COUPLING LINKAGES BETWEEN ECONOMIC EFFICIENCY PATHWAYS AND ECOLOGICAL RESILIENCE: A TOPSIS METHOD STUDY OF THE TUOJIANG RIVER BASIN OF CHINA

JIANG, A. C.[1] – ZHOU, W. M.[2*] – YANG, R.[1] – MARTEK, I.[3]

[1]*School of Management, Chengdu University of Information Technology, Chengdu, Sichuan 610665, China*

[2]*School of Finance and Business, Chengdu Vocational &Technical College of Industry, Chengdu, Sichuan 610665, China*

[3]*School of Architecture and Built Environment, Deakin University, Geelong, VIC 3220, Australia*

**Corresponding author*
e-mail: zhouwenmei@cdivtc.edu.cn

(Received 4th Aug 2025; accepted 15th Dec 2025)

Abstract. This paper examines the coordinated development of economic efficiency (EE) and ecological resilience (ER) in the Tuojiang River Basin (TRB), China. Using panel data from nine urban agglomerations in the TRB from 2011 to 2021, the spatial-temporal patterns and driving factors of ER, as well as the coupling degree between EE and ER, were analyzed. The analysis employs the TOPSIS method, a coupling degree model, and Panel Quantile Regression (PQR). The results indicate the following: (1) The EE of the major cities within the river basin varies significantly, it is crucial to leverage leading city effect and encourage the cross-regional flow of assets. (2) The economic development, ecological protection, and environmental governance of six major cities in the TRB are in a state of severe imbalance, with the situation unlikely to improve in the short term. Urbanization and the growth of the tertiary industry are key drivers for enhancing urban ER. It is necessary for government to allocate resources aimed at addressing shortcomings while also prioritizing urbanization development within the TRB. (3) The current extensive economic development model and high energy consumption in the TRB inhibit improvements in urban ER. To enhance ER, findings indicate transition the economic development model to one promoting industries that shift from carbon-based energy sources to clean and renewable energy sources.
Keywords: *economic efficiency, ecological resilience, coupling effect, TOPSIS, panel quantile regression*

Introduction

River basins suffer from anthropogenic pressures worldwide brought on by urbanization, industrialization, and population growth (Ceola et al., 2019; Foti et al., 2022; Yang et al., 2023). China's permanent urban population reached an urbanization rate of 66.16% in 2023. The Chinese government aims to establish a balance between economic growth and ecological improvement, so that growth may be accommodated synergistically. At the macro level, a series of policies have been implemented to this end. However, China's river basins remain under great ecological pressures. As rates of urbanization continue to increase, new measures are introduced for sustainable development (Wang and Zhou, 2024). The aim is to improve the resilience of ecosystems while at the same time mitigating the contradiction between urban economic growth and ecological protection.

The Tuojiang River Basin (TRB), is an industrial and economic hub within Sichuan. Sichuan Province is a pivotal strategic region in Western China. Economic inefficiencies there combined with insufficient ecological protections are particularly pronounced. For

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_513529

example, ecologically, due to its unique topography, Sichuan faces greater challenges in dispersing air pollutants compared to other regions. From 2018 to 2020, Sichuan Province recorded an average of just 289 days per year (79% of the year) of safe air quality. The water environment also suffers from pollution caused by urban life, livestock breeding, and agricultural activities, with nitrogen pollution (TN) being especially severe (Ying et al., 2022). Regional ecological protection is essential to safeguarding the Yangtze River barrier within the TRB, which serves as an ecological red line for the region (Zeng et al., 2021). The cities along the TRB are key centers within Sichuan for energy, basic industries, raw materials, and chemicals. At the same time, the ecological environment of the area is highly fragile, while environmental pollution has proven difficult to manage. In recent years, increasing human activity has exerted additional stress on the ecological environment of the basin. Therefore, understanding how best to proceed with the simultaneous advancement of high-quality economic growth in parallel with ecological preservation is of great theoretical and practical significance to the sustainable development of the TRB, as well as regions beyond.

Resilience, also referred to as elasticity or toughness, is used to describe the inherent flexibility of a material or organism to resist distortive change (Hosseini et al., 2016; Cheng et al., 2022). It is a concept rooted in materials science within the field of physics. In the early 21st century, the concept of a “resilient city” was first introduced at the United Nations Global Summit on Sustainable Development. Since then, research on various aspects of resilience, such as ER (Chaparro-Pedraza, 2024; Song et al., 2024; Dakos and Kéfi, 2022), community resilience (Boston et al., 2024; Robertson et al., 2021), economic resilience (Chavas, 2024; Zhang et al., 2024), city resilience (Elmqvist et al., 2019; Wang and Li, 2024) and infrastructure resilience (Balaei et al., 2018), have gradually emerged and continue to develop. Holling was the first to introduce the term resilience in the field of ecology in describing the capacity of natural ecosystems (Holling, 1973). ER is generally defined as the ability to recover, respond, and adapt to new conditions (Rus, Kilar and Koren, 2018; Cerè et al., 2017; Asadzadeh et al., 2017). Although the literature offers many definitions of ER, most emphasize three key attributes: absorption, adaptability, and recovery (Meerow and Newell, 2019).

ER refers to the capacity of an ecosystem to recover from external disturbances. Research on ER mainly focuses on developing an index system for ER aimed at measuring the coupling relationship between ER and economic development. In terms of index construction, Hu et al. proposed a three-dimensional ecological environment resilience evaluation index based on the “resistance-recovery-adaptation” characteristics of resilience. They analyzed the driving factors and influencing mechanisms in respect of the ecological resilience of urban agglomerations in the Yangtze River Delta (Hu et al., 2024). Li et al. developed ER indicators based on the “pressure-response” model (Li et al., 2022).

Additionally, some scholars have integrated ER with ecosystem services and ecological risk in an effort to construct ecological zoning from a risk perspective (Aydın et al., 2018). The assessment of ecological resilience is another key research focus. Notably, the methodologies developed have shifted from qualitative to quantitative approaches. In earlier research, spatial correlation analysis and the geographic detector methods were employed to measure the spatial and temporal patterns of ER in the urban agglomerations of the Yellow River Basin (Wang et al., 2023). Niu et al. used a super-efficient Windows-EBM-DEA model, which assessed unexpected outputs using a weighted summation method to measure the coordination and coupling relationship

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_513529

between ecological efficiency and ER (Niu et al., 2023). Wang et al. used the entropy weight-TOPSIS method to measure the ER of seven urban agglomerations in the Yellow River Basin, analyzing the temporal and spatial characteristics through a spatial Markov chain (Wang et al., 2023). Shi et al. used a multiple linear regression model to evaluate the ecological resilience and driving factors of the Beijing-Tianjin-Hebei urban agglomeration (Shi et al., 2022). The study found that ecological resilience decreased as urban population increased, even while GDP increased. Generally speaking, urban ecological resilience is a multi-dimensional concept, which is influenced by climate change (Aydın et al., 2018; Datola, 2023; Xu et al., 2024), urbanization (Zhao et al., 2024), urban green space construction (Xu et al., 2024), waste water and waste gas emissions, as well as other human interference factors (Shi et al., 2022). Thus, it is necessary to comprehensively consider economic, social, institutional, and technical factors, when assessing urban ecological resilience. (Hu et al., 2024; Shi et al., 2022; Datola, 2023).

