

The possible limitation of this study is that it has not considered the influence of geological environment factors and other natural factors on urban resilience, which is mainly reflected in the construction of index systems and the identification of key factors. The main reasons include the following two aspects. On the one hand, it is relatively difficult to obtain the indicators of geological environmental factors, and it involves a wide range of remote sensing technology and field research. On the other hand, other natural factors have uncertain values, such as precipitation and average temperature, and the model in this study cannot solve such problems. Therefore, combining remote sensing technology with this study to find new methods and build a new index system is the focus of future research. Additionally, for the calculation and simulation of uncertain values,

future research will consider using the hesitancy fuzzy TOPSIS model for calculation, aiming to remedy the shortcomings in existing research.

In terms of future investigations, based on considering the shortcomings of this study, focusing on the development of a single city in a fragile ecological environment area, constructing a new index system to measure the urban resilience of a single region, determining the model method of relative accuracy by comparing the change of error rate under different models, and introducing a dynamic analysis method to explore the spatial-temporal evolution characteristics of urban resilience will be key.

8. Conclusions

The assessment of urban resilience in ecologically fragile areas is of great significance to the realization of the harmonious relationship between ecological environmental protection and social economy. For areas with frequent natural disasters and fragile ecological environment, a comprehensive assessment of the urban resilience system and exploration of key factors are key elements to cope with unstable natural and human factors. Based on deconstructing the DPSIR framework and the concept of urban resilience, an evaluation index system for urban resilience in ecologically fragile areas has been established, and the entropy weight TOPSIS model and the CCD model have been adopted to explore the urban resilience and coupling coordination relationship of the Loess Plateau from 2010 to 2019. In addition, the Tobit model has been selected to investigate the driving factors of urban resilience in ecologically fragile areas.

In terms of measurement results of urban resilience, the empirical results showed that most cities present low and medium levels of urban resilience, indicating that the urban resilience of the Loess Plateau from 2010 to 2019 is not ideal. There is a significant spatial difference in the Loess Plateau from 2010 to 2019 of the urban resilience, and cities with low-level urban resilience are located in the southeastern region of the Loess Plateau. Additionally, the CCD model has shown a significant imbalance in spatial difference, and the spatial characteristics are presented by "central depression" with the temporal evolution. The pressure subsystem of urban resilience in the Loess Plateau has the highest score from 2010 to 2019, while the driving force subsystem and state subsystem have the lowest score, resulting in a low-level CCD of urban resilience. Most cities have presented a low level of CCD and the average value of CCD in most cities is less than 0.3, indicating that there is a significant incongruous relationship between driving-pressure-state-impact-response of urban resilience in these areas. Regarding the key factors of urban resilience of the Loess Plateau, institutional quality, scientific and technological expenditure, and industrial upgrading have a significant positive impact on urban resilience, while gross industrial output, urban carbon emissions, and urban population density have significant limiting effects on urban resilience. These findings show that unreasonable urban expansion and industrialization are not conducive to the improvement of urban resilience in ecologically fragile areas, while the improvement of government governance capacity, green sustainable production and economic growth brought by technological innovation and industrial upgrading are conducive to the improvement of urban resilience. This study provides a case study in urban resilience and driving factors identification under the DPSIR framework, aiming to provide information and decision-making reference for urban resilience exploration and urban planning in ecologically sensitive area. Besides, the theoretical framework of this study can also be applied to the assessment of urban resilience in other regions or the assessment of urban complex system resilience. For other ecologically fragile areas, such as water-fragile areas, these findings can provide a reference for decision-makers of urban expansion and ecological environment protection.

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