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Quantitative evaluation of urban resilience in underdeveloped regions: a study of six cities in Sichuan & Tibet, China

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Introduction: Urban resilience construction can aid in the management of urban crises and enhance the quality of the human living environment. Compared to metropolises in developed regions, cities in underdeveloped regions with unsatisfactory natural environments, insufficient economic and social development, and inadequate infrastructure construction are highly vulnerable to challenges posed by natural disasters, epidemics, and climate change. Comprehensive quantitative evaluations are needed to identify avenues for enhancing urban resilience.

Methods: This study employs the TOPSIS entropy weight method and coupled coordination model to evaluate the economic, social, environmental, and infrastructure resilience of six cities and states along the Sichuan-Tibet Railway in China from 2015 to 2020. Furthermore, correlation and gray correlation analysis are used to identify the primary factors influencing the urban resilience of underdeveloped regions.

Results: Firstly, during 2015-2020, the overall urban resilience of each city and state maintained an increasing trend, with different trends in the evolution of the four resilience indices and differences among cities, and the highest overall resilience is in Lhasa. Secondly, the coupling coordination between the overall resilience and each resilience aspect maintained an increasing trend and differed significantly from each other. Finally, the social and economic resilience of each city and state maintained an increasing trend and differed significantly from each other.

Discussion: Economic, social, environmental, and infrastructure factors each have their own characteristics in influencing urban resilience. Based on the results, we present a three-dimensional evaluation model for analyzing the evolutionary trajectories and resilience patterns of cities. This work intends to present new concepts for assessing and optimizing urban resilience in underdeveloped regions using quantitative methodologies, as well as providing references for urban resilience construction in these places.

KEYWORDS

resilient city, underdeveloped region, TOPSIS, coupled coordination model, built-up environment

1 Introduction

As complex systems, cities are exposed to long-term disturbances and shocks from the external environment, such as natural disasters (Zhou et el., 2022; Kondo and Lizarralde, 2021), economic crises (Ulfarsson et al., 2015; Tomao et al., 2021), climate change (Zimmerman and Faris, 2011) and the spread of infectious diseases (Cheng et al., 2022; Jin et al., 2023). City managers have incorporated the engineering concept of "resilience" into urban planning and construction to mitigate the negative effects of these shocks and assist cities in developing stably and sustainably (Murgatroyd and Hall, 2020; Wang L, 2022), as well as to improve the quality of the living environment and the standard of living for residents (Snep et al., 2020; Talubo et al., 2022). The concept of urban resilience is a comprehensive concept with multiple attributes (Dianat et al., 2022; Khatibi et al., 2022). Therefore, quantitatively assessing the overall resilience of cities from the perspectives of economy, society, culture, institutions, ecology, environment, and infrastructure (Lu et al., 2022a; Lin et al., 2022; Zhao et al., 2022), can aid in the construction and planning of urban resilience.

As the essence of increasing comprehensive urban resilience, it is necessary to promote coordination along economic and social development, ecological environment, urban governance, and infrastructure construction. Compared to metropolises in economically developed regions that regard communities as the basic unit of urban resilience (Graham et al., 2016; Bixler et al., 2021; Collier et al., 2013), cities in underdeveloped regions with lower levels of economic development, unfinished infrastructure construction, and weaker social governance are more susceptible to external shocks (Li et al., 2022; Song et al., 2022), while their population density is lower. These cities are frequently located in high-altitude and alpine regions, environmentally fragile locations, and regions with a high frequency of geological disasters (Arifin, 2022), and their urban systems are extremely susceptible to severe damage from natural disasters, climate change, and epidemics (Dobson, 2017; Wu et al., 2022). Consequently, it is of the utmost importance to conduct a complete quantitative evaluation of urban resilience in underdeveloped regions and to investigate ways to strengthen urban resilience with this support.

The Sichuan-Tibet Railway is a significant project for China to maintain national unity, enhance national cohesion, and promote economic development and social stability in Western Sichuan and Tibet's underdeveloped regions. The majority of the cities along its route are located in high-altitude and alpine regions, as well as minority gathering areas, which are constrained by the natural environment. The economic development and spatial evolution patterns of Chengdu, located at the eastern terminus of the railroad, differ significantly from those of other cities. The building and inauguration of the railroad and the influx of external resources have, on the one hand, contributed to the local economic and social development and, on the other hand, posed new difficulties to their urban resilience. Consequently, this study selects six typical cities and states along the Sichuan-Tibet Railway, namely Lhasa, Lhoka, Nyingchi, Qamdo, Garzê Tibetan Autonomous Prefecture, and Ya'an, combines the TOPSIS entropy weight method and coupled coordination model to quantitatively assess and compare the comprehensive urban resilience and coordination degree during 2015–2020 from economic resilience, social resilience, environmental resilience, and infrastructure resilience. Using Pearson correlation analysis and gray correlation analysis, this study analyzes the primary factors influencing urban resilience. It then employs a three-dimensional evaluation model to study and evaluate the development state and evolution pattern of urban resilience. The study provides a new comprehensive urban resilience evaluation system that can be used to explore the path of resilience evolution and to introduce resilience construction in underdeveloped regions of China and elsewhere.

The following sections comprise the remainder of this study: The "Literature Review" section reviews existing studies on urban resilience evaluation and analyzes the major methodological approaches to comprehensive urban resilience evaluation. The "Data" section describes the basic overview of the research subjects and the meaning and sources of the research indicators. The "Methodology" section introduces the framework for the comprehensive evaluation and analysis methods used in this study. The "Results" presents the outcomes of the comprehensive evaluation, coupled coordination analysis, and correlation analysis. The "Discussion" section discusses the results and the evolution of urban resilience. The "Conclusion" section summarizes the study's key findings, ramifications, and limitations.

2 Literature review

The concept of urban resilience derives from engineering and ecological resilience (Holling, 1973; Liao, 2012). Its definition is flexible and diverse (Meerow et al., 2016), generally referring to the defense, adaptation, and transformation capacity of urban composite systems in response to a variety of natural and man-made disaster disturbances (Pickett et al., 2004; Mou et al., 2021). The application of scientific and systematic evaluation criteria to quantify urban resilience can, on the one hand, enrich the theory of resilience and aid in the study of the development path of resilient cities (Ahern, 2011; Brown et al., 2012), and on the other hand, provide macro guidance for the practice of resilient city planning and construction.

