Spatiotemporal Evolution of Coordinated Development of Regional Social-Ecological System Resilience: A Case Study of Shaanxi Province (Postprint)

Authors: Huang Jiao

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Abstract

Driven by multiple factors such as population growth, resource development, and urbanization, resilience provides a new research perspective for the sustainable development of regional social-ecological systems. Taking Shaanxi Province as the study area, this study constructs an indicator system based on three subsystems—social, economic, and ecological—by comprehensively considering system vulnerability and coping capacity. The social-ecological system resilience of 107 county-level administrative units in Shaanxi Province is measured through the Set Pair Analysis method. Based on the resilience measurement results, the Coupling Coordination Degree model is employed to analyze the coordinated development degree of binary (social-economic, social-ecological, economic-ecological) and ternary (social-economic-ecological) subsystems, revealing their spatiotemporal evolution characteristics from 2000 to 2020 at the regional level. Subsequently, the bivariate spatial autocorrelation model is introduced to further explore the quantitative and spatial correlation characteristics of the coordinated development degree changes between binary and ternary subsystems. The results show that: (1) During the study period, the social and economic resilience of Shaanxi Province increased significantly, while ecological resilience exhibited a slight declining trend, and the social-ecological system resilience rose from 0.303 to 0.779. (2) The coordinated development degree of all subsystems demonstrated an upward trend; the coordinated development disparity of the social-economic subsystem, characterized by high values in the south and low values in the north, weakened; the social-ecological and economic-ecological subsystems formed a coordinated development pattern with low values in the central region and high values in both the north and south; the coordinated development degree of the social-economic-ecological subsystem overall maintained a spatial distribution characteristic of high values in the south and low values in the north. (3) The coordinated development changes of binary subsystems exhibited a strong positive correlation with those of ternary subsystems in both quantity and space, primarily manifested by the concentrated distribution of high-high and low-low type evaluation units in the northern and central parts of the province.

Full Text

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HUANG Jiao[12], CHEN Hai[12], WANG Jiayu[12], BAI Xiaojuan[12]

[1]College of Urban and Environmental Science, Northwest University, Xi' an 710127, Shaanxi, China
[2]Shaanxi Key Laboratory of Earth Surface System and Environmental Carrying Capacity, Xi' an 710127, Shaanxi, China

Abstract

Driven by multiple factors such as population growth, resource development, and urbanization, resilience provides a new research perspective for the sustainable development of regional social-ecological systems. To clarify the trend of the coordinated development of the social-ecological system in Shaanxi Province, northwest China from the perspective of resilience and provide theoretical support for the sustainable development of the regional social-ecological system based on the three subsystems of society, economy, and ecology, comprehensively considering the vulnerability and coping capacity of the system, a resilience evaluation index system was constructed. The social-ecological system resilience of 107 county-level administrative units in Shaanxi Province was measured using set-pair analysis. According to the results of the resilience measurement, the coupling coordination degree model was used to analyze the coordinated development degree of binary (social-economic, social-ecological, and economic-ecological) and ternary (social-economic-ecological) subsystems. The spatiotemporal evolution characteristics of the coordinated development degree of the subsystems from 2000 to 2020 were revealed at the regional level. The bivariate spatial autocorrelation model was introduced to further explore the quantitative and spatial correlation characteristics of the coordinated development degree changes in the binary and ternary subsystems. The results showed the following: (1) During the study period, the social and economic resilience of Shaanxi Province increased significantly, ecological resilience showed a weak downward trend, and social-ecological system resilience increased from 0.303 to 0.779. (2) The coordinated development degree of the subsystems showed an upward trend; the coordinated development degree of the social-economic subsystem increased from 0.422 to 0.823, and the difference between the high in the south and low in the north weakened. The coordinated development degree of social-ecological and economical-ecological subsystems increased from 0.471 and 0.394 to 0.714 and 0.727, respectively. These two types of binary subsystems formed a coordinated development pattern of low in the middle and high in the north and south, respectively. The coordinated development degree of social-economic-ecological subsystem increased from 0.424 to 0.755 and generally maintained the spatial distribution characteristics of high in the south and low in the north. (3) The changes in the coordinated development of the social-economic, social-ecological, and economic-ecological subsystems were positively correlated with the change in the coordinated development of the social-economic-ecological subsystem in quantity and space. There were obvious spatial agglomeration characteristics in the coordinated development degree changes of the three types of binary and ternary subsystems. The positive correlation of high-high and low-low type evaluation units was mainly distributed in the northern and middle parts of Shaanxi Province, whereas the correlation was not significant in the southern part; the evaluation units with agglomeration characteristics were scattered.