While there is limited research on the coupling between ER and economic development, the coupling relationship between economic development and the environment has been well examined. The classical hypothesis of the environmental Kuznets curve provides key theoretical insight, suggesting that environmental governance can initially slow economic growth by increasing external costs or depleting production resources (Xia and Zhong, 2016). However, environmental conditions can be expected to worsen before any significant improvement in economic development manifests. Numerous scholars have explored this theory using panel data (Shi and Ren, 2019; Rasheed and Liu, 2024). From a temporal perspective, environmental governance has a positive short-term effect on economic growth but a significant negative long-term effect (Ocolișanu et al., 2022; Huang et al., 2018). The coupling coordination model is widely used to study the relationship between economic development and the environment (Liu et al., 2020; Wang et al., 2024; Sun et al., 2018). For example, Zheng et al. used the TOPSIS entropy method to measure the coupling coordination degree between high-quality urban economic development and environmental protection in western China, from 2004 to 2018 (Zheng et al., 2022). This analysis examined the regional differentiation characteristics and dynamic evolution trends. Similarly, Wang et al. examined the parallel development of urbanization and the ecological environment in the Yangtze River Economic Belt (Wang and Yu, 2019). Economic efficiency (EE) is implemented through optimized resource allocation (industrial structures and capital deployment) to maximize productivity and innovation outputs without depleting ecological carrying capacities. Conversely, ecological resilience (ER) denotes the socio-natural system's capacity to absorb disturbances, reorganize through adaptation, and sustain foundational ecosystem services amid urbanization shocks. Crucially, resilience and efficiency operate as fundamentally interdependent mechanisms requiring synergistic integration (Belhadi et al., 2022) to maximize long-term sustainability in socio-economic systems confronting anticipated future disruptions. Substantively, global institutions including the United Nations Environment Programme, World Bank, and the Greater London Authority have embedded resilience-efficiency nexus objectives into urban master planning and ground-level implementation (Wang et al., 2024).

In summary, existing literature has made some progress in constructing indices and in measuring ER. While recent studies (Niu et al., 2023; Wang et al., 2024) have examined the interaction between economic efficiency (EE) and ER. However, there remains fundamental uncertainty about how different economic growth trajectories affect

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_513529

resilience thresholds, particularly in ecologically sensitive areas such as river basins. Previous studies have not thoroughly investigated the key factors influencing the resilience and economic efficiency of urban clusters in river basins. First, research on the coupling relationship and mechanisms between EE and ER remains unclear, and the identification of the underlying processes driving this relationship remains ambiguous. Second, there is limited research on ER that specifically considers the characteristics of river basins. This study aims to address these gaps by identifying the driving factors of the coupling development between EE and ER through the establishment of an ER evaluation method that incorporates the vulnerability characteristics of river basins, thereby contributing to the existing body of research on ER.

Materials and methods

Research regions

According to the Overall Plan for the Construction of the Tuojiang Green Development Economic Belt, the construction scope of the Tuojiang Green Development Economic Belt covers county-level administrative regions through which the main stream and primary tributaries of the Tuojiang River flow. The drainage area spans 21,800 km^2. In 2021, the permanent population of the Tuojiang Green Development Economic Belt reached 18.55 million, accounting for 22% of Sichuan Province's population. The basin connects the Chengdu Plain Economic Zone and the South Sichuan Economic Zone, making it a key industrial agglomeration area in Sichuan Province. The number of industrial enterprises and the total industrial output value in this region represent more than one-third of the provincial totals, with the basin's gross domestic product (GDP) amounting to 1.25 trillion yuan. The Basin also features diverse landforms and biological landscapes, including mountains, hills, and river valleys. Cities within the basin face the dual pressures of economic development and ecological fragility. Given the limited data availability of the Aba Tibetan and Qiang Autonomous Prefectures, these were excluded from the study. Nevertheless, these areas constitute only a small portion of the Basin under study and would not significantly skew findings. Thus, ultimately, nine cities were selected for the purposes of this research (as illustrated in *Fig. 1*).

City name	Area (unit: square kilometers)	Basin area ratio
Neijiang	5159.68	95.82%
Zigong	3188.23	72.79%
Ziyang	3616.69	62.94%
Deyang	3645.16	61.67%
Chengdu	6374.92	44.47%
Meishan	1940.77	27.19%
Luzhou	1216.1	9.94%
Yibin	332.54	2.51%
Leshan	59.51	0.47%

Figure 1. *The distribution of the 9 sampling sites along the TRB*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_513529

Data sources

The data for this study primarily come from the Statistical Yearbook of Sichuan Province, Bulletin of Environmental Quality of Sichuan Province, China City Statistical Yearbook, and the Statistical Bulletin of National Economic and Social Development for various cities. In this study, indicator x16 has missing data in Leshan, Meishan, and Ziyang in 2011, accounting for 0.18% of the total data volume, which has little impact on the results. The missing data are filled using the median method.

Research methods

This paper firstly constructed measurement indicators for EE and ER, using the entropy-weighted TOPSIS analysis method to demonstrate the current situation and spatial-temporal differences of EE and ER in urban agglomerations within the TRB. This approach is particularly suitable for panel data indicator systems as the entropy weight method objectively assigns weights based on information entropy, avoiding subjective bias in multi-dimensional assessments. Standardized data were weighted to construct a normalized decision matrix, where TOPSIS quantified relative closeness to ideal solutions for comparative ranking—making it effective for integrating heterogeneous economic-ecological indicators. Secondly, a theoretical analysis model of coupling effects is introduced to examine the coordinated development status of EE and ER in these urban areas. Lastly, the key factors influencing ER were analyzed using the PQR and OLS method. Based on the findings from these three parts, governance strategies for the coordinated development of ER and EE in the TRB were proposed. The research framework is illustrated in *Figure 2*.