Although the current research on urban resilience theories, principles, and characteristics has reached a relatively mature stage, the operational dimensions lack a scientific, consistent, and systematic evaluation methodology. Existing resilience evaluation studies predominantly begin from a single perspective, such as urban disaster preparedness and resilience under the influence of natural disasters (Capozzo et al., 2019; Liu et al., 2022) and climate evolution (Leichenko, 2011; Feldmeyer et al., 2019), as well as environmental resilience (Doherty et al., 2016; Bao et al., 2022), energy resilience (Sharifi and Yamagata, 2016), transportation resilience (Faturechi and Miller-Hooks, 2015; Tang et al., 2020), and infrastructure resilience (Alizadeh and Sharifi, 2020). Among them, Wang et al. (2023) assess the resilience of ecological networks in urban agglomerations from the perspective of robustness and redundancy balance. Tang proposed the Bayesian Network Model (BNM) to quantitatively evaluate the resilience of urban transportation systems by combining different factors in the design, construction, operation, management, and innovation phases. Another portion of the studies primarily takes communities as the evaluation objects and investigates community disaster preparedness and resilience (Jordan and Javernick-Will, 2013; Sharif, 2016). Cimellaro et al. (2016) proposed the PEOPLES assessment model based on seven dimensions of community resilience, including population and demographics, environmental and ecosystem, organized governmental services, physical infrastructures, lifestyle and community competence, economic development, and social-cultural capital. The model became one of the main frameworks for quantitatively measuring community resilience. As cities are complex systems, a single perspective evaluation system cannot assess all aspects of urban resilience, including economic, social, cultural, environmental, institutional, and infrastructure resilience. Therefore, a more systematic way of thinking and approach is required for city-based resilience evaluation.

Existing comprehensive urban resilience evaluation system construction concepts several types. Among them, some scholars take the basic constituent elements of cities as the main metric aspects of urban resilience, such as economic resilience, social resilience, organizational resilience, institutional resilience, ecological resilience, and infrastructure resilience, etc., and use them to establish an indicator system (Joerin et al., 2014; Song et al., 2018). Four subsystems, including economic, social, environmental, and infrastructure, are covered by a multidimensional and comprehensive urban resilience assessment model that is based on the system dynamics model (Datola et al., 2022). Numerous quantitative studies of cities or urban agglomerations in China also categorize urban resilience into these four categories (Lu et al., 2022b; Shen et al., 2022; Xia and Zhai, 2022), or replace environmental resilience with ecological resilience. Additionally, some studies have the assessment system take into account institutional (Zhao et al., 2022), demographic (Ye et al., 2022), and technical (Lu et al., 2022a) variables. For instance, Zhao established five levels of indicators combined with the barrier degree, including economic, social, institutional, environmental, and infrastructure. In general, these comprehensive resilience assessment techniques are comparable to conventional urban evaluation techniques, typically employed in current research.

Moreover, some scholars assess the resilience, redundancy, wisdom, rapidity, and other capacity characteristics of cities (Parsons and Morley, 2017), such as Heeks and Ospina (2019) establishing two types of indicator systems, including functional characteristics and enabling characteristics, and combining social equity elements to assess the urban resilience of developing countries. Such evaluation methods are more closely integrated with resilience theory. In addition, other Scholars start from the staging process of urban development, such as resistance (Bruneau et al., 2003), adaptation, and recovery. For instance, Bozza et al. (2017) presented a time-series-based independent, comprehensive quantitative evaluation methodology, which can simulate the probability of occurrence and damage state of urban disasters at different stages and uncover shortcomings in the resilience construction process, and permit targeted adjustments.

In conclusion, the establishment of a quantitative urban resilience evaluation system need to be based on the characteristic elements of urban resilience in the resilience theory, take into account different aspects of urban development to establish a systematic and comprehensive index system, and comprehend the dynamic nature of urban evolution and the differences between cities. This study, therefore, adopts an evaluation system based on the criteria of urban elements, including economic and social, ecological and environmental, and infrastructural elements. Most current resilience assessment studies concentrate on examining the features of integrated urban resilience's regional and temporal distribution, as well as the determining influence of each element on integrated urban resilience. This study examines these factors with the TOPSIS model and correlation analysis. In order to analyze the balance and coordination state among the urban resilience subsystems, this study also includes a coupled coordination analysis. Additionally, since the majority of underdeveloped regions are still in the early stages of resilience construction, this study builds a multidimensional model to illustrate the evolution trend of each city's comprehensive resilience. This model makes the presentation of the analysis results more comprehensible and convincing and offers recommendations for the ensuing resilience building of cities.

3 Data

3.1 Study object

Sichuan-Tibet Railway connects China's Sichuan Province and Tibet Autonomous Region, beginning in Chengdu (Sichuan) in the east and ending in Lhasa (Tibet) in the west, with an operating mileage of 1567.33 km, consisting of three parts. The Chengdu-Ya'an section is located in the Chengdu Plain, and opened for operation in 2018, with a total length of 140 km and a total of 11 stations. The Ya'an-Nyingchi segment traverses the Hengduan Mountains, whose topography, geology, climate, and other variables make building exceedingly challenging. The stretch from Lhasa to Nyingchi is situated in the midst of the Tibetan plateau and has a total length of 403 km. Construction began in June 2015 and was completed in June 2021. The Sichuan-Tibet Railway passes through Lhasa, Lhoka, Nyingchi, Qamdo, Garzê Tibetan Autonomous Prefecture, Ya'an, and Chengdu from west to east. Among them, Chengdu is one of the seven megacities in China with a high level of economic and social development and does not belong to the category of underdeveloped areas. Therefore, the other six cities and states are selected as the study objects in this study (Figure 1).

3.2 Study indicators

Based on pertinent domestic and international studies, this study classifies urban resilience into four aspects: economic resilience, social resilience, environmental resilience, and infrastructure resilience, and proposes an index system following these classifications. Among them, economic resilience reflects the level of economic and industrial development and the capacity to withstand economic risks, including indicators related to the national economy, industry, finance, banking, and urbanization levels. Social resilience reflects the living standard of residents and the level of urban social services, including indicators related to income, consumption, savings, and public service levels. Environmental resilience reflects the level of urban ecological services and environmental health, including indicators related to air quality, urban greening, and environmental hygiene. Infrastructure resilience reflects the efficiency of urban infrastructure development and resource use, including indicators related to transportation, water, and gas supply. The majority of the data used in this study come from the 2015–2020 China Urban Statistical Yearbook and the China Urban Construction Statistical Yearbook. The remaining data come from the statistical yearbooks of

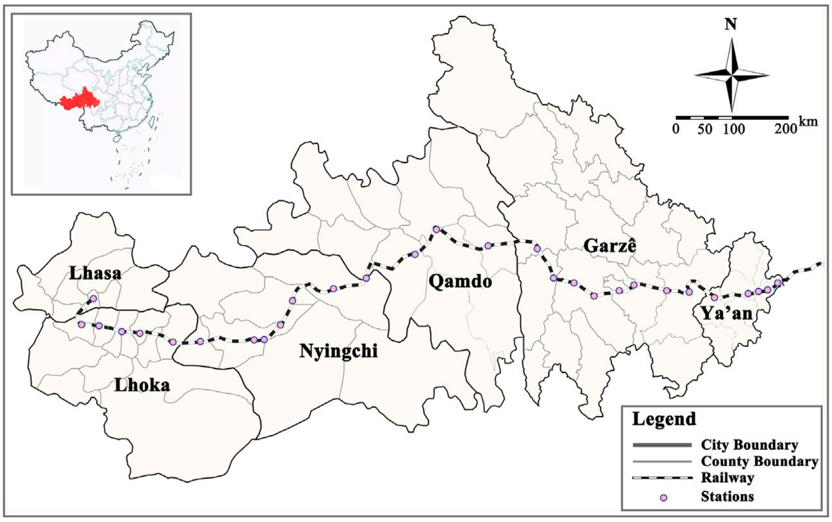

FIGURE 1
Sichuan-Tibet Railway and six cities (states) as study objects. GS (2022) 1873.