Key words: social-ecological system resilience; coordinated development; bivariate correlation; Shaanxi Province

Introduction

Social-ecological systems are coupled systems formed through the interaction and mutual influence between social and ecological systems, characterized by holism, internal hierarchy, complexity, and uncertainty. Resilience, as a key attribute of social-ecological systems, is defined as the ability of a system to withstand disturbances and maintain its structure, functions, characteristics, and feedback mechanisms. Extensive research has been conducted on the measurement and assessment of resilience at national and provincial scales, focusing primarily on single disturbance factors such as tourism development, mining activities, climate change, and natural disasters. Currently, few studies have analyzed regional social-ecological system resilience driven by multiple factors at the county level. Against the background of resilience theory, quantitative evaluation of resilience is crucial for understanding the mechanisms of social-ecological system resilience change. However, no unified paradigm has been established for assessing social-ecological system resilience. Measurement methods mainly include model evaluation and alternative indicator system assessment. Some studies have quantified system resilience based solely on vulnerability models by exploring the relationship between vulnerability and resilience, but these approaches lack attention to coping capacity. Presently, numerous studies have adopted social, economic, and ecological subsystems as measurement units, constructing indicator systems based on both vulnerability and coping capacity, and then implementing quantitative evaluation of social-ecological system resilience through comprehensive index methods and set pair analysis. As a systematic theoretical method for handling uncertainty problems, set pair analysis has been widely applied in vulnerability assessment, safety evaluation, and multi-attribute decision-making, offering certain advantages for quantifying the resilience of complex and uncertain social-ecological systems. Based on resilience evaluation, existing research has primarily focused on analyzing influencing factors of social-ecological system resilience using regression analysis and obstacle degree models, while studies on the spatiotemporal evolution of coordinated development of social-ecological system resilience remain scarce. Existing research on coordinated resilience development indicates that coupled system resilience emphasizes coordination and integration among internal subsystems, and healthy system development requires coordinated evolution among subsystems. Investigating the mutual coordination relationships among subsystems can better reflect the development status of social-ecological systems.

In view of this, this paper takes Shaanxi Province, which is affected by multiple factors such as urbanization development, resource exploitation, and climate, as the research object. The province is divided into social, economic, and ecological subsystems to construct an evaluation index system. Using set pair analysis and taking counties as evaluation units, the social-ecological system resilience of Shaanxi Province is measured. Based on the resilience measurement results, binary and ternary coupling coordination degree models are employed to analyze the coordinated development level of the social-economic-ecological system. The spatiotemporal evolution characteristics of the coordinated development degree of binary (social-economic, social-ecological) and ternary (social-economic-ecological) subsystems are revealed at the regional level. Through grey correlation analysis and bivariate spatial analysis, the quantitative correlation degree and spatial correlation relationship of coordinated development changes between binary and ternary subsystems are further explored. This research can provide theoretical basis and decision-making support for sustainable management and development strategy formulation of regional social-ecological systems.

Study Area and Methods

Study Area

Shaanxi Province is located in central China, in the middle reaches of the Yellow River, with a land area of 2.056×10^{5} km^2. The terrain is high in the north and south and low in the middle, forming three natural regions in geographical space: the Northern Shaanxi Loess Plateau, the Guanzhong Plain, and the Southern Shaanxi Qinba Mountains [Figure 1: see original paper]. Temperature and annual average precipitation gradually decrease from south to north. Northern Shaanxi features fragmented terrain with numerous gullies, belonging to a semi-arid region with fragile ecological environment. The Guanzhong Plain lies between the Northern Shaanxi Loess Plateau and the Qinling Mountains, with flat terrain and mild climate. Southern Shaanxi has a landform structure of "two mountains flanking one river basin" formed by the Qinling Mountains, Daba Mountains, and Hanjiang River Basin, belonging to a humid region with high annual precipitation and frequent geological disasters such as landslides and flash floods. Shaanxi Province governs 10 prefecture-level cities with 107 county-level administrative units. By 2020, the province had a permanent population of 3.955$\times10^{7}$ people and a gross regional product of 2.618$\times10^{12}$ yuan. Northern Shaanxi is rich in energy resources with a prominent energy industry and rapid economic development. Guanzhong has dense population, convenient transportation, diversified industrial development, and superior economic conditions. Southern Shaanxi has a weak economic foundation, and its industrial development is constrained by mountainous terrain and ecological protection, with low industrialization level and social-economic benefits. The significantly different natural geographical environments and socio-economic development levels among the three major natural regions of Northern Shaanxi, Guanzhong, and Southern Shaanxi, combined with diverse social-ecological systems, provide an excellent study area for analyzing the spatiotemporal evolution of coordinated development of regional social-ecological system resilience.

