Postprint: Analysis of Urban Ecological Resilience, Social Networks and Their Influencing Factors in the Yellow River Basin

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Abstract

Analyzing the social networks and influencing factors of urban ecological resilience facilitates the promotion of regional green coordinated development. This study selects relevant data from 63 prefecture-level cities in the Yellow River Basin for the period 2012-2021 and constructs a Pressure-State-Response model. Employing CRITIC-TOPSIS, gravity model, and multiscale geographically weighted regression model, it analyzes urban ecological resilience, linkage relationships, and influencing factors in the Yellow River Basin. The results indicate: (1) The overall ecological resilience in the Yellow River Basin fluctuates around 0.5, demonstrating a pattern of "upstream > downstream > midstream" , with average annual growth rates of 0.41%, 0.30%, and 0.40% for the respective basin sections. (2) The Yellow River Basin can be broadly categorized into seven major urban networks (N1-N7), with the degree of basin agglomeration and urban connectivity progressively increasing from upstream to midstream to downstream. (3) Considering direct effects, moderating effects, and substitution effects, industrial structure upgrading exerts a greater enhancing effect on the urban ecological resilience of urban networks N1-N4, with impact coefficients of 0.4213, 0.4210, 0.5085, and 0.8883, respectively, whereas industrial structure rationalization is more beneficial for enhancing the urban ecological resilience of urban networks N5-N7, with impact coefficients of 0.8483, 0.5669, and 0.8128.

Full Text

Urban Ecological Resilience, Social Networks and Their Influencing Factors in the Yellow River Basin

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Abstract: Analyzing the social network of urban ecological resilience and its influencing factors contributes to promoting regional green synergistic development. Using data from 2012 to 2021 for 63 prefecture-level cities in the Yellow River Basin, this study constructs a pressure-state-response model and employs the CRITIC-TOPSIS method, gravity model, and multi-scale geographically weighted regression (MGWR) to analyze urban ecological resilience levels, linkage relationships, and influencing factors. The results indicate: (1) The overall ecological resilience of the Yellow River Basin fluctuates around 0.5, exhibiting a spatial pattern of "upstream > downstream > midstream," with average annual growth rates of 0.41%, 0.30%, and 0.40% for the upper, middle, and lower reaches, respectively. (2) The basin can be broadly divided into seven major city networks (N1-N7), where the degree of urban connectivity and basin agglomeration increase sequentially from upstream to downstream. (3) Considering direct effects, moderating effects, and substitution effects, industrial structure upgrading demonstrates a greater enhancing effect on ecological resilience for city networks N1-N4, with impact coefficients of 0.4213, 0.4210, 0.5085, and 0.8883, respectively. Conversely, industrial structure rationalization more effectively enhances ecological resilience for city networks N5-N7, with impact coefficients of 0.8483, 0.5669, and 0.8128.

Keywords: ecological resilience; spatial structure; CRITIC-TOPSIS; multi-scale geographically weighted regression; Yellow River Basin

Introduction

The 14th Five-Year Plan and Long-Range Objectives Through the Year 2035 propose building resilient cities. As a critical component of multi-dimensional urban resilience, ecological resilience describes a city' s capacity to survive, adapt, and develop in the face of disturbances [?]. With rapid urbanization, urban ecological problems have become increasingly severe, while regional collaborative governance remains ineffective [?]. Frequent natural disasters have drawn widespread attention to urban ecological security and vulnerability, making the enhancement of urban disaster resistance and rapid recovery capabilities a primary research focus in ecological resilience.

The ecological protection and high-quality development of the Yellow River Basin represent a major national strategy. As a vital ecological barrier and key region for population and economic activity in China, the basin holds significant importance for socio-economic development and ecological security [?]. Strengthening ecological protection and governance to build a resilient urban ecological environment is crucial for high-quality development and improved living conditions across the basin. However, extensive economic growth, low resource utilization efficiency, and systemic ecological problems with difficult recovery [?] necessitate comprehensive consideration of inter-city development relationships when addressing basin-wide ecological issues. Therefore, analyzing urban ecological resilience levels, social network structures, and their influencing factors in the Yellow River Basin holds important practical significance for enhancing resilience and promoting high-quality development.