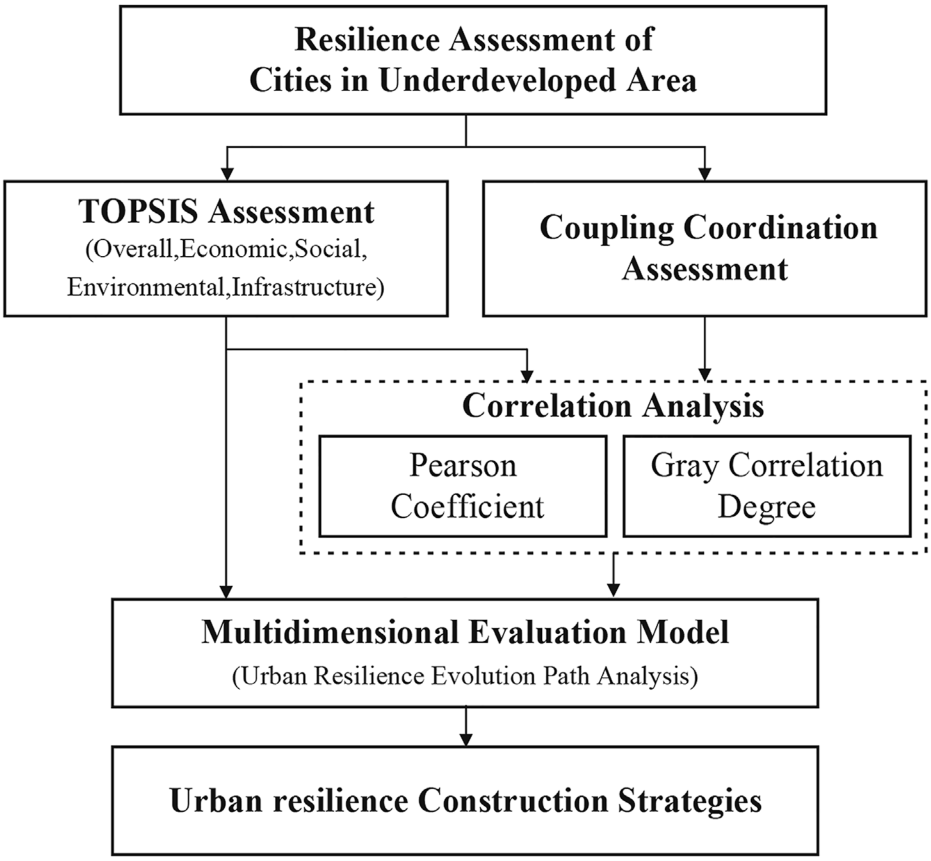

FIGURE 2
Framework for quantitative evaluation methodology.

TABLE 1 Evaluation indicators and weights.

Aspects	Indicators	Entropy	Utility value	Weight
Economic Resilience (0.2814)	GDP *per capita* (+)	0.919	0.081	0.0514
	GDP growth (+)	0.978	0.022	0.0142
	Share of tertiary industry (+)	0.965	0.035	0.0221
	Government revenue *per capita* (+)	0.942	0.058	0.0363
	Bank loan *per capita* (+)	0.929	0.071	0.0448
	Fixed asset investment *per capita* (+)	0.919	0.081	0.0509
	Share of tourism revenue (−)	0.974	0.026	0.0167
	Urbanization rate (+)	0.929	0.071	0.0451
Social Resilience (0.3114)	Bank balance *per capita* (+)	0.886	0.114	0.0719
	Disposable income *per capita* (+)	0.962	0.038	0.023
	Urban-rural income ratio (−)	0.983	0.017	0.0106
	Consumer price index (−)	0.975	0.025	0.0156
	Engel coefficient (−)	0.952	0.048	0.03
	Medical resources (+)	0.924	0.076	0.0483
	Compulsory education resources (+)	0.965	0.035	0.0222
	Mobiles *per capita* (+)	0.896	0.104	0.0658
	Pension insurance coverage (+)	0.964	0.036	0.024
Environmental Resilience (0.1841)	Park green space *per capita* (+)	0.925	0.075	0.0471
	Green coverage in the built-up area (+)	0.963	0.037	0.0232
	Average PM2.5 concentration (−)	0.977	0.023	0.0144
	Average air quality index (−)	0.963	0.037	0.0234
	Domestic waste disposal rate (+)	0.969	0.031	0.0197
	Sewage disposal rate (+)	0.988	0.012	0.0078
	Road cleaning rate (+)	0.923	0.077	0.0485
Infrastructure Resilience (0.2231)	Water supply penetration rate (+)	0.969	0.031	0.0197
	Gas supply penetration rate (+)	0.956	0.044	0.0276
	Road area *per capita* (+)	0.923	0.077	0.0484
	Road freight volume (+)	0.918	0.082	0.0517
	Density of water and drainage pipes (+)	0.971	0.029	0.0182
	Share of infrastructure land (+)	0.909	0.091	0.0575

Sichuan Province and Tibet Autonomous Region, cities and counties yearbooks, and the national economic statistical bulletins issued by city statistical bureaus. This study uses the interpolation approach to complete the few missing data (Figure 2).

Before undertaking an urban resilience evaluation, it is necessary to give weights to the selected indicators. Using information entropy, the Entropy Weight Method approach determines the coefficient of variation of indicators (Xu et al., 2018). The smaller the information entropy, the greater the coefficient of variation and the greater the weight of indicators. This strategy can avoid the apparent subjectivity of indicators and is more appropriate for the assignment of indicators for resilience evaluation. Table 1 displays the indicator weights derived from the entropy weighting method.