Data Sources and Processing

The data for this study were mainly obtained from: (1) Publicly available materials including the China County Statistical Yearbook, Shaanxi Statistical Yearbook, Shaanxi Regional Statistical Yearbook, statistical yearbooks of various cities in Shaanxi Province, and statistical bulletins on national economic and social development of relevant districts and counties from 2000 to 2020. Some missing data were estimated using growth rates or interpolated from adjacent years. (2) Land use data. The data were derived from the land use vector dataset of the Western China Environmental and Ecological Science Data Center, resampled to 1 km$\times$1 km raster grids. Land types were classified into six categories: cultivated land, forest land, grassland, water area, construction land, and unused land. Extraction analysis and raster area calculation were performed according to the county-level administrative divisions of Shaanxi Province. To eliminate dimensional and magnitude differences among indicators, the data were standardized using the extremum method based on the nature of indicator impacts. In the comprehensive index system measurement, objective weighting methods determine indicator weights according to the information content provided by each indicator. To avoid bias from subjective factors, the entropy weight method was adopted to determine indicator weights, with specific calculation steps detailed in reference [31].

Index System Construction

The selection of resilience measurement indicators varies due to regional characteristics, system types, element selection, and research perspectives. Currently, no unified paradigm has been established for constructing resilience evaluation index systems. Theoretically, resilience measurement is manifested through the influence of social, economic, ecological, and policy factors [27,29], where policy and cultural factors are mostly reflected through other elements [7]. Under external disturbance, system instability and resistance, as the main factors for resilience measurement, can be characterized through system vulnerability and coping capacity [27,29]. Vulnerability reflects the degree of damage to system structure and function after disturbance, representing the interaction between system pressure and its own sensitivity [32]. Coping capacity represents the system' s ability to resist interference through self-improvement and structural adjustment [33]. Therefore, referring to relevant studies [7,27,32] and considering research scale, regional basic conditions, and system sustainable development, this paper selects three subsystems—social, economic, and ecological—as measurement units. Vulnerability factors of each subsystem triggered by regional natural geographical environment and human activities are used to measure system instability, while coping capacity factors that facilitate subsystem development and enhance system resilience to a certain extent are selected to measure system resistance. Through correlation analysis and following principles of systematicity, representativeness, and data availability, a total of 28 indicator factors were selected (Table 1) to measure the social-ecological system resilience of Shaanxi Province.

Models

Set Pair Analysis Method Based on set pair analysis for multi-attribute evaluation, let Q = {f_1, f_2, , f } be the set of evaluation schemes, D = {d_1, d_2, , d } be the set of evaluation indicators, W = {w_1, w_2, , w } be the set of evaluation indicator weights, and e be the evaluation object. Through comparison within the same space, the optimal indicators in each evaluation scheme constitute the optimal evaluation set U = {u_1, u_2, , u }, while the worst indicators constitute the worst evaluation set V = {v_1, v_2, , v }, where u and v represent the optimal and worst values of indicators, respectively. The connection degree between evaluation scheme f and the optimal scheme set U on V is established as:

$$\mu_{f_m} = a_m + b_m i + c_m j = \sum w_p a_{pk} + i \sum w_p b_{pk} + j \sum w_p c_{pk} \quad (p = 1, 2, \cdots, n)$$

where: is the connection degree of the set; f is the evaluation scheme; a is the identity degree; b is the difference degree; c is the opposition degree; i and j are coefficients of difference degree and opposition degree, respectively; a and c are the identity degree and opposition degree between evaluation indicator d and u , respectively; w is the weight of the p-th indicator. When d has a positive effect on the evaluation result, a = d /u , c = u /d ; when d has a negative effect, a = u /d , c = d /u . The relative closeness degree r between scheme f and the optimal scheme set U can be defined as:

$$r_m = \frac{a_m}{a_m + c_m}$$

where: r reflects the connection degree between the evaluated scheme f and the optimal scheme set U, and a larger r value indicates that the evaluated object is closer to the optimal scheme.

Coupling Coordination Degree Model The coupling coordination degree model includes coupling degree and coordination degree, which can be used to describe the interaction degree and coordinated development level between two or more systems [34]. By introducing the coupling coordination degree model and drawing on existing research results [35], the coordinated development degree is divided into 10 levels (Table 2) to analyze the interaction relationships and coordination states among the resilience of social, economic, and ecological subsystems, thereby further reflecting the coordinated development change degree of the social-ecological system.