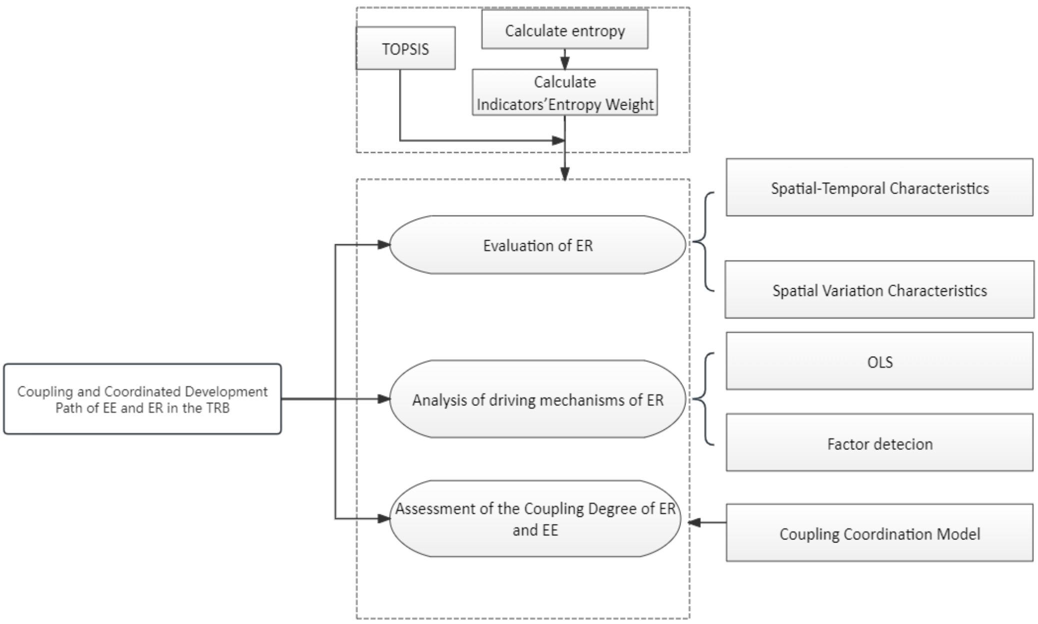

Figure 2. *Research framework*

Evaluation of ER

Construction of evaluation index system. Based on a review of the relevant literature, it has been observed that urbanization establishes a connection with ecological resilience

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_513529

through various factors, including population growth, economic development, industrial structure upgrading, and spatial expansion. Specifically, resistance refers to the capacity to withstand external disturbances and cope with uncertainties, as demonstrated by Urbanization rate, energy consumption. Adaptation entails the ability to maintain stable operations when confronting disturbances, characterized by the systematic assimilation of waste streams within evolving urban metabolic activities, characterized by Industrial wastewater discharge. Resilience denotes the possibility of reverting to pre-disturbance states or developing through transformative reorganization after damage, facilitated by Excellent weather number. This study constructs an index system for EE and ER in the TRB. The index system is presented in *Table 1*.

Table 1. *Index system of urban EE and ER*

Primary index		Secondary index	Index number	Attribute	Unit
EE	Economic aggregate	Per capita GDP	x1	+	Yuan
		Per capita investment in fixed assets	x2	+	Yuan
	Industrial structure	Increase rate of primary industry	x3	+	%
		Increase rate of secondary industry	x4	+	%
		Increase rate of tertiary industry	x5	+	%
	Economic vitality	Per capita disposable income	x6	+	Yuan
		Total retail sales of social consumer goods	x7	+	Hundred million Yuan
ER	Resistance	Financial expenditure on environmental protection	x8		Ten thousand Yuan
		Per capita green space	x9	+	㎡
		Energy consumption	x10	-	%
		Urbanization rate	x11	+	%
	Adaptability	Industrial wastewater discharge	x12	-	Ten thousand tons
		Industrial sulfur dioxide emission	x13	-	Tons
		Industrial nitrogen oxide emissions	x14	-	Tons
		Average annual concentration of Pm2.5	x15	-	Microgram/m3
	Resilience	Excellent weather number	x16	+	No.
		Centralized treatment rate of sewage treatment plant	x17	+	%
		Harmless treatment rate of domestic garbage	x18	+	%

Calculation of the evaluation indexes. Entropy weight method to calculate the weight. Let w_i represent the weight of the j-th index, andE_i denote the information entropy of the j-th index. m represents the number of evaluation years, and k is the Boltzmann constant. The formula is as follows: $p_{ij}w_i$ and E_i.

$$\mathrm{P}_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \tag{Eq.1}$$

$$E_i = -k \sum_{i=1}^{n} p_{ij} \ln p_{ij}\, , k = \frac{1}{\ln n} \tag{Eq.2}$$

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_513529

$$\mathrm{g}_j = 1 - e_j \quad \text{(Eq.3)}$$

$$\mathrm{w}_i = \frac{g_j}{\sum_{i=1}^{m} g_j} \quad \text{(Eq.4)}$$

Using the TOPSIS method to calculate the index. First, a normalized weighted data matrix is constructed using the entropy weights calculated above. Then, the ideal solution and the negative ideal solution for each index in the evaluation year are determined, denoted as Z_{ij}.

$$Z^{+} = \{Z_1^{+},\ Z_2^{+},\ \cdots Z_m^{+},\ \} = \{maxZ_{ij}\} \quad \text{(Eq.5)}$$

$$Z^{-} = \{Z_1^{-},\ Z_2^{-},\ \cdots Z_m^{-},\ \} = \{minZ_{ij}\} \quad \text{(Eq.6)}$$

Using the Euclidean norm as a measure of distance, the distance between each feasible solution and the positive and negative ideal solutions for each index in each year is calculated.

$$d_i^{*} = \sqrt{\sum_{j=1}^{m} \left(z_{ij} - z_j^{+}\right)^2} \quad \text{(Eq.7)}$$

$$d_i^{0} = \sqrt{\sum_{j=1}^{m} \left(z_{ij} - z_j^{-}\right)^2} \quad \text{(Eq.8)}$$

Finally, the closeness coefficient C of each index to the ideal solution is calculated. The formula is:

$$C_i^{*} = {d_i^{0}}\big/{\left(d_i^{0} + d_i^{*}\right)} \quad \text{(Eq.9)}$$

Taking the relative closeness of the feasible solution to the ideal solution for that year as the evaluation level of development in the TRB, the closer z_{ij} is to the ideal solution, the closer C_i^{*} is to 1. Conversely, the closer C_i^{*} is to the negative ideal solution, the closer it is to 0. By ranking the evaluation levels of development in the TRB using C_i^{*}, we can observe the trend of ER reduction in the TRB.

Analysis of driving mechanisms of ER

Panel quantile regression analyzes the impact of influencing factors on urban ER at different quantiles, providing more information about the relationships between observed variables. This method avoids the idealization of mean regression, making the research conclusions more reliable. The specific calculation steps are as follows:

$$Q_\tau(Y_{it}|X_{it}) = X_{it}'\beta_\tau + u_{it} \quad \text{(Eq.10)}$$

where $Q_\tau(Y_{it}|X_{it})$ is the conditional quantile function of urban ER; Y_{it} represents the value of urban ER; X_{it} is a vector of explanatory variables; and β_τ is the vector of quantile regression coefficients, which indicates the marginal effect of the explanatory variables

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_513529

on the dependent variable at the τ-th quantile. Linear programming methods are typically used for estimation.

$$T = \alpha U_1 + \beta U_2 \quad \text{(Eq.11)}$$

$$C = \frac{2\sqrt{U_1 U_2}}{U_1 + U_2} \quad \text{(Eq.12)}$$

$$D = \sqrt{TC} \quad \text{(Eq.13)}$$

Here, T represents the comprehensive coordination index, while U_1 and U_2 are the comprehensive level indices of the EE and ER systems, respectively. The values of α and β are both set to 1/2, indicating that the two systems have equal weight. C represents the coupling degree, and D denotes the coupling coordination degree. The higher the value of D, the more coordinated and balanced the coupling between the two systems. Following existing research (Yu et al., 2024), the coupling coordination degree is divided into ten levels using a uniform distribution method, as shown in *Table 2*.