4 Methodology

This study presents a framework for quantitative evaluation that incorporates the TOPSIS approach, a linked coordination model, and correlation analysis. First, the overall urban resilience and economic, social, environmental, and infrastructure resilience are assessed by the TOPSIS method, while the degree of coordination of urban resilience is assessed by the coupled coordination model. On this basis, the degree of connection among the influencing factors of urban resilience is explored by correlation analysis, and the calculation results are combined with the resilience evaluation results to develop a multidimensional model to analyze urban resilience. Work is performed to aid urban resilience planning and construction.

4.1 Topsis

In this study, TOPSIS approach (Technique for Order Preference by Similarity to an Ideal Solution) is utilized as the major method for analyzing urban resilience in underdeveloped locations (Lai et al., 1994; Olson, 2004), which is essentially a relatively objective method for determining the relative proximity of each object to the optimal solution. Its computation technique consists of two stages, first calculating the normalized weighted matrix to determine the ideal and inferior options.

$$V_{ij} = X_{ij} \times W_i$$

$$V_i^+ = \left\{ maxV_{ij} \middle| i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \right\}$$

$$V_i^- = \left\{ minV_{ij} \middle| i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \right\}$$

where X is the normalization matrix and W is the weight of the indicators using the entropy value approach. V_{ij} is the value of the indicator j of the object i. V_i^+ and V_i^- are the maximum and minimum of the values.

After obtaining the optimal and inferior solutions, the Euclidean distance and the relative closeness between the evaluation object and the optimal and inferior solutions must be determined.

$$D_j^+ = \sqrt{\sum_{i=1}^{m} \left(V_{ij} - V_i^+ \right)^2}$$

$$D_j^- = \sqrt{\sum_{i=1}^{m} \left(V_{ij} - V_i^- \right)^2}$$

$$T_j = \frac{D_j^-}{D_j^+ \times D_j^-}$$

where, D_j^+ is the distance between the evaluation object and the ideal solution, D_j^- is the distance between the evaluation object and the worst solution, T_j is the relative proximity to the optimal solution, and has a range of values between 0 and 1. The greater the relative proximity, the more resilient the city. When it is larger than 0.6, it implies that the level of urban resilience is high; when it is less than 0.3, it suggests that the level of urban resilience is low.

4.2 Coupled coordination degree

In addition to assessing the level of urban resilience, the degree of coordinated development of each resilience must also be evaluated. Therefore, we employ the coupled coordination degree model (CCDM) for our research (Wang X et al., 2022). The degree of coupling reflects the degree of dependency and mutual constraints among multiple systems. And the degree of coordination relates to the magnitude of benign coupling in the linked interaction relationship, which might indicate whether coordination is excellent or poor. The following model can be used to depict the coupling degree model of numerous system interactions.

$$C_n = \left\{ \frac{(u_1 \cdot u_2 \cdots\cdots u_n)}{\prod (u_1 + u_2)} \right\}^{1/n}$$

$$u_i = \sum_{i=1}^{m} w_{ij} u_{ij}, \sum_{j=1}^{m} w_{ij} = 1$$

where C_n is the coupling degree of the n-element system. Respectively, u_n is the contribution of the n-th subsystem to the total system order. In the ordered calculation, u_{ij} is the normalized value of the j-th indicator in the i-th subsystem. And using the entropy weight method, w_{ij} is the weight of the j-th indicator in the i-th subsystem. In some instances, the coupling index is difficult to accurately reflect the overall efficiency and synergy of the subsystem, and the extreme value calculation is dynamic and unbalanced. On this premise, the degree of coupling coordination can be computed using the following formula.

$$D = (C \cdot T)^{1/2}, T = au_1 + bu_2 + \cdots\cdots + iu_n$$

where C is the coupling degree and D is the coupling coordination degree, which is determined to lie between 0 and 10 and can be divided into six coordination levels (Table 2). T is a comprehensive evaluation index of the level of coupled and coordinated development. u_n designating the n-th system, a–i refer to the relative weights of each system.

TABLE 2 Standard of coupling coordination degree level.

D	Level	D	Level
$D < 1$	Severely uncoordinated	$5 \le D < 7$	Elementary coordinated
$1 \le D < 3$	Medium uncoordinated	$7 \le D < 9$	Medium coordinated
$3 \le D < 5$	Mildly uncoordinated	$D > 9$	Superiorly coordinated

4.3 Correlation analysis

This study uses the Pearson correlation coefficient to compare and analyze the correlation between four urban resilience influencing factors and urban resilience indicators, to examine and evaluate the degree of association between different factors and indicators and the level of urban resilience in underdeveloped areas, as well as to test the rationality of indicator selection. Following is the precise calculating formula.

$$\rho_{x,y} = \frac{\sum (X - \bar{X})(Y - \bar{Y})}{\sqrt{\sum (X - \bar{X})^2 + \sum (Y - \bar{Y})^2}}$$

where X and Y are the values of the two variables, respectively, and $\rho_{x,y}$ is correlation coefficients with values ranging from [−1, 1]. When the value is close to 1, the two variables exhibit a strong positive correlation, when it is close to −1, the two variables exhibit a strong negative correlation, and when the value is closer to 0, the correlation between the two variables is weaker.

Pearson correlation coefficient can effectively reflect the correlation degree between indicators (Yang et al., 2022), and gray correlation analysis

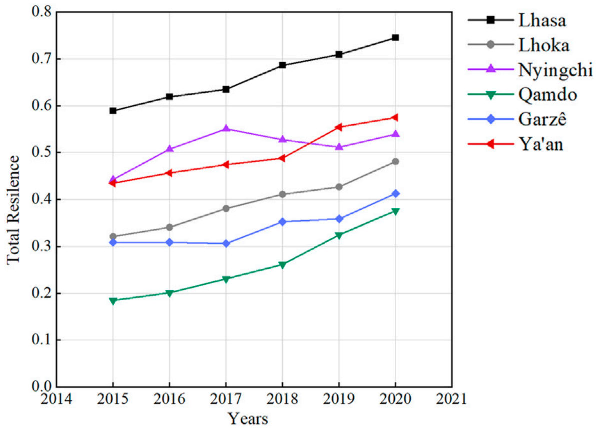

FIGURE 3
Trends in the evolution of the overall resilience level of study objects.

can be used to calculate the correlation degree between indicators and overall toughness level. Gray correlation analysis is a method for analyzing the correlation degree between factors of the system by comparing the similarity degree of data series geometric relationship and curve geometry (Liu and Yu, 2007). Following is the precise calculating formula.

$$\gamma_i(\mathbf{k}) = \frac{\min\limits_i \min\limits_k |x_0(k) - x_i(k)| + \mu \cdot \max\limits_i \max\limits_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \mu \cdot \max\limits_i \max\limits_k |x_0(k) - x_i(k)|}$$

where γ_i is the grey correlation degree of factor i and takes values from 0–1. And μ is the resolution factor and takes values from 0–1. The smaller the resolution coefficient, the larger the disparity between the correlation coefficients and the better the capacity to differentiate, which is typically 0.5.