Wang Shujia et al. [35] modified the coupling degree model, which increases the discrimination of coupling degree (C) values and demonstrates better measurement validity. Therefore, this paper employs the modified coupling degree model to construct binary and ternary subsystem coupling coordination degree models as follows:

For binary subsystems:

$$C = 1 - \frac{(U_1 - U_2)^2}{(U_1 + U_2)^2}, \quad T = \alpha U_1 + \beta U_2, \quad D = \sqrt{C \times T}$$

For ternary subsystems:

$$C' = 1 - \frac{(U_1 - U_2)^2 + (U_2 - U_3)^2 + (U_1 - U_3)^2}{(U_1 + U_2 + U_3)^2}, \quad T' = \alpha U_1 + \beta U_2 + \gamma U_3, \quad D' = \sqrt{C' \times T'}$$

where U_1, U_2, and U_3 represent the resilience of social, economic, and ecological subsystems, respectively; C and C'are coupling degrees; D and D'are coordinated development degrees; T and T' are comprehensive coordination indices; α, β, and γ are undetermined weights. This paper considers the three subsystems equally important, taking $\alpha = \beta = \gamma = 1/3$.

Bivariate Spatial Autocorrelation Bivariate spatial autocorrelation analysis can reveal the correlation between spatial variables and other variables in neighboring spaces [36], using global Moran' s I for characterization, calculated as:

$$I = \frac{\sum \sum W_{ij} z_i z_j}{S^2}$$

Bivariate local spatial autocorrelation is further employed to reflect the agglomeration and differentiation characteristics of two variables in local regions [37], using local Moran' s I for characterization, calculated as:

$$I_i = z_i \sum W_{ij} z_j$$

where: I and I are the bivariate global and local Moran' s I, respectively; W is the spatial weight matrix between spatial units i and j; x and y are the values of the independent and dependent variables in spatial units i and j, respectively; x̄ and ȳ are the mean values of the independent and dependent variables, respectively; S^2 is the variance of variable values across all spatial units; z and z are variance-standardized variable values of spatial units. Based on I values, four clustering patterns can be identified: high-high agglomeration, low-low agglomeration, high-low agglomeration, and low-high agglomeration. LISA cluster maps are drawn accordingly.

Results

Resilience Measurement Results and Trend Analysis

This study uses GeoDa 1.18 software to establish a spatial weight matrix based on adjacency relationships and explores the spatial correlation relationship between binary and ternary subsystem coordinated development changes through bivariate spatial autocorrelation.

Subsystem Resilience Change Trend Analysis The social resilience of Shaanxi Province increased from 0.302 in 2000 to 0.779 in 2020. Social resilience in Southern Shaanxi, Guanzhong, and Northern Shaanxi increased from 0.323, 0.322, and 0.254 to 0.786, 0.826, and 0.704, respectively. With rapid urbanization development, fiscal support across regions has been strengthened, infrastructure facilities have been gradually improved, and social undertakings such as education, medical care, and social security have developed rapidly. People' s living environment and quality of life have continuously improved, and regional differences in social development have gradually narrowed, showing an overall growth trend in social resilience. The economic resilience of Shaanxi Province increased significantly from 0.264 in 2000 to 0.823 in 2020. Economic resilience in Southern Shaanxi, Guanzhong, and Northern Shaanxi increased from 0.236, 0.334, and 0.210 to 0.744, 0.892, and 0.833, respectively. Active industrial structure adjustment has led to a significant upward trend in economic resilience. Guanzhong has maintained the highest economic resilience due to its rapid economic growth rate and strong competitiveness. Northern Shaanxi has experienced the largest increase in economic resilience driven by the rise of energy extraction and processing industries based on petroleum, coal, and natural gas, with continuously increasing economic aggregate. From 2000 to 2020, the ecological resilience of Shaanxi Province slightly decreased to 0.638. Ecological resilience in Southern Shaanxi, Guanzhong, and Northern Shaanxi changed from 0.715, 0.551, and 0.634 to 0.739, 0.558, and 0.620, respectively. Southern Shaanxi has high forest coverage, and its ecological resilience has always been higher than that of Guanzhong and Northern Shaanxi. Guanzhong has concentrated urban distribution, and its ecological resilience has always been the lowest. Northern Shaanxi has shown a slight declining trend in ecological resilience with the gradual reduction of afforestation area.