Table 2. *Classification of coupling coordination degree*

Coupling coordination value	Coordination grade	Divide	Coupling coordination value	Coordination grade	Divide
[0,0.1]	Extreme disorder	Lose balance	(0.5,0.6]	Reluctantly coordinate	Coordinate
(0.1,0.2]	Serious maladjustment		(0.6,0.7]	Primary coordination	
(0.2,0.3]	Moderate disorder		(0.7,0.8]	Intermediate coordination	
(0.3,0.4]	Mild disorder		(0.8,0.9]	Good coordination	
(0.4,0.5]	On the verge of disorder		(0.9,1.0]	Quality coordination	

Results and discussions

Spatial-temporal characteristics of ER in the TRB

From 2011 to 2021, the comprehensive index of ER exhibited a steady evolutionary trend. As can be seen from *Figure 3*, the trend of ER in the urban agglomerations of the TRB is relatively consistent, generally fluctuating between 0.29 and 0.79, with a slow downward trend. The performance of upstream cities generally stronger than midstream and downstream cities. In 2011, the ER values of Chengdu, Deyang, and Ziyang were 0.75, 0.62, and 0.67, respectively, while Leshan and Neijiang were relatively weaker, with values of 0.5 and 0.47, respectively (*Fig. 4*). The upstream cities, typified by Chengdu, are situated within gentle-gradient alluvial plains that facilitate enhanced fluvial advection efficiency, leading to pollutant diffusion capacities exceeding those of downstream counterparts. The midstream cities are represented by Ziyang, which is located in the flood detention area on the concave bank of the Tuo River, and industrial pollutants are retained for a long time. The downstream cities are represented by Neijiang, and the narrowing of the river channel has weakened the recovery capacity of the system. The coefficient of variation reached its peak in 2018, and was close to 0.15 in both 2011 and 2021. At the individual city level, Chengdu had the strongest ER, leading the urban agglomerations prior to 2018, but has subsequently declined. In comparison, Leshan, Yibin, and Neijiang, had relatively low ER values. The peak of the coefficient of variation in 2018 marked the critical point of policy intervention, and the 2015-2017 Chengdu-

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_513529

Chongqing Urban Agglomeration Plan promoted the increase of ecological investment in Chengdu, but the supporting facilities of secondary cities were insufficient. The range of differences in ER among the cities gradually grew post 2018, but this difference narrowed somewhat in 2021. In 2021, the basin compensation mechanism will be implemented, Ziyang will receive ecological transfer payments, and the ecological gap in the basin will converge. Overall, the economic development efficiency of the TRB significantly lags behind its ER level. However, in recent years, the development levels of both systems have fluctuated within ranges that have come closer to each other.

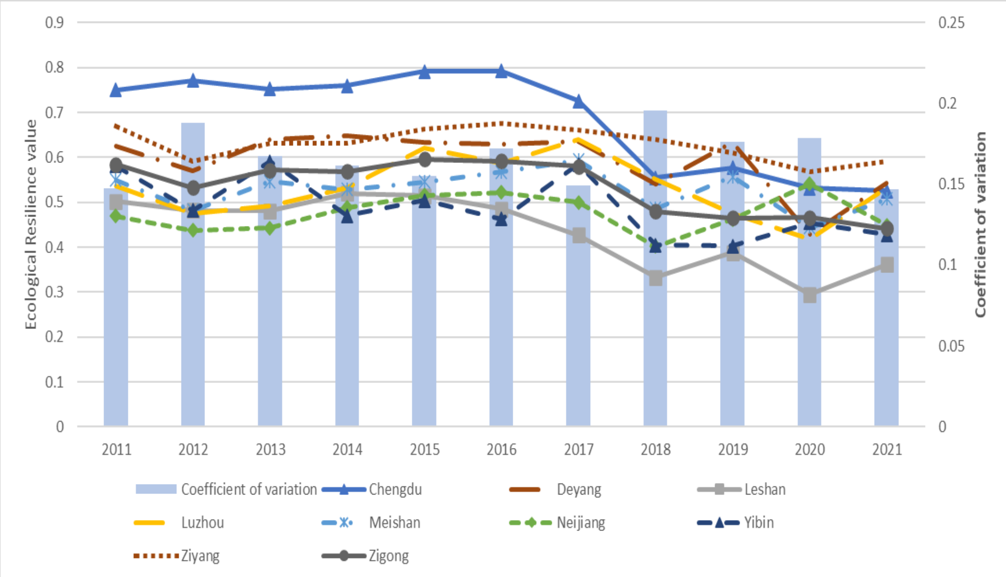

Figure 3. *Temporal and spatial characteristics of ER in urban agglomerations of the TRB*

The coupling degree between EE and ER in the TRB

During the period from 2011 to 2021, there were significant spatio-temporal differences in the coupling coordination degree between EE and ER in the TRB (*Table 3*). Overall, at the beginning of the observation period, three cities were in a loosely coordinated state, five cities were in a primary coordinated state, while only Chengdu was in a well-coordinated state. Over time, the coupling coordination degree of the various cities changed. Chengdu had the highest coupling coordination degree between EE and ER in the TRB, but showed an inverted V-shaped trend during the observation period. In the first five years of the observation period, Chengdu's coupling coordination degree between EE and ER gradually improved from well-coordinated to optimally coordinated. But after 2016, it slowly declined, falling to a moderately coordinated level by the end of the observation period. Moreover, Luzhou, Deyang, Neijiang, Meishan, and Yibin showed an upward trend in the degree of coupling coordination between EE and ER (with an average annual increase of more than 0.05).

Luzhou had the fastest increase, progressing from barely coordinated at the beginning of the observation period to moderately coordinated by the end. Deyang and Neijiang both advanced one level in coupling coordination during the observation period, while Meishan and Yibin advanced from low values in the primary coordination level to higher values. By contrast, the coupling coordination degree of Zigong and Leshan showed a less significant upward trend (with an average annual increase of less than 0.05), and both

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_513529

remained at the primary coordination level by the end of the observation period. Ziyang experienced considerable fluctuations in its coupling coordination degree, but overall, showed a downward trend, dropping from a high value of primary coordination at the beginning of the observation period to a lower value at the end.