5 Results

5.1 Urban resilience evaluation

Using the TOPSIS entropy weighting approach, we calculate the overall resilience of the six cities and states along the Sichuan-Tibet Railway (Figure 3). During the period 2015–2020, the overall resilience of each city exhibits an upward trend. This indicates that the national policy support and the influx of external resources brought by the major project of the Sichuan-Tibet Railway have contributed to the development of towns and cities in underdeveloped areas along the route, regardless of whether or not the construction of the railroad begins. Lhasa has the highest overall resilience and has been at a high resilience development level since 2016. Nyingchi and Ya'an have the same overall resilience at the start of the study, but Nyingchi's resilience level is hindered after a high rate of increase, while Ya'an's resilience level steadily increases and gradually surpasses

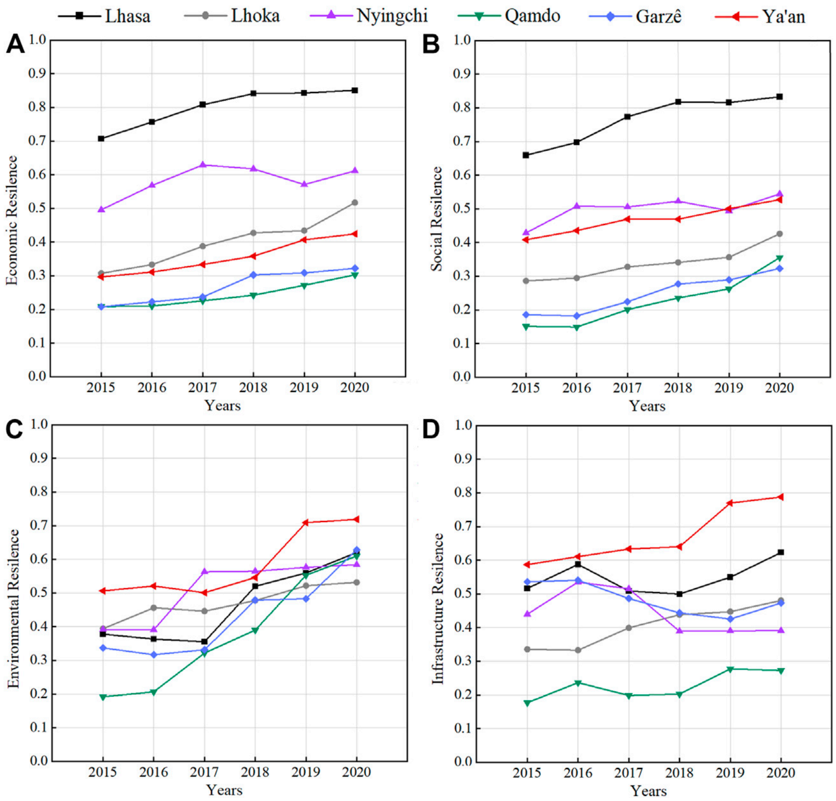

FIGURE 4
Trends in the evolution of various aspects of resilience levels. (A) Economic resilience. (B) Social resilience. (C) Environmental resilience. (D) Infrastructure resilience.

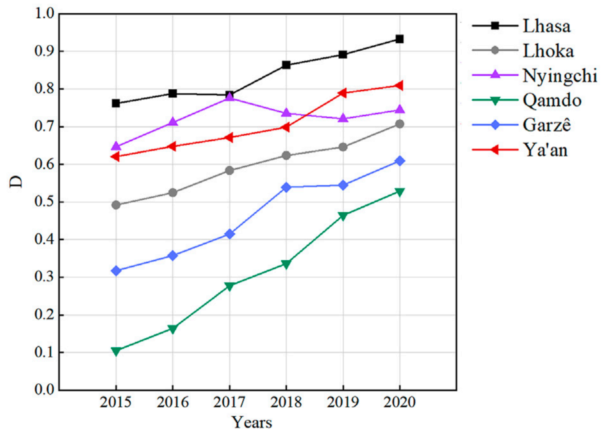

FIGURE 5
Trends in the evolution of resilience coupling coordination.

Nyingchi. Lhoka and Garzê have a similar process of urban resilience improvement, while Lhoka, which is in the railroad constriction zone, has a higher growth rate of resilience. Qamdo has the lowest level of resilience, but its overall resilience has increased throughout the study period, rising from low to medium resilience.

Figure 4 depicts the outcomes of the analysis of urban resilience levels in several economic, social, environmental, and infrastructure aspects across six cities and states. During the period 2015–2020, the economic and social resilience of each city has a consistently increasing trend, the environmental resilience demonstrates an inconsistent upward jump trend, and the infrastructure resilience fluctuates with clear city-to-city variances. Lhasa has the strongest economic and social resilience among all cities, and its environmental resilience has risen dramatically since 2017. Ya'an has greater environmental and infrastructure resilience than the other two aspects. Nyingchi shows a trend of stagnant development after a rapid increase in all resilience, and economic and infrastructure resilience has even declined. And Lhoka is at a medium level of development in all resilience, with a stable overall growth trend. Qamdo and Garzê, as cities without complete railroad projects, exhibit comparable tendencies in the evolution of various forms of resilience, with environmental resilience increasing more rapidly than infrastructure resilience, which remains essentially unchanged or declines somewhat.

5.2 Resilience coupling coordination

In the coupled coordination model computation, we assessed the total degree of coordination between the aspects of resilience and the degree of coordination between the two dimensions. In general (Figure 5), the overall coupling coordination degree of urban resilience for each city and state steadily increases and follows the same evolutionary pattern as the overall urban resilience. The coupling coordination degree of Lhasa is also the highest among the cities and provinces, essentially maintaining the intermediate and high-quality coordination status. Qamdo and Garzê are far behind the other cities, but their rate of improvement is faster, and they have gradually developed from a dysfunctional status to a preliminary coordination status. The evolutionary trends of Lhoka, Nyingchi, and Ya'an are similar. The coupling coordination degree in Nyingchi has gradually declined since 2017, which is consistent with the evolutionary characteristics of its urban resilience.

On this basis, we aggregate the economic, social, environmental, and infrastructure resilience and calculate their degree of linkage coordination (Figure 6). Comparatively, the evolution of the degree of coupling coordination between economic and social resilience is relatively similar, whereas the evolution of environmental and infrastructure resilience is more independent, indicating that the degree of connection between economic and social development may be closer than the other two aspects. Moreover, the evolution of the degree of coupling and coordination of each city's resilience also varies. For instance, the coupling coordination among economic, social, and infrastructure resilience in Lhasa is significantly higher than in other cities, maintaining a high-quality coordination status, whereas the coupling coordination with environmental resilience shows a phased increase. The coupling coordination among social, environmental, and infrastructure resilience in Ya'an is significantly higher, whereas the coordination degree of economic resilience is relatively low. In Qamdo, the coupling coordination among social, environmental, and infrastructure resilience is significantly higher, whereas the coordination degree of economic resilience in Garzê has the highest degree of coupling coordination between environmental and infrastructure resilience, while Qamdo has the fastest degree of coupling coordination between social resilience and environmental resilience.