Research on ecological resilience primarily focuses on two aspects. First, conceptual studies examine resilience characteristics and development mechanisms. Resilience represents a system' s ability to recover after shocks or disturbances [?]. Holling [?] introduced resilience to ecology, defining it as the magnitude of disturbance that natural systems can withstand or absorb under natural and anthropogenic influences. Esteve et al. [?] summarized ecological resilience features, including shock absorption capacity, self-organization, and adaptive capacity, emphasizing that systems capable of learning from disturbances and adjusting feedback outputs can leverage feedback loops effectively. Second, empirical studies measure ecological resilience and analyze influencing factors. Most measurements employ comprehensive indicator methods based on "resistance-recovery" or "pressure-state-response" frameworks [?], using entropy weighting, coefficient of variation, or CRITIC methods for weighting and calculation. For instance, Tao et al. [?] analyzed ecological resilience agglomeration characteristics and influencing factors from a resistance-recovery perspective at the urban agglomeration level. Zhang and Ren [?] constructed a spatial Durbin model to examine direct effects of environmental regulation on ecological resilience and the mediating role of technological innovation, analyzing spatial spillover effects. Zhou et al. [?] measured ecological resilience for 73 cities in the Yellow River Basin using entropy-weighted summation and analyzed its co-evolution with ecological efficiency. Zhou and Chao [?] examined the coupling relationship between digital infrastructure, economic development resilience, and environmental protection.

Overall, existing research emphasizes individual city resilience evaluation and improvement pathways. However, ecological resilience reflects not only a city' s capacity to resist and recover from disasters but also the adaptability of urban clusters within social networks when facing natural and anthropogenic shocks. Few studies examine social network structures constrained by urban ecological resilience levels or analyze influencing factors based on network structures. Therefore, this study employs CRITIC-TOPSIS to measure urban ecological resilience, uses a modified gravity model to calculate inter-city ecological resilience linkages, constructs social networks for analysis, and applies MGWR to examine influencing factors.

1. Data and Methods

1.1 Study Area

According to the Yellow River Protection Law of the People' s Republic of China (effective April 1, 2023) and the Yellow River Water Resources Commission, the Yellow River Basin includes the catchment areas of the Yellow River' s main stream, tributaries, and lakes across Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong provinces. Considering data availability and completeness, this study covers 63 prefecture-level cities, excluding Aba Prefecture in Sichuan and Haidong, Hainan Tibetan Autonomous Prefecture, Haixi Mongolian and Tibetan Autonomous Prefecture, and Haibei Tibetan Autonomous Prefecture in Qinghai (Figure 1).

[Figure 1: see original paper]

1.2 Indicator System and Data Sources

Considering that urban ecological resilience undergoes three stages—pre-disturbance, during disturbance, and post-disturbance—corresponding to pressure, state, and response processes [**?**], the indicator system is constructed as follows. Pressure reflects human impacts and natural disasters on the environment. State indicates the existing level of ecological construction. Response represents managerial efforts and resources invested to improve the urban ecological environment. Drawing on Wang and Niu [**?**] and Niu et al. [**?**], we construct an evaluation index system for ecological resilience in the Yellow River Basin (Table 1).

[Figure 2: see original paper]

Data primarily come from the *China City Statistical Yearbook* (2012-2021) and provincial/municipal statistical yearbooks. Environmental quality information derives from provincial environmental statistics bulletins. Natural disaster data are from the Global Natural Disaster Database (National Cryosphere Desert Data Center, http://disaster.casnw.net/#/root/view). Energy conservation and environmental protection expenditure data come from provincial/municipal statistical yearbooks and municipal finance bureau budget reports. Missing data are interpolated using spline interpolation.