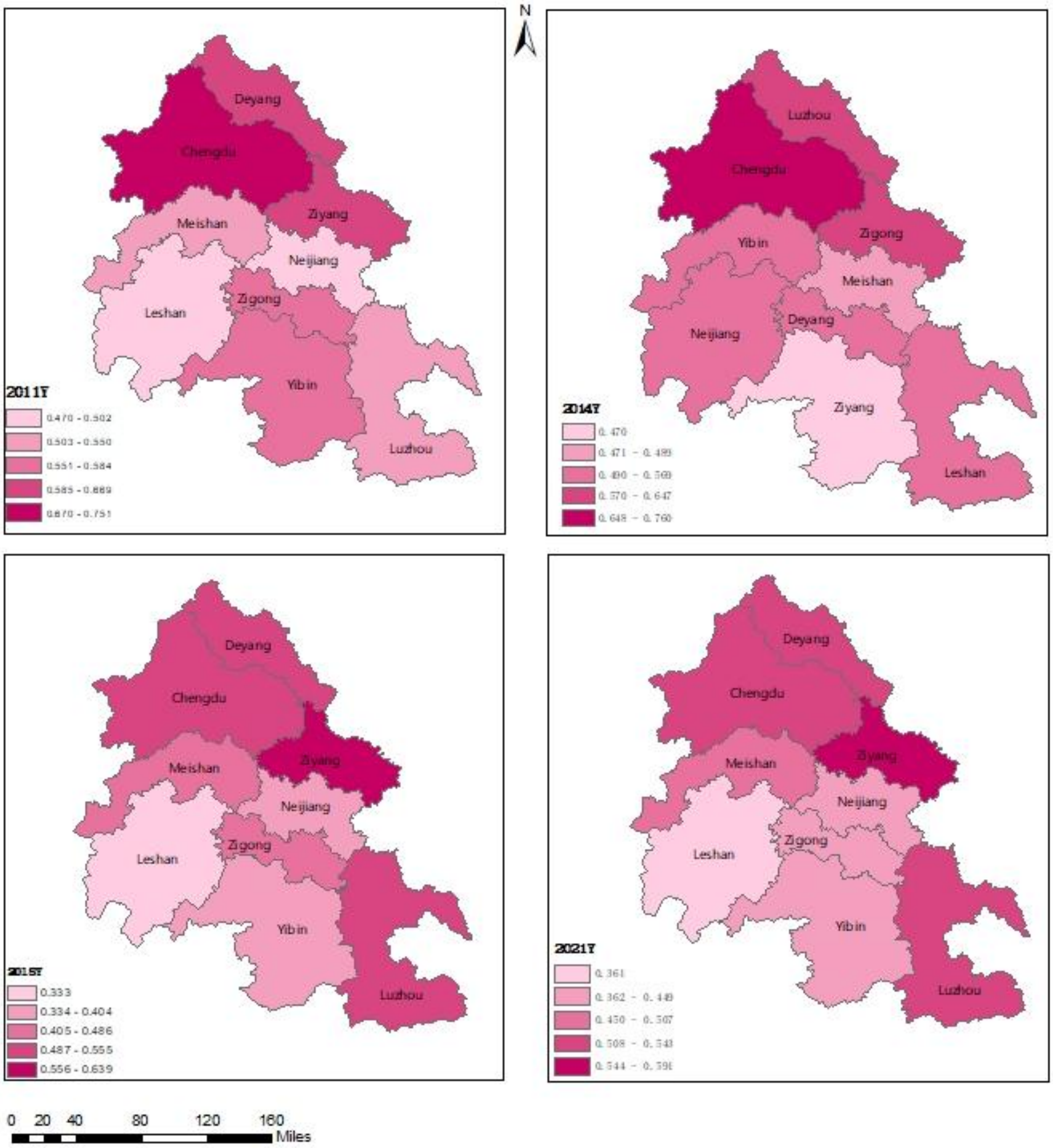

Figure 4. *Spatial variation characteristics of ER in urban agglomerations of the TRB*

At present, there are significant shortcomings in the coordinated development of EE and ER in the TRB. Chengdu, as the most developed city in the basin, has long played a leading role, but over the past five years, due to the continuous decline in ER, Chengdu's coupling coordination degree between EE and ER has shown a clear regressive trend. This reversal is a warning signal that merits attention. The other cities in the basin remain in the primary and moderate coordination stages, with significant room for improvement, being far from achieving optimal coordination levels.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_513529

Table 3. *Coupling coordination coefficient of EE and ER in TRB in 2011-2021*

Year	Chengdu	Zigong	Luzhou	Deyang	Neijiang	Leshan	Meishan	Yibin	Ziyang
2011	0.84	0.61	0.57	0.63	0.5	0.56	0.6	0.62	0.66
2012	0.86	0.6	0.61	0.63	0.5	0.58	0.64	0.63	0.67
2013	0.86	0.64	0.63	0.68	0.52	0.6	0.64	0.6	0.64
2014	0.87	0.61	0.67	0.73	0.55	0.61	0.61	0.58	0.65
2015	0.87	0.62	0.71	0.62	0.51	0.6	0.6	0.56	0.6
2016	0.88	0.59	0.69	0.64	0.54	0.59	0.64	0.57	0.64
2017	0.86	0.64	0.71	0.7	0.46	0.57	0.55	0.66	0.63
2018	0.78	0.67	0.64	0.66	0.57	0.61	0.54	0.61	0.53
2019	0.79	0.58	0.63	0.62	0.56	0.58	0.64	0.66	0.5
2020	0.81	0.65	0.68	0.59	0.64	0.58	0.66	0.68	0.62
2021	0.79	0.64	0.71	0.73	0.6	0.6	0.67	0.68	0.62

Factors influencing the ER of Urban EE in the TRB

This study analyzes the impact of the economic development level, urbanization level, industrial structure, and energy consumption patterns on the ER of major cities in the TRB, China. The study sets quantile points at 10%, 25%, 50%, 75%, and 90% for the panel quantile regression model. To avoid potential endogeneity issues in the data, ordinary least squares (OLS) regression is also conducted for comparison. *Table 4* and *Figure 5* report the panel quantile regression results and the visual representation of the effects of key factors on ER in the TRB. Findings are as follows.