[Figure 2: see original paper]

Social-Ecological System Resilience Change Trend Analysis From 2000 to 2020, the social-ecological system resilience of Shaanxi Province increased from 0.303 to 0.779. The social-ecological system resilience of Southern Shaanxi, Guanzhong, and Northern Shaanxi increased from 0.425, 0.402, and 0.366 to 0.790, 0.792, and 0.719, respectively. In Southern Shaanxi, significant improvements in social and economic resilience have driven the growth of social-ecological system resilience. Guanzhong' s flat terrain and convenient transportation provide a good foundation for social and economic development, and its social-ecological system resilience level is the highest. Northern Shaanxi has shown significant growth in social-ecological system resilience due to substantial economic resilience increase and greening construction maintaining relatively high ecological resilience.

Social-Ecological System Coordinated Development Spatiotemporal Change Analysis

Based on the resilience measurement results, the coordinated development degree of binary and ternary subsystems for each evaluation unit from 2000 to 2020 was calculated according to formulas (6)-(8). Following the evaluation grades described previously (Table 2), the coordination stages were classified, and the proportion of counties in each coordination stage for each region was obtained (Table 3), along with differentiation maps (Fig. 3).

[Figure 3: see original paper]

Social-Economic Subsystem Coordinated Development Spatiotemporal Change Characteristics From 2000 to 2020, the coordinated development degree of the social-economic subsystem in Shaanxi Province increased from 0.422 to 0.823. The proportions of disharmony and decline and transitional harmony stages decreased from 54.21% and 45.79% to 0.00% and 4.67%, respectively. The overall pattern maintained a distribution of high in the south and low in the north, but spatial differences weakened (Fig. 3). The coordinated development degree of the two subsystems in Southern Shaanxi, Guanzhong, and Northern Shaanxi increased from 0.424, 0.457, and 0.384 to 0.795, 0.847, and 0.824, respectively, consistently following the order of Guanzhong > Southern Shaanxi > Northern Shaanxi. Southern Shaanxi has relatively weak social-economic foundations, but under the influence of resettlement projects for immigration, implementation of circular economy planning, poverty alleviation policies, and the radiating effect of the Guanzhong-Tianshui Economic Zone, urbanization construction has accelerated, economic development momentum has strengthened, and both economic and social resilience have improved jointly. The proportion of counties in the coordinated development stage increased by 84.00%, with well-coordinated counties concentrated around municipal districts. In Guanzhong, the proportion of counties in the coordinated development stage increased by 96.00%, with obvious agglomeration characteristics of well-coordinated and high-quality coordinated counties. This is because Guanzhong has obvious location advantages, strong population absorption capacity, more complete transportation and public facilities, and Xi' an City, as a "growth pole," radiates and drives economic development in surrounding areas, strengthening the mutual promotion between the two subsystems. In Northern Shaanxi, the huge economic benefits created by the development of energy and chemical industries have enhanced the driving effect on social construction, with 96.00% of counties in the coordinated development stage. However, due to uneven resource distribution, low population density, and large differences in county-level economic development within the region, the spatial distribution characteristic of low in the south and high in the north remains unchanged.

Social-Ecological Subsystem Coordinated Development Spatiotemporal Change Characteristics From 2000 to 2020, the coordinated development degree of the social-ecological subsystem in Shaanxi Province increased from 0.471 to 0.714. The proportion of counties in the coordinated development stage grew by 57.95%, forming a distribution pattern of low in the middle and high in the north and south (Fig. 3). The coordinated development degree of the two subsystems in Southern Shaanxi, Guanzhong, and Northern Shaanxi changed from 0.542, 0.446, and 0.426 to 0.769, 0.687, and 0.687, respectively, with the coordination degree shifting to Southern Shaanxi > Northern Shaanxi > Guanzhong. Southern Shaanxi serves as an ecological security barrier in central China and the main water source area for the middle route of the South-to-North Water Transfer Project, with high ecological resilience. With the substantial improvement in social resilience, the proportion of counties in the coordinated development stage increased to 85.71%, mainly characterized by concentrated distribution of well-coordinated counties. In Guanzhong, the proportion of counties in the coordinated development stage increased from 40.74% to 88.89%, but 11.11% of counties remained in the disharmony and decline stage. The distribution difference of low in the center and high around became prominent, mainly because urban expansion centered on Xi' an City led to reduced green space area and weakened ecological functions, resulting in relatively weak coordination between the two subsystems. In Northern Shaanxi, with the implementation of projects such as returning farmland to forest and the improvement of social development level, the proportion of counties in the coordinated development stage increased to 96.00%, with primary and intermediate coordinated counties distributed contiguously, and the spatial distribution difference of low in the south and high in the north weakened.