1.3 Methods

1.3.1 CRITIC-TOPSIS Model CRITIC measures indicator objective weights by considering contrast intensity and conflict among indicators, eliminating the influence of highly correlated indicators to reduce information overlap [**?**]. TOPSIS is a multi-objective decision method that identifies optimal and worst solutions among finite alternatives [**?**]. Combining CRITIC for weighting and TOPSIS for evaluation provides comprehensive assessment.

(1) Dimensionless processing: For m evaluation samples with n indicators, standardize indicators as:

$$x'_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad \text{(positive indicators)}$$

$$x'_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \quad \text{(negative indicators)}$$

where x_{ij} is the jth indicator for city i, and x'_{ij} is the standardized value.

(2) Indicator weights: CRITIC calculates weights using standard deviation for variability and correlation coefficients for conflict:

$$S_j = \sqrt{\frac{\sum_{i=1}^{m}(x'_{ij} - \bar{x}_j)^2}{m-1}}$$

$$R_j = \sum_{k=1}^{n}(1 - r_{jk})$$

$$C_j = S_j \times R_j$$

$$W_j = \frac{C_j}{\sum_{j=1}^{n} C_j}$$

where $\bar{x}_j$ is the mean of indicator j, r_{jk} is the Pearson correlation between indicators j and k, S_j, R_j, and C_j represent variability, conflict, and information quantity, respectively, and W_j is the weight.

(3) Define ideal solutions: Positive and negative ideal solutions are:

$$A^+ = (\max(x'_{1j}), \max(x'_{2j}), \cdots, \max(x'_{nj}))$$

$$A^- = (\min(x'_{1j}), \min(x'_{2j}), \cdots, \min(x'_{nj}))$$

(4) Calculate ecological resilience: Compute weighted Euclidean distances to ideal solutions and normalize:

$$D_i^+ = \sqrt{\sum_{j=1}^{n} W_j (x'_{ij} - A_j^+)^2}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} W_j (x'_{ij} - A_j^-)^2}$$

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-}$$

where S_i is the ecological resilience level for city i.

1.3.2 Social Network Analysis Social networks comprise actors (nodes) and their connections (ties). We treat cities as nodes and use linkage intensity as edge weights.

(1) Urban ecological resilience linkage: The gravity model measures spatial connections between entities [?]. Following Qiu et al. [?], we calculate inter-city linkages (G_{il}) as:

$$G_{il} = \frac{kS_iS_l}{d_{il}^{\alpha_i\beta_l}}$$

where k is the gravitational constant (typically 1.0), S_i and S_l are ecological resilience levels, α_i represents city i' s external absorption capacity (inverse of natural log of import value), β_l represents city l' s external output capacity (inverse of natural log of export value), and d_{il} is the geographic distance between cities.

(2) Network construction: Cities are network nodes. Linkage intensity forms weighted directed edges. Using the mean linkage as a threshold, values above the threshold are retained while others are set to 0, creating an inter-city weighted network matrix. Linkages are categorized by quartiles. Following Wang et al. [?], we dynamically analyze spatial structures across basin segments.

1.3.3 Multi-Scale Geographically Weighted Regression (MGWR) Industrial activity significantly impacts regional ecological pressure [?]. Industrial structure upgrading and rationalization critically affect ecological resilience stability. To analyze spatial effects, we examine industrial upgrading (X_1), rationalization (X_2), and their interaction (X_3). Upgrading reflects changes in output, labor, and income shares across sectors [?], measured using the vector angle method based on three-industry value-added proportions [?]. Rationalization reflects resource-environment 良性循环 during optimization [?], calculated using weighted deviations of industrial structure [?].

Technological innovation significantly impacts industrial development and ecological protection [?]. We include it as a control variable using government S&T expenditure share and green technology patent grants, representing policy support and innovation output capacity. Data come from statistical yearbooks and the China Research Data Services (CNRDS) platform.