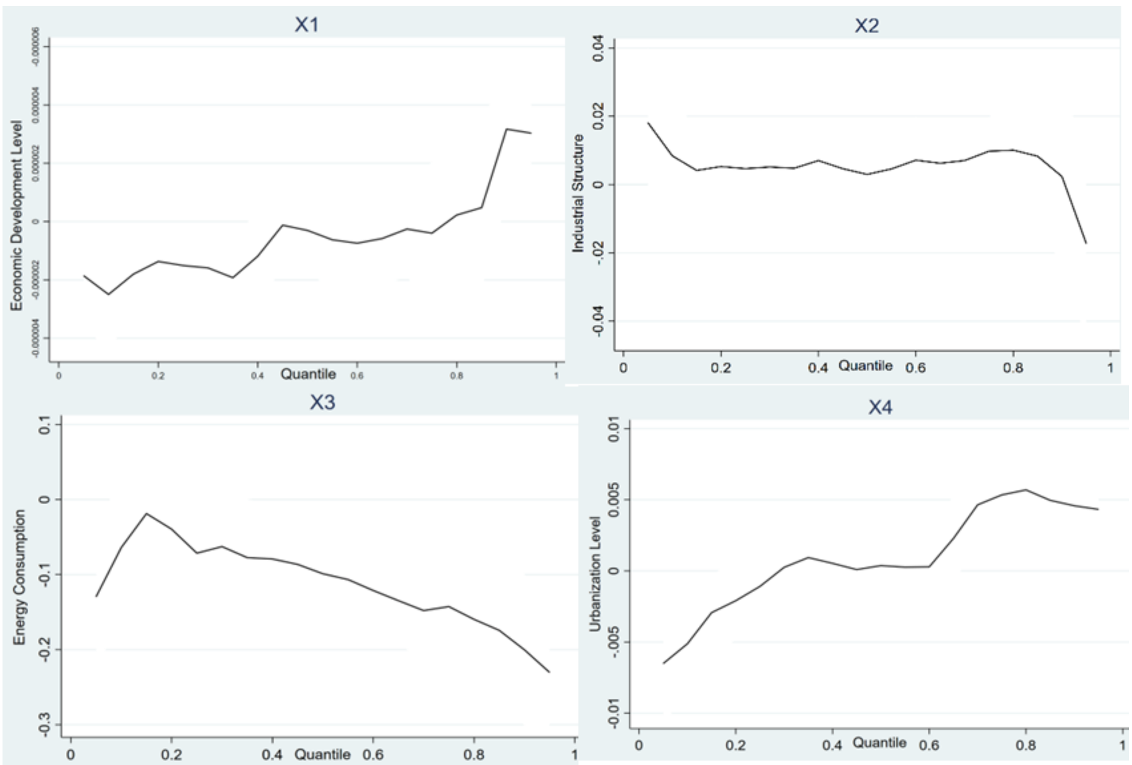

Figure 5. *Panel data regression model test results*

***Table 4.** Results of the panel data regression model tests*

Variable	Method of least squares	Panel quantile regression				
		10%	25%	50%	75%	90%
X1	0.000* (-6.45)	0.000* (-4.71)	0.000* (-5.09)	0.000* (-7.34)	0.000* (-4.77)	0.008* (-2.71)
X2	0.080* (1.77)	0.647 (0.46)	0.029* (2.21)	0.079 (1.78)	0.040* (2.08)	0.028* (2.24)
X3	0.000* (-6.42)	0.009* (-3.2)	0.002* (-4.97)	0.000* (-5.94)	0.000* (-4.37)	0.000* (-6.84)
X4	0.000* (5.19)	0.002* (2.68)	0.000* (3.13)	0.000* (5.34)	0.000* (5.69)	0.000* (4.25)
cons	0.533 (-0.62)	0.803 (0.25)	0.318 (-1)	0.518 (-0.65)	0.194 (-1.31)	0.274 (-1.1)

T statistics are in brackets. It is significant at the level of 5%

Economic development level (X1)

On one hand, economic development provides the material foundation for urban ecological civilization; on the other hand, increased economic development implies expanded production scale and consumption demand, indirectly leading to higher energy consumption and pollution emissions. Economic development level shows a significant negative impact on urban ER, with the most substantial negative effect at the 50% quantile. This to some extent reflects the inhibitory effect of the previous extensive economic development model in the TRB on ER. As ER values increase, the negative effect of economic development gradually diminishes, indicating that a strong economic foundation is necessary to build higher ER.

Industrial structure (X2)

Industrial structure serves as an important link between economic activity and the ecological environment. Adjustments in industrial structure will affect the coordination between economic and ecological systems. The impact of industrial structure on urban ER shows notable variation. At the 25%, 75%, and 90% quantiles, the growth of the tertiary sector significantly enhances urban ER. However, at the 10% and 50% quantiles, the positive effect of the tertiary sector's growth does not pass significance tests.

Energy consumption (X3)

Under the "dual carbon" goals, urban development must shift towards renewable and clean energy sources, replacing traditional high-pollution energy sources like coal, to reduce the environmental impact of economic growth. Energy consumption exhibits a significant negative impact on urban ER, with the most significant negative effect at the 90% quantile. This suggests that the high energy consumption model, dominated by coal, has suppressed the enhancement of urban ER in the TRB.

Urbanization level (X4)

A high level of urbanization is conducive to resisting ecological vulnerability. It enhances ER by reducing ecological fragility. Urbanization level demonstrates a significant positive effect on urban ER, reaching its highest at the 75% quantile.

In summary, urbanization and the growth of the tertiary sector are key drivers for improving urban ER. The current extensive economic development model and high energy consumption patterns in the TRB have suppressed the enhancement of urban ER. In order to improve the ER of cities in the basin, attention must be paid to changing the economic development model. Under the impetus of China's "dual carbon" goals, it is crucial that the transition of industries towards clean and renewable energy sources be more carefully coordinated and supported.

Conclusions

The economic efficiency of this river basin shows a significant spatial imbalance with Chengdu being dominant and the surrounding areas lagging behind. Therefore, transforming the extensive economic and high energy consumption development model of the surrounding cities and strengthening green transformation are the key paths to overall enhance the ecological efficiency of the basin. And a summary of key conclusions and indicated recommendations are as follows:

The EE of the major cities within the river basin varies significantly, with Chengdu's development level far surpassing that of other cities. It is crucial to leverage Chengdu's leading city effect and encourage the cross-regional flow of assets. By capitalizing on Chengdu's developmental advantages, its resources, industries, and skill sets, should also be channeled toward surrounding areas, thereby supporting the coordinated development of the entire urban system of the river basin.

From the analysis of the coupling coordination degree of the six major cities in the TRB, it is evident that the overall economic development of the surrounding cities is slow, while ecological protection also hovers at a low level. The economic development, ecological protection, and environmental governance of these cities are in a state of severe imbalance, with the situation unlikely to improve in the short term. Therefore, it is necessary for government to allocate resources aimed at addressing shortcomings while also prioritizing urbanization development within the TRB. By tailoring strategies to local conditions and clarifying high quality developmental goals of urbanization across the region, the overall quality of the cities can be expected to improve.

The ER of major cities in the TRB is primarily influenced by economic developmental levels, urbanization rates, industrial structure, and energy consumption patterns. Urbanization and the growth of the tertiary sector are key driving forces for improving the ER of cities in the basin. In order to improve the ER of cities in the TRB, it is essential to revise the economic developmental model. Under the "dual carbon" goals, efforts should be made to transition industries from high carbon activities to clean energy and renewable energy development.

Policy recommendations

Firstly, according to the research conclusion, the level of economic development has a significant negative impact on the ecological efficiency (ER) of cities, with the most significant effect at the 50th percentile. Therefore, for cities with an ER around 50%, it is recommended to prioritize the development of energy-saving and environmental protection service industries, and the government should provide partial research and development investment subsidies for the local development of the digital economy and other green tertiary industries.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_513529

Secondly, the research results show that energy consumption has a significant negative impact on the ecological resilience (ER) of cities, with the most significant effect at the 90th percentile. Therefore, it is suggested that the government encourage local high-energy-consuming enterprises to consume a certain proportion of renewable energy electricity annually.