Economic-Ecological Subsystem Coordinated Development Spatiotemporal Change Characteristics From 2000 to 2020, the coordinated development degree of the economic-ecological subsystem in Shaanxi Province increased from 0.394 to 0.727. The proportions of disharmony and decline and transitional harmony stages decreased by 51.40% and 34.58%, respectively, with 90.65% of counties in the coordinated development stage (Table 3). The spatial distribution difference of low in the middle and high in the north and south became apparent (Fig. 3). The coordinated development degree of the two subsystems in Southern Shaanxi, Guanzhong, and Northern Shaanxi changed from 0.415, 0.404, and 0.363 to 0.754, 0.708, and 0.720, respectively, with larger increases in Southern Shaanxi and Northern Shaanxi, and the coordination degree shifting to Southern Shaanxi > Northern Shaanxi > Guanzhong. Southern Shaanxi has implemented a circular economy development strategy, alleviating the trade-off relationship between ecological environment and economic development. In 72.00% of counties, intermediate and good coordination dominate, showing a distribution pattern of high in the south and low in the north. In the east-central part of Guanzhong, the improvement of ecological resilience is constrained by rapid economic development, and the coordinating effect of the economic-ecological subsystem is slow, generating positive correlation characteristics with surrounding areas where the coordinated development degree change of the ternary subsystem is small, forming a low-low type spatial agglomeration pattern. In Northern Shaanxi, high-high type agglomeration is mainly distributed in the eastern marginal areas with poor basic conditions but significant improvements in economic and ecological resilience. While the synergistic effect of the economic-ecological subsystem is enhanced in this region, it promotes a substantial improvement in the coordinated development degree of the ternary subsystem in surrounding areas, forming a positively correlated high-high type agglomeration.

Social-Economic-Ecological Subsystem Coordinated Development Spatiotemporal Change Characteristics From 2000 to 2020, the coordinated development degree of the social-economic-ecological subsystem in Shaanxi Province increased from 0.424 to 0.755, showing a significant growth trend. The proportion of counties in the coordinated development stage increased from 14.95% to 92.52%, generally maintaining the spatial distribution characteristics of high in the south and low in the north (Fig. 3). In 2000, the coordinated development degree of the three subsystems in Southern Shaanxi, Guanzhong, and Northern Shaanxi changed from 0.466, 0.439, and 0.367 to 0.777, 0.743, and 0.744, respectively, consistent with the changes in social-ecological and economic-ecological subsystems. Guanzhong's ecological resilience is relatively low, and the gap with social and economic resilience has widened, resulting in a gradually lower coordination degree than Southern Shaanxi and Northern Shaanxi. In Southern Shaanxi, the proportion of counties in the coordinated development stage increased by 82.15%, changing the pattern of continuous distribution of counties with low-level coordinated development within the region, with prominent agglomeration effects of well-coordinated counties. In Guanzhong, the proportions of disharmony and decline and transitional harmony stages both decreased by 7.41%, and the proportion of counties in the coordinated development stage increased to 81.48%, forming a spatial distribution characteristic of low in the center and high around. This is mainly because areas dominated by Xi' an municipal districts have strong human activity impacts on ecosystems, and relatively low ecological resilience leads to lower coordinated development degree among subsystems. In Northern Shaanxi, social and economic resilience have increased substantially along with large investments in greening construction, showing a significant growth trend in coordinated development degree. In 2020, all counties in the region were in the coordinated development stage, and the distribution difference of low in the south and high in the north weakened.

Correlation Analysis

Quantitative Correlation Analysis Based on grey correlation analysis, the correlation degrees between the three types of binary subsystems and the social-economic-ecological subsystem coordinated development degree change values were calculated as 0.87, 0.83, and 0.91, respectively. During the study period, there was high correlation between the coordinated development degree changes of the three types of binary subsystems and the ternary subsystem. The degree of influence follows the order: social-ecological > economic-ecological > social-economic. This indicates that regional efforts in industrial development, environmental protection, and quality of life improvement have strengthened the interaction degree among social, economic, and ecological subsystems. The three subsystems have developed in a mutually beneficial, complementary, and orderly manner. Under the joint driving effect of coordinated development changes in binary subsystems, the ternary subsystem has shifted toward the coordinated development stage.

Global and Local Spatial Correlation Analysis Using the 2020 coordinated development degree change value of Shaanxi Province's ternary subsystem as the first variable and the coordinated development degree change values of the three types of binary subsystems as the second variables, GeoDa 1.18 spatial analysis software was employed to calculate the bivariate Moran' s I between the three types of binary subsystems and the ternary subsystem coordinated development changes. The Monte Carlo simulation method was used for significance testing. The bivariate Moran' s I values between the three types of binary subsystems and the social-economic-ecological subsystem coordinated development degree change were 0.412, 0.387, and 0.436, respectively, all passing the significance test at the $P<0.01$ level. This indicates that during the study period, there was a significant spatial positive correlation between the coordinated development degree changes of binary subsystems and those of the ternary subsystem, with high-high and low-low agglomeration phenomena in their spatial distribution .