Traditional GWR assumes uniform spatial scales [?], while MGWR allows variable bandwidths for different relationships [?]. We employ MGWR to analyze variable effects:

$$UER_i = \beta_0(v_i) + \sum_{k=1}^{n} \beta_k(v_i)x_{ik} + \varepsilon_i$$

where UER_i is urban ecological resilience for city i, x_{ik} are explanatory variables, $\beta_k(v_i)$ are location-specific coefficients, and ε_i is the error term.

2. Results

2.1 Ecological Resilience Evaluation in the Yellow River Basin

Using MatlabR2022b, we calculated ecological resilience for 63 cities and visualized the results (Figure 3). In the upper reaches, notable improvements concentrated in the southern region, with average annual growth exceeding 0.70% in Linxia and Pingliang. Ulanqab and Bayannur in Inner Mongolia experienced slight declines (0.48% and 0.32% annually). The upper reaches showed significant volatility due to frequent natural disasters (fires, droughts, earthquakes) and substantial annual variations in environmental protection expenditure.

[Figure 3: see original paper]

The midstream mean resilience decreased from 0.45 to 0.41, with major declines in Taiyuan, Datong, Linfen (Shanxi), Yan' an (Shaanxi), and Jiyuan, Sanmenxia (Henan) (0.42%-0.86% annually). Changzhi and Xinzhou showed notable increases (1.81% and 2.37% annually). Compared to the upper reaches, midstream cities are predominantly resource- and industry-oriented, making resilience stability more challenging.

The lower reaches showed smaller average changes (Figure 3). High-value areas in 2021 concentrated in Hebi (Henan) and Tai'an, Dezhou, Qingdao (Shandong), though these cities experienced significant declines (0.67% and 0.90% annually for Hebi and Tai' an). Most other lower-reach cities showed upward trends, with over 70% of 25 prefecture-level cities achieving average growth above 0.40%.

Temporal analysis reveals an "upstream > downstream > midstream" pattern (Figure 3). The upper reaches, with lower industrial density and better new energy development, exhibit higher resilience despite ecological fragility. Average annual growth rates were 0.41%, 0.30%, and 0.40% for upper, middle, and lower reaches, respectively, with overall resilience below 0.5, indicating low resilience levels.

2.2 Urban Ecological Resilience Network Structure

Using the gravity model, we calculated and standardized inter-city linkages, visualizing network structures across basin segments (Figure 4). The upper reaches formed four city networks (N1-N4). N1 comprises Xining and central-western Gansu cities. Baiyin, a key non-ferrous metals base, has heavy industry-dominated structure with underdeveloped modern services. N2 centers on Yinchuan, Wuzhong, Shizuishan, and Alxa, focusing on energy industries and new materials. N3 comprises Guyuan, Tianshui, and others with low-level internal connections. N4 includes Hohhot, Ordos, Ulanqab, and Baotou, accounting for over 60% of Inner Mongolia' s economy with high consistency in innovation resources, infrastructure connectivity, and ecological governance.

[Figure 4: see original paper]

The midstream formed two networks (N5–N6). N5 includes Xi’ an, Xianyang, and Tongchuan. Xi’ an focuses on high-tech manufacturing, energy, and materials, while Xianyang has weaker infrastructure. Tongchuan’ s coal dependence threatens human settlements. N6 comprises Taiyuan, Jinzhong, Xinzhou, Zhengzhou, and Luoyang. Taiyuan and Jinzhong cooperate on energy services, technology innovation, and infrastructure. The “Zheng-Luo-Ji-Jin” chain-like spatial pattern links Henan’ s core cities with Shanxi’ s southern cities.

The lower reaches form one network (N7) with two sub-networks. Northern Henan cities (Jiyuan, Jiaozuo) share ecological resources, while Shandong’s western and central network centers on Jinan, Puyang, and Kaifeng. The Jiaodong Economic Circle links Qingdao, Zibo, Weifang with strong complementarity in ecological and economic resources.