5.3 Resilience correlation

The analysis of urban resilience trends and coupling coordination reveals that the development and evolution of economic resilience and social resilience are relatively similar to the evolution of urban resilience as a whole, whereas environmental and infrastructure resilience reflects unique characteristics. We can therefore validate them using Pearson correlation analysis and gray correlation analysis. Figure 7 displays the results of the Pearson correlation coefficient calculation, which demonstrates that economic and social elements have a stronger relationship with urban resilience. Moreover, the correlation coefficients between economic and social resilience are extremely high, indicating that they interact closely. The correlation between environmental and infrastructure resilience and other resilience factors is weak, suggesting that their roles are relatively independent of overall urban resilience. Figure 8 depicts the findings of additional correlation analysis among the indicators. Among all evaluation indicators, those about city finances, residents' lives, and social services have the highest correlation with city resilience. And there are mostly certain connections between city economic and social resilience indicators. The majority of urban environmental and infrastructure resilience indicators do not correlate significantly with economic and social resilience indicators, and their internal correlation is similarly modest.

By doing a gray correlation study between each indicator and urban resilience as a whole, we may gain a deeper understanding of the magnitude of the driving power of each indicator on the urban resilience of underdeveloped cities, as detailed in Table 3. Indicators related to the urban economy and resident's lives, such as bank deposit balance *per capita* and GDP *per capita*, as well as

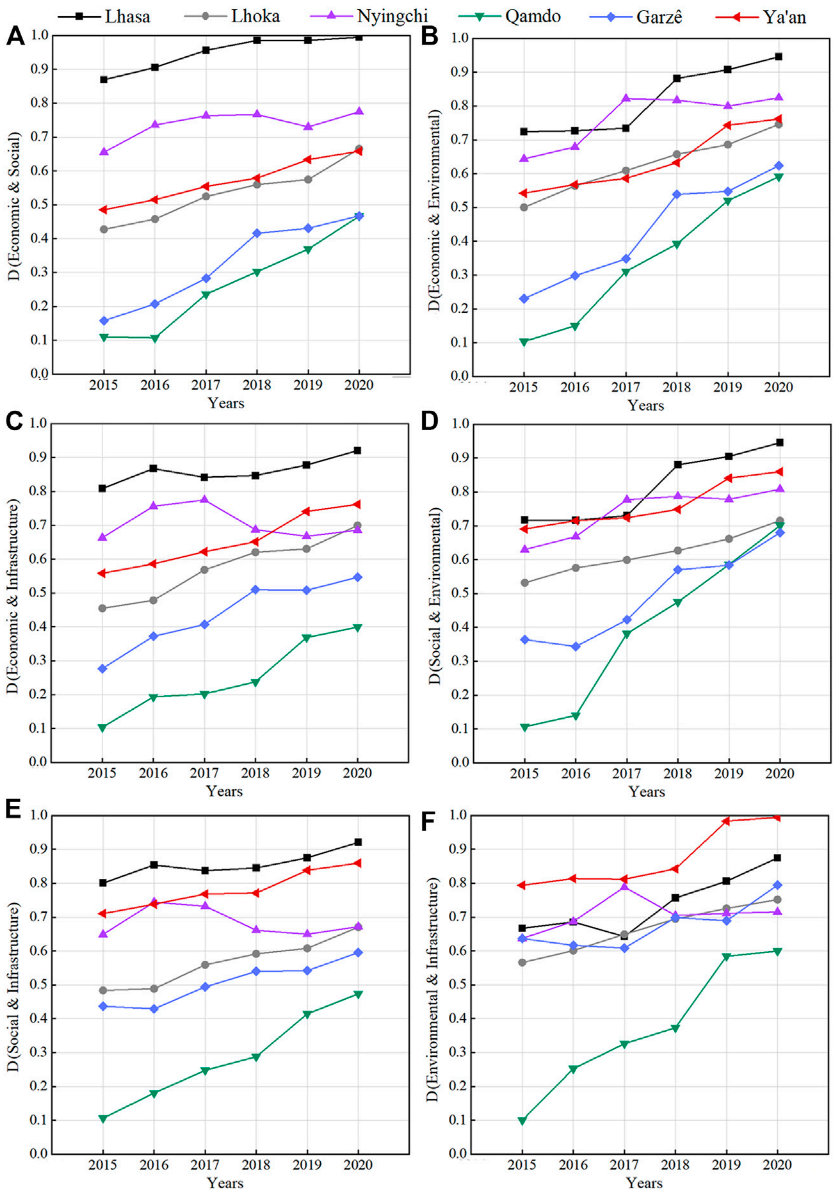

FIGURE 6
Trends in the evolution of aspects of resilience coupling coordination. **(A)** Economic & social. **(B)** Economic & environmental. **(C)** Economic & infrastructure. **(D)** Social & environmental. **(E)** Social & infrastructure. **(F)** Environmental & infrastructure.

indicators related to public services, such as the number of mobiles *per capita*, have a higher degree of correlation with urban resilience. Indicators of urban environmental resilience and infrastructure resilience have a relatively lower correlation with urban resilience, which is essentially consistent with the results.

6 Discussion

6.1 Influencing factors of urban resilience

The urban resilience of cities in underdeveloped regions is inadequate, but under the influence of significant construction projects and national aid policies, diverse resources pour fast into these cities, resulting in constant improvement. Lhasa, Lhoka, Nyingchi, and Ya'an, in which railway subjects are under construction or already in operation, have significantly higher urban resilience (especially economic and social resilience) than Qamdo and Garzê, in which railway construction is not yet complete. While their urban resilience tends to increase significantly at the beginning of the railroad construction and opening to traffic, such as Nyingchi and Lhoka at the beginning of the railway operation period. However, not all indicators of urban resilience maintain continuous growth after the construction or operation of major projects, such as Nyingchi after a period of railroad construction (2017–2020), when all its resilience levels begin to decline and are difficult to improve further. Whereas for other cities and states, economic, social, environmental, and