Moran's I only reflects the overall spatial correlation of coordinated development degree changes between binary and ternary subsystems, failing to display local spatial information. Therefore, based on this, bivariate local spatial autocorrelation analysis is further employed to reflect the local association between the two at the regional level. Through z-test (P<0.05), bivariate local spatial autocorrelation LISA cluster maps are drawn, showing four types in space: positively correlated high-high and low-low clusters, and negatively correlated high-low and low-high types [Figure 4: see original paper].

[Figure 4: see original paper]

There were 46 evaluation units in Shaanxi Province where the coordinated development degree changes between the social-economic subsystem and the ternary subsystem showed agglomeration characteristics, accounting for 4.35%, 52.17%, and 43.48% in Southern Shaanxi, Guanzhong, and Northern Shaanxi, respectively. In the central-southern counties of Southern Shaanxi, the social-economic subsystem coordinated development degree has a low base level but large improvement potential. Under the spatial spillover effect of surrounding areas' social-economic subsystem coordinated development degree improvement, the ternary subsystem coordinated development degree in counties with agglomeration characteristics shows concentrated high-high type distribution, while neighboring counties exhibit heterogeneous low-high type spatial agglomeration characteristics with significant ternary subsystem coordinated development degree improvement. In Xi' an City and its surrounding areas in Guanzhong, driven by factors such as increased population density and industrial enterprise development, the social-economic subsystem coordinated development degree has a high base and maintains an upward trend, but the change value is relatively small, with limited driving effect on the improvement of surrounding areas' ternary subsystem coordinated development degree, resulting in low-low type distribution. In the northern energy-rich areas of Northern Shaanxi, strong economic competitiveness and rapid infrastructure construction create spatial spillover effects from adjacent counties' social-economic subsystem coordinated development degree, with high-high type distribution. In the east-central part of Northern Shaanxi, Yuyang District, which has relatively small ternary subsystem coordinated development degree improvement values, is surrounded by counties with significant social-economic subsystem coordinated development degree improvement, showing low-high type negative correlation characteristics.

There were 34 evaluation units in Shaanxi Province where the coordinated development degree changes between the social-ecological subsystem and the ternary subsystem showed agglomeration characteristics, accounting for 2.94%, 52.94%, and 44.12% in Southern Shaanxi, Guanzhong, and Northern Shaanxi, respectively. In the southeastern part of Southern Shaanxi, the ecological resilience of Ankang municipal district shows a declining trend due to urban expansion, and the ternary subsystem coordinated development degree improves slowly. Surrounded by counties with significant social-ecological subsystem coordinated development degree improvement, it exhibits low-high type heterogeneous spatial agglomeration characteristics. The ecological subsystem of the Guanzhong

Plain has relatively low resilience under strong human activity disturbance, and the social-ecological subsystem coordinated development degree has a small increase. In counties where spatial correlation characteristics emerge, the ternary subsystem coordinated development change shows certain convergence with the social-ecological subsystem coordinated development change in surrounding adjacent counties, with concentrated low-low type distribution. In southern Northern Shaanxi, the ecological environment is relatively good, and the improvement of social capital investment and social consumption capacity has promoted the coordinated development of social and ecological subsystems, with the social-ecological subsystem and ternary subsystem coordinated development degrees improving synergistically, and high-high type counties distributed contiguously.

There were 24 evaluation units in Shaanxi Province where the coordinated development degree changes between the economic-ecological subsystem and the ternary subsystem showed agglomeration characteristics, accounting for 4.17%, 70.83%, and 25.00% in Southern Shaanxi, Guanzhong, and Northern Shaanxi, respectively. In the southern foothill area of the Qinling Mountains in Southern Shaanxi, driven by the significantly upward-trending economic-ecological subsystem coordinated development degree, the increase in coordinated development degree between economic and ecological subsystems is substantial, promoting the improvement of the ternary subsystem coordinated development degree in neighboring counties, with high-high type distribution. In the east-central part of Guanzhong, the improvement of ecological resilience is constrained by rapid economic development, and the coordinating effect of the economic-ecological subsystem is slow, generating positive correlation characteristics with surrounding areas where the ternary subsystem coordinated development degree change is small, forming a low-low type spatial agglomeration pattern. In Northern Shaanxi, high-high type agglomeration is mainly distributed in the eastern marginal areas with poor basic conditions but significant improvements in economic and ecological resilience. While the synergistic effect of the economic-ecological subsystem is enhanced in this region, it promotes a substantial improvement in the ternary subsystem coordinated development degree in surrounding areas, forming a positively correlated high-high type agglomeration.