Limitation and future study

When studying Yangtze River Economic Belt and the Yellow River Basin, it was found that differences in restoration as well as adaptative capabilities were the key intrinsic factors influencing the resilience (Wang and Liu, 2024). In the future, the roles of restoration and adaptive capabilities in ecological resilience can be further explored in the Tuojiang River Basin (TRB). Population, environmental stress, and economic vitality significantly influence the resilience of composite ecosystems; meanwhile, total energy consumption and the number of workers in the transportation, storage, and postal sectors were identified as key factors affecting the resilience of most districts and counties (Hang et al., 2023) in previous study. In future research, it is advisable to further investigate the boundary conditions under which energy consumption changes and its impacts on ecological resilience when multiple factors are at play.

The study area covered by this research is limited, and there is a lack of horizontal comparison with adjacent basins. In the future, the area for data collection can be further expanded. It is also possible to attempt multi-scale tracking data research on "enterprises - counties - urban agglomerations" to accurately identify the differences in economic efficiency at different scales.

Acknowledgements. This research is funded by Chengdu Water Ecological Civilization Construction Research Centre, grant number SST2025-10; Chengdu University of Information and Technology of "Research on the Life Cycle Performance Evaluation of China's Rural Infrastructure from the Perspective of Inclusive Growth", grant number KYTZ 202232; grant number KYZS202514.

REFERENCES

[1] Asadzadeh, A., Kötter, T., Salehi, P., Birkmann, J. (2017): Operationalizing a concept: the systematic review of composite indicator building for measuring community disaster resilience. – International Journal of Disaster Risk Reduction 25: 147-162. https://doi.org/10.1016/j.ijdrr.2017.09.015.

[2] Aydin, B., Tezer, A., Türkay, Z., Karaçor, E. K., Güler, İ., Uzun, O., et al. (2018): Resilience through participatory planning for the integrated ecological risks in Düzce. – Resilience 2(2): 105-121. https://doi.org/10.32569/resilience.484946.

[3] Balaei, B., Wilkinson, S., Potangaroa, R., Hassani, N., Al-Shoshtari, M. (2018): Developing a framework for measuring water supply resilience. – Natural Hazards Review 19(4): 04018013. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000292.

[4] Belhadi, A., Kamble, S. S., Venkatesh, M., Chiappetta Jabbour, C. J., Benkhati, I. (2022): Building supply chain resilience and efficiency through additive manufacturing: an ambidextrous perspective on the dynamic capability view. – International Journal of Production Economics 249: 108516. https://doi.org/10.1016/j.ijpe.2022.108516.

[5] Boston, M., Bernie, D., Brogden, L., Forster, A., Galbrun, L., Hepburn, L. A., et al. (2024): Community resilience: a multidisciplinary exploration for inclusive strategies and scalable

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_513529

solutions. – Resilient Cities and Structures 3(1): 114-130. https://doi.org/10.1016/j.rcns.2024.03.005.
[6] Ceola, S., Laio, F., Montanari, A. (2019): Global-scale human pressure evolution imprints on sustainability of river systems. – Hydrology and Earth System Sciences 23(9): 3933-3944. https://doi.org/10.5194/hess-23-3933-2019.
[7] Cerè, G., Rezgui, Y., Zhao, W. (2017): Critical review of existing built environment resilience frameworks: directions for future research. – International Journal of Disaster Risk Reduction 25: 173-189. https://doi.org/10.1016/j.ijdrr.2017.09.018.
[8] Chaparro-Pedraza, P. C. (2024): Evolution alters ecological resilience. – Nature Ecology & Evolution: 1-2. https://doi.org/10.1038/s41559-024-02542-1.
[9] Chavas, J.-P. (2024): Economic resilience: measurement and assessment across time and space. – Research in Economics 78(2): 100953.https://doi.org/10.1016/j.rie.2024.100953.
[10] Cheng, Y., Elsayed, E. A., Huang, Z. (2022): Systems resilience assessments: a review, framework and metrics. – International Journal of Production Research 60(2): 595-622.https://doi.org/10.1080/00207543.2021.1971789.
[11] Dakos, V., Kéfi, S. (2022): Ecological resilience: what to measure and how. – Environmental Research Letters 17(4): 43003. https://doi.org/10.1088/1748-9326/ac5767.
[12] Datola, G. (2023): Implementing urban resilience in urban planning: a comprehensive framework for urban resilience evaluation. – Sustainable Cities and Society 98: 104821. https://doi.org/10.1016/j.scs.2023.104821.
[13] Elmqvist, T., Andersson, E., Frantzeskaki, N., McPhearson, T., Olsson, P., Gaffney, O., et al. (2019): Sustainability and resilience for transformation in the urban century. – Nature Sustainability 2(4): 267-273. https://doi.org/10.1038/s41893-019-0250-1.
[14] Foti, G., Bombino, G., D'Agostino, D., Barbaro, G. (2022): The effects of anthropogenic pressure on rivers: a case study in the metropolitan city of Reggio Calabria. – Remote Sensing 14(19): 4781. https://doi.org/10.3390/rs14194781.
[15] Hang, Y., Hu, J., Ma, C., Chen, Y., Wang, Y. (2023): Spatio-temporal differentiation of the composite ecosystem resilience in the ecologically fragile area in the upper reaches of the Yellow River: a case study in Ningxia. – Arid Zone Research 40(2): 303-312.
[16] Holling, C. S. (1973): Resilience and stability of ecological systems. – Annual Review of Ecology and Systematics 4(1): 1-23. https://doi.org/10.1146/annurev.es.04.110173.000245.
[17] Hosseini, S., Barker, K., Ramirez-Marquez, J. E. (2016): A review of definitions and measures of system resilience. – Reliability Engineering & System Safety 145: 47-61. https://doi.org/10.1016/j.ress.2015.08.006.
[18] Hu, H., Yan, K., Shi, Y., Lv, T., Zhang, X., Wang, X. (2024): Decrypting resilience: the spatiotemporal evolution and driving factors of ecological resilience in the Yangtze River Delta Urban Agglomeration. – Environmental Impact Assessment Review 106: 107540. https://doi.org/10.1016/j.eiar.2024.107540.
[19] Huang, Q. H., Hu, J. F., Chen, X. D. (2018): Environmental regulation and green total factor productivity: dilemma or win-win. – China Population, Resources and Environment 28: 140-149.
[20] Li, X., Liu, K., Tian, S., Guan, Y., Liu, H. (2022): Evaluation of urban human settlements resilience based on DPSIR model: a case study of the Yangtze river delta urban systems. – Human Geography 37(1): 54-62.
[21] Liu, Y., Yang, L., Jiang, W. (2020): Coupling coordination and spatiotemporal dynamic evolution between social economy and water environmental quality—a case study from nansi lake catchment, China. – Ecological Indicators 119: 106870. https://doi.org/10.1016/j.ecolind.2020.106870.
[22] Meerow, S., Newell, J. P. (2019): Urban resilience for whom, what, when, where, and why? – Urban Geography 40(3): 309-329. https://doi.org/10.1080/02723638.2016.1206395.