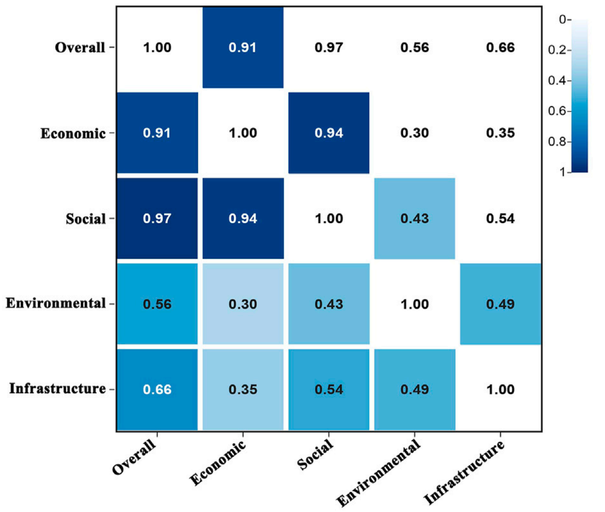

FIGURE 7
Pearson correlation coefficient for each aspect.

infrastructure factors do not have the same influence on urban resilience. Consequently, based on the comprehensive assessment of urban resilience, the effect of each component on the overall resilience of cities should be assessed separately in order to explore the characteristics and trends of urban resilience's evolution in a focused manner.

6.1.1 Economic resilience

The degree of urban economic development is the basis of sustainable urban development and a crucial determinant of urban resilience (Sabatino, 2016; Feng et al., 2023). When cities resist external disturbances, greater economic resilience enables them to accumulate sufficient material reserves and maintain basic operational efficiency to quickly compensate for the direct losses and indirect impacts of the disturbances (Wang S et al., 2022). And after the external disturbances have subsided, cities with greater economic resilience can also establish themselves more quickly, allowing them to quickly regain or even surpass their prior development position.

Improving the economic resilience of cities in underdeveloped regions is essential for enhancing the living standards of residents, promoting harmonious and stable social development, enhancing the living environment, and promoting the construction of urban and rural infrastructure, thereby making these cities and towns less susceptible to collapse in the face of external disturbances. For cities and states along the Sichuan-Tibet Railway, differences in economic resilience are caused by factors such as urban location, attributes, and transportation infrastructure conditions. Regardless of whether it is Lhasa with high resilience or other cities transitioning from low to medium resilience, economic development is steadily improving. With the completion and gradual opening of the Sichuan-Tibet Railway, external human, logistics, information, technology, and capital flows will accelerate into the surrounding towns and cities, thereby accelerating the economic development of these cities, which must adhere to a path of sustainable development and prevent structural disorders and ecological damage caused by excessive urban development.

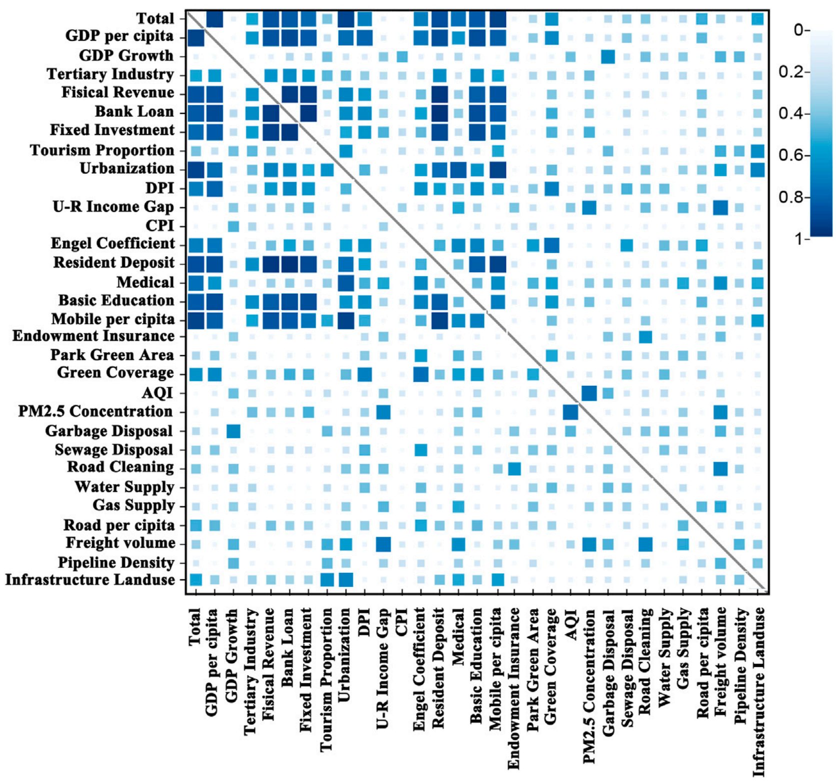

FIGURE 8
Pearson correlation coefficient for each indicator.

TABLE 3 Grey correlation of each indicator.

Indicator	*Correlation*	Rank	Indicator	*Correlation*	Rank
Bank balance *per capita*	0.89	1	Road freight volume	0.786	16
GDP *per capita*	0.88	2	Average air quality index	0.786	17
Urbanization rate	0.858	3	Gas supply penetration rate	0.784	18
Mobiles *per capita*	0.857	4	GDP growth	0.78	19
Compulsory education resources	0.856	5	Government revenue *per capita*	0.772	20
Medical resources	0.843	6	Share of infrastructure land	0.771	21
Disposable income *per capita*	0.84	7	Density of water & drainage pipes	0.762	22
Sewage disposal rate	0.83	8	Park green space *per capita*	0.75	23
Government revenue *per capita*	0.823	9	Engel coefficient	0.738	24
Share of tertiary industry	0.82	10	Road area *per capita*	0.736	25
Government revenue *per capita*	0.82	11	Road cleaning rate	0.733	26
Fixed asset investment per cipita	0.81	12	Share of tourism revenue	0.728	27
Water supply penetration rate	0.809	13	Consumer price index	0.714	28
Green coverage in built-up area	0.805	14	Urban-rural income ratio	0.713	29
Domestic waste disposal rate	0.8	15	Average PM2.5 concentration	0.682	30

6.1.2 Social resilience

The social system of a city is a complex system comprised of numerous areas of life, healthcare, education, management, and culture, and its level of resilience is an essential component of urban overall resilience (Maclean et al., 2014; Saja et al., 2019). A higher level of social resilience implies, on the one hand, that urban residents have a higher standard of living and that households and communities have sufficient resources and capacity to withstand losses from external disturbances, on the other hand, that cities have a higher level of public services to meet the sharply rising demand for social services and grassroots management during external disturbances.

The low degree of social development is one of the defining characteristics of underdeveloped cities, and the big wealth disparity and major public service gaps pose significant threats to the development of urban resilience. In the event of severe natural disasters or outbreaks of infectious diseases, it will be difficult to mobilize social resources, and without the timely influx of external resources, significant societal losses will occur (such as the Wenchuan and Ya'an earthquakes). Due to this, the construction of the Sichuan-Tibet Railway had the most evident impact on the social resilience of the communities along the route. After the completion of the large-scale project, the living income and employment level of residents in the towns along the route will continue to increase, thereby bolstering social resilience; in the event of external disturbances, external resources can also be imported quickly *via* rail, thereby enhancing the buffer capacity and recovery speed of the cities.