Discussion

As a key region for China' s "Western Development" and "Belt and Road" initiatives, Shaanxi Province has strong economic development momentum, and the quality of social living environment has been continuously optimized. The social and economic resilience of various regions have improved synergistically with significant and gradually narrowing gaps. Meanwhile, Shaanxi Province is one of the first provinces in China to implement the "Returning Farmland to Forest" ecological construction project, with large capital investment in ecological construction. Under the influence of ecological policies, ecological resilience is relatively strong. However, with the development of energy industries, accelerated urbanization construction, and reduced afforestation area, ecological resilience shows a weak downward trend, with strong spatial heterogeneity within the province. During the study period, Guanzhong' s ecological resilience was consistently lower than that of Southern Shaanxi and Northern Shaanxi, which aligns with Ding Zhenmin et al.' s [38] analysis of continuously expanding construction land area in the Guanzhong Plain, mainly converted from cultivated land, based on land use transfer in Shaanxi Province.

Internal disharmony and external imbalance in ecosystems may be caused by the lag of any subsystem within the system. Synchronous coordinated development of various binary subsystems is a prerequisite for improving the coordinated development level of ternary subsystems [39]. The significant enhancement of social and economic resilience in Shaanxi Province has effectively promoted the orderly development among binary subsystems in each region. The coordinated development degree of the ternary subsystem has shifted toward the coordinated development stage driven by the common improvement of binary subsystems' coordinated development degree. Among them, the quantitative and spatial correlation between the economic-ecological subsystem coordinated development degree change and the ternary subsystem coordinated development degree change is higher than that of social-economic and social-ecological subsystems, indicating that while maintaining the positive development trend of economic resilience, promoting the collaborative improvement of ecological resilience in various regions is crucial for the overall coordinated development of the social-ecological system. As Tang Xiaoling et al. [40] stated, Shaanxi Province should focus on economic construction in its development process and promote the coordinated development and common progress of regional economy and ecological environment. Given the importance of ecological resilience in the coordinated development of Shaanxi' s social-ecological system, this study proposes several suggestions for improving ecological resilience and coordinated development in each region based on different local ecological conditions: (1) Southern Shaanxi has superior natural ecological conditions but high sensitivity. This region should prioritize ecological protection and develop ecological industries according to local conditions. (2) Guanzhong has concentrated urban construction and strong human activity intensity. It should strengthen ecological restoration to improve regional land use efficiency, expand urban green space, and reduce negative impacts of social and economic development on the ecological environment. (3) Northern Shaanxi has prominent energy and chemical industries with high-speed economic development, but suffers from severe soil erosion and fragile ecological environment. This region should continue to consolidate the achievements of "returning farmland to forest," and adhere to the coordination and unity of ecological environment and economic development.

Although this study conducted a multi-dimensional analysis of the coordinated development degree of Shaanxi's social-ecological system based on resilience measurement results, several limitations remain. The evolution of complex social-ecological systems requires long time series resilience measurement. This study only analyzed the change pattern of the social-ecological system from 2000 to 2020, which is a relatively short time span. The construction of resilience measurement index systems has not yet formed a unified paradigm. This paper combined socio-economic statistical data with land use data and selected indicators from multiple levels, but due to data availability limitations, there remain problems of coarse and incomplete indicator selection. Future research should expand the time range, establish more complete index systems, and further explore the stage characteristics and influence mechanisms of social-ecological system resilience coordinated development, providing more objective theoretical support for regional construction and adaptive management.

Conclusion

(1) From 2000 to 2020, the social-ecological system resilience of Shaanxi Province improved significantly, with social and economic subsystem resilience showing substantial enhancement, while ecological subsystem resilience exhibited a weak downward trend. (2) During the study period, the coordinated development degree of social-economic, social-ecological, and economic-ecological subsystems in Shaanxi Province showed an upward trend. The spatial scope of coordination stage improvement for the social-economic subsystem continuously expanded, and the spatial distribution difference of high in the south and low in the north weakened. The social-ecological and economic-ecological subsystems gradually formed a coordinated development pattern of low in the middle and high in the north and south. The coordinated development degree of the social-economic-ecological subsystem generally maintained the spatial distribution characteristics of high in the south and low in the north. (3) The coordinated development changes of binary subsystems in Shaanxi Province had substantial correlations with those of the ternary subsystem in both quantity and space, mainly characterized by the concentrated distribution of high-low type evaluation units in the northern and central parts of the province.

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Note: Figure translations are in progress. See original paper for figures.