Network connectivity and basin agglomeration increase from upstream to downstream. Upper-reach cities are geographically dispersed with lower development and 组团式 spatial structures. Midstream networks center on “Xi’ an-Xianyang” and Taiyuan with distinct industrial layouts. Downstream cities have more complete industrial chains, higher inter-city connectivity, and better conditions for ecological collaboration.

2.3 Influencing Factors

We estimated MGWR models (Table 2). Model tests show MGWR’ s residual standard error, maximum likelihood, AIC, and BIC values are lower than GWR’ s, with R^2 and adjusted R^2 above 0.95, indicating superior performance.

Regression results (Table 3) show industrial upgrading (X_1) has positive direct effects on resilience (Model 1), with coefficients of 0.4213, 0.4210, 0.5085, and 0.8883 for N1–N4. The direct effect exceeds that of rationalization (X_2), which is insignificant overall. Upgrading’ s direct improvement effect is greater in midstream and downstream due to higher economic development, industrial transformation foundations, and resource agglomeration.

Interaction effects (X_3) are insignificant, but when considering X_2, X_1’ s effect strengthens significantly, showing substitution effects [?]. For N1–N3, upgrading’ s direct improvement is more significant because these networks are dominated by mid-low-end industries with high environmental dependence and lack high-tech industries. Transformation can substantially improve development conditions. For N4, despite good new energy development, the industrial system relies on new materials, chemicals, and agricultural processing, requiring transformation to enhance resource utilization. For N5–N7, most cities are energy-oriented where transformation is difficult; optimizing resource allocation within existing structures better improves resilience.

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3. Discussion

Using the pressure-state-response framework, we evaluated ecological resilience and analyzed spatial linkages. Few studies examine ecological spatial structure, but comparisons with carbon emission and economic networks [?] show similar multi-center structures centered on Lanzhou, Xi' an, Taiyuan, Zhengzhou, Jinan, and Qingdao, aligning with the 14th Five-Year Plan urban agglomeration strategies and providing theoretical support for green development.

Results indicate industrial transformation and efficient resource allocation enhance resilience, with resource allocation showing substitution effects for industrial upgrading. Upper-reach cities dominated by low-capacity industries benefit more from upgrading, while midstream and downstream regions with better industrial structures benefit more from optimizing resource allocation alongside upgrading.

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4. Conclusions and Recommendations

4.1 Conclusions

(1) The Yellow River Basin' s ecological resilience fluctuates around 0.5, showing an "upstream > downstream > midstream"pattern with average annual growth rates of 0.41%, 0.30%, and 0.40%, respectively.

(2) Seven stable city networks (N1-N7) exist. Upper-reach networks are dispersed with weak connectivity, while midstream and downstream connectivity strengthens sequentially.

(3) Industrial upgrading positively affects all networks, while rationalization shows weaker direct effects but substitution effects with upgrading. For midstream and downstream networks, emphasizing rationalization and resource allocation efficiency better supports resilience.

4.2 Recommendations

(1) **Diversify industrial chains and strengthen modern services.** Upper-reach cities lack industrial diversity and resource recycling. Developing information services and modern logistics will improve resource utilization and reduce environmental pressure.

(2) **Enhance inter-city infrastructure sharing.** Midstream cities show high economic disparities. Strengthening infrastructure co-construction and sharing, particularly in Xi' an-Xianyang, Taiyuan-Jinzhong, and Zhengzhou-Luoyang economic circles, will reduce resource gaps and enhance resilience.

(3) **Strengthen innovation-driven development and optimize industrial layout.** Lower-reach cities have diverse but poorly connected indus-

tries. Increasing innovation investment will accelerate traditional industry transformation, promote sectoral integration, and improve resource efficiency and resilience.

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