[23] Niu, J., Xin, B., Wang, M. (2024): Evaluation of coordinated development and identification of obstacle factors for urban ecological efficiency and ecological resilience. – Statistics and Decision 640 (004) :79-84. 10.13546/j.cnki.tjyjc.2024.04.014
[24] Oclisanu, A., Dobrotă, G., Dobrotă, D. (2022): The effects of public investment on sustainable economic growth: empirical evidence from emerging countries in central and eastern Europe. – Sustainability 14(14): 8721. https://doi.org/10.3390/su14148721.
[25] Rasheed, M., Liu, J. (2024): Unraveling the environmental Kuznets curve: interplay between CO_2 emissions, economic development, and energy consumption. – Environmental Science and Pollution Research 31(9): 13372-13391. https://doi.org/10.1007/s11356-023-31747-3.
[26] Robertson, T., Docherty, P., Millar, F., Ruck, A., Engstrom, S. (2021): Theory and practice of building community resilience to extreme events. – International Journal of Disaster Risk Reduction 59: 102253. https://doi.org/10.1016/j.ijdrr.2021.102253.
[27] Rus, K., Kilar, V., Koren, D. (2018): Resilience assessment of complex urban systems to natural disasters: a new literature review. – International Journal of Disaster Risk Reduction 31: 311-330. https://doi.org/10.1016/j.ijdrr.2018.05.015.
[28] Shi, B., Ren, B. P. (2019): Strategic competition, spatial effects and the convergence of economic growth in China. – Journal of Economic Perspectives 2: 47-62.
[29] Shi, C., Zhu, X., Wu, H., & Li, Z. (2022): Assessment of urban ecological resilience and its influencing factors: a case study of the Beijing-Tianjin-Hebei urban agglomeration of China. – Land 11(6): 921. https://doi.org/10.3390/land11060921.
[30] Song, S., Wang, S., Gong, Y., Yu, Y. (2024): The past and future dynamics of ecological resilience and its spatial response analysis to natural and anthropogenic factors in Southwest China with typical Karst. – Scientific Reports 14(1): 19166. https://doi.org/10.1038/s41598-024-70139-6.
[31] Sun, Q., Zhang, X., Zhang, H., Niu, H. (2018): Coordinated development of a coupled social economy and resource environment system: a case study in Henan Province, China. – Environment, Development and Sustainability 20(3): 1385-1404. https://doi.org/10.1007/s10668-017-9926-8.
[32] Wang, B., Yu, F. W. (2019): Research on coupling coordination degree and spatial-temporal evolution between urbanization and ecological environment in the Yangtze River economic belt. – East China Economic Management 33(3): 58-63.
[33] Wang, J., Zhou, X. (2024): Measurement and synergistic evolution analysis of economic resilience and green economic efficiency: evidence from five major urban agglomerations, China. – Applied Geography 168: 103302. https://doi.org/10.1016/j.apgeog.2024.103302.
[34] Wang, L., Gong, W., Wang, C., Li, W. (2023): Spatial-temporal evolution and influencing factors of urban ecosystem resilience in the Yellow River Basin. – Global Nest Journal 25(1): 66-76.
[35] Wang, L., Li, G. (2024): The impact of sustainable development planning on urban ecological resilience in resource-based cities: evidence from China. – Environmental Science and Pollution Research 31(8): 12245-12256. https://doi.org/10.1007/s11356-024-31847-8.
[36] Wang, Q., Li, Y., Li, R. (2024): Rethinking the environmental Kuznets curve hypothesis across 214 countries: the impacts of 12 economic, institutional, technological, resource, and social factors. – Humanities and Social Sciences Communications 11(1): 1-19. https://doi.org/10.1057/s41599-024-02736-9.
[37] Wang, Z., Liu, W. (2024): A comparative study of urban ecological resilience in the Yangtze River economic belt and the Yellow River basin. – Humanities and Social Sciences Communications 11(1): 1471. https://doi.org/10.1057/s41599-024-04017-x.
[38] Xia, Y., Zhong, M. C. (2016): Relationship between EKC hypothesis and the decoupling of environmental pollution from economic development: based on China prefecture-level cities' decoupling partition. – China Population, Resources and Environment 26(10): 8-16.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_513529

[39] Xu, C., Huo, X., Hong, Y., Yu, C., de Jong, M., Cheng, B. (2024): How urban greening policy affects urban ecological resilience: quasi-natural experimental evidence from three megacity clusters in China. – Journal of Cleaner Production 452: 142233. https://doi.org/10.1016/j.jclepro.2024.142233.

[40] Yang, M., Gao, X., Siddique, K. H. M., Wu, P., Zhao, X. (2023): Spatiotemporal exploration of ecosystem service, urbanization, and their interactive coercing relationship in the Yellow River Basin over the past 40 years. – Science of the Total Environment 858: 159757. https://doi.org/10.1016/j.scitotenv.2022.159757.

[41] Ying, Z., Yuan, C., Luo, Z., Jiang, W. (2022): Ecological resilience assessment of an emerging urban agglomeration: a case study of Chengdu-Chongqing Economic Circle, China. – Polish Journal of Environmental Studies 31(3). https://doi.org/10.15244/pjoes/144098.

[42] Yu, T., Jia, S., Cui, X. (2024): From efficiency to resilience: unraveling the dynamic coupling of land use economic efficiency and urban ecological resilience in Yellow River basin. – Scientific Reports 14(1): 16518. https://doi.org/10.1038/s41598-024-67364-4.

[43] Zeng, Z., Luo, W. G., Wang, Z., Yi, F. C. (2021): Water pollution and its causes in the Tuojiang River Basin, China: an artificial neural network analysis. – Sustainability 13(2): 792. https://doi.org/10.3390/su13020792.

[44] Zhang, L., Lin, G., Lv, X., Su, W. (2024): Suppression or promotion: research on the impact of industrial structure upgrading on urban economic resilience. – Humanities and Social Sciences Communications 11(1): 1-14. https://doi.org/10.1057/s41599-024-03329-2.

[45] Zhao, B., Fang, L., Zhang, J., Li, W., Tao, L., Yu, Q., Wen, C. (2024): Impact of digital finance on urban ecological resilience: evidence from the Yangtze River Economic Belt in China. – Environmental Science and Pollution Research 31(6): 9218-9236. https://doi.org/10.1007/s11356-023-31431-6.

[46] Zheng, T., Zhou, P. (2022): Coupling coordination between economic development and ecological environment in western Chinese cities: a study based on the perspective of green development. – Science and Technology Management Research 42(13):209-215. 10.3969/j.issn.1000-7695.2022.13.027

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_513529