6.1.3 Environmental resilience

The environmental resilience of cities encompasses urban ecology, resources, and environmental health, and is an inherent factor that supports the regular operation and sustainable growth of cities (Alberti and Marzluff, 2004; Perrings, 2006). The maintenance and transformation of urban environmental benefits and urban economic and social development interact in a dynamic equilibrium, and adherence to ecologically coordinated green development is conducive to enhancing the quality of urban economic development, as well as promoting the improvement of the human habitat and the living standards of urban residents (Pickett et al., 2014). Greater environmental resilience can reduce the risk of the spread of infectious diseases in urban areas while also enabling cities to obtain more suitable ecological buffers and a wealthier supply of resources in the face of natural disasters, thereby ensuring that cities can resist disturbances and recover rapidly from them.

Due to a lack of comprehensive social governance capacity and reasonable urban planning, environmental sanitation conditions in underdeveloped regions cannot meet the needs of inhabitants. Nevertheless, the environmental resilience basis of cities varies widely, and climate, geology, hydrology, and resources are all characteristics that have the potential to become significant limiting factors for their development. The development of large-scale projects in underdeveloped regions would, on the one hand, stimulate the expedited construction of sanitation projects and increase the quality of urban sanitation, but it will also represent a significant threat to their delicate urban ecological environment. It is vital to closely regulate the environmental degradation and resource consumption caused by the project's construction, to maintain a balance between economic and environmental benefits, and to support the green and sustainable development of the communities along the route.

6.1.4 Infrastucture resilience

This research focuses primarily on the infrastructure (such as water supply and drainage, power supply and heating, gas, road construction, network communication, etc.) that maintains the operation of cities, and the construction and maintenance of these facilities are closely related to the economic and social development of cities as well as the resource utilization and environmental protection

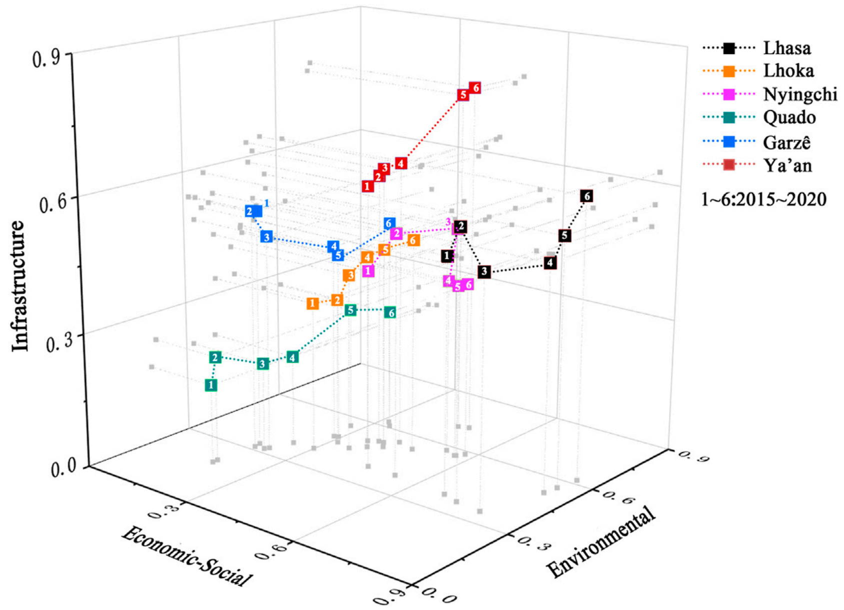

FIGURE 9
Three-dimensional evaluation model of urban resilience.

requirements. Therefore, improving the resilience of urban infrastructure is a process of continuously fulfilling the new demands of urban development, which is typically a sluggish and lagging process. High infrastructure resilience is the fundamental guarantee for urban operation in the face of external shocks (Alderson et al., 2015; Labaka et al., 2016; Liu and Song, 2020), hence urban crises produced by inadequate infrastructure resilience are more severe than those caused by other resilience aspects (e.g., insufficient urban power supply and road damage caused by natural disasters).

Due to the weak economic and social foundations of cities, infrastructure development in underdeveloped regions lags substantially behind that of economically developed regions, yet towns in these regions are also relatively less dependent on infrastructure. The speed of infrastructure construction in cities along the Sichuan-Tibet Railway has accelerated steadily due to the construction of large-scale projects, but this will be a protracted and ongoing process that cannot be completed overnight. To achieve the coordination of urban growth pace and development quality in less-developed areas, it is vital to maintain the synchronization of infrastructure construction with economic and social development and improvement of the human living environment.

6.2 Evolutionary paths of urban resilience

The combination of urban resilience evaluation, coupled coordination degree analysis, and correlation analysis can determine the evolution process and coordination relationship of each dimension of urban resilience. And the multidimensional evaluation model combining economic, social, environmental, and infrastructure can then determine the path and mode of urban resilience evolution from an overall standpoint. Since economic and social resilience are correlated, whereas environmental and infrastructure resilience is rather independent, a three-dimensional model for assessing urban resilience can be developed by incorporating economic-social resilience as one of the dimensions (Figure 9). We categorize the results of the city resilience evaluation into three levels: high resilience (>0.6), medium resilience (0.3–0.6), and poor resilience (0.3) to evaluate the evolution of urban resilience in each dimension. When the economic-social resilience level of a city is significantly lower than the environmental and infrastructure resilience levels, it indicates that economic and social development momentum is insufficient. Therefore, the city should accelerate the introduction of external resources and activate the leading industries in order to accelerate economic and social development. When environmental resilience is significantly lower, it indicates that excessive development and pollution levels are unsustainable. When infrastructure resilience is significantly lower, it indicates that urban infrastructure construction is lagging behind urban development and it is vital to strengthen infrastructure investment and encourage high-quality urban development. When all aspects are maintained at a high level, the economic and social development of a city is coordinated with the urban environment and the construction of infrastructures. It means overall resilience is high.

Figure 10 depicts the evolution of urban resilience development in each city and state along the Sichuan-Tibet Railway. By evaluating the evolution pattern of resilience in various cities and states, we may determine their resilience development path and current state of development and then anticipate and direct their future development.

(1) Lhasa's overall resilience demonstrates a pattern of prioritizing economic development and limiting the improvement of environmental and infrastructure resilience, which then transitions to a sustainable development path of slowing economic and social development and prioritizing environmental and infrastructure construction, and then enters a phase of high resilience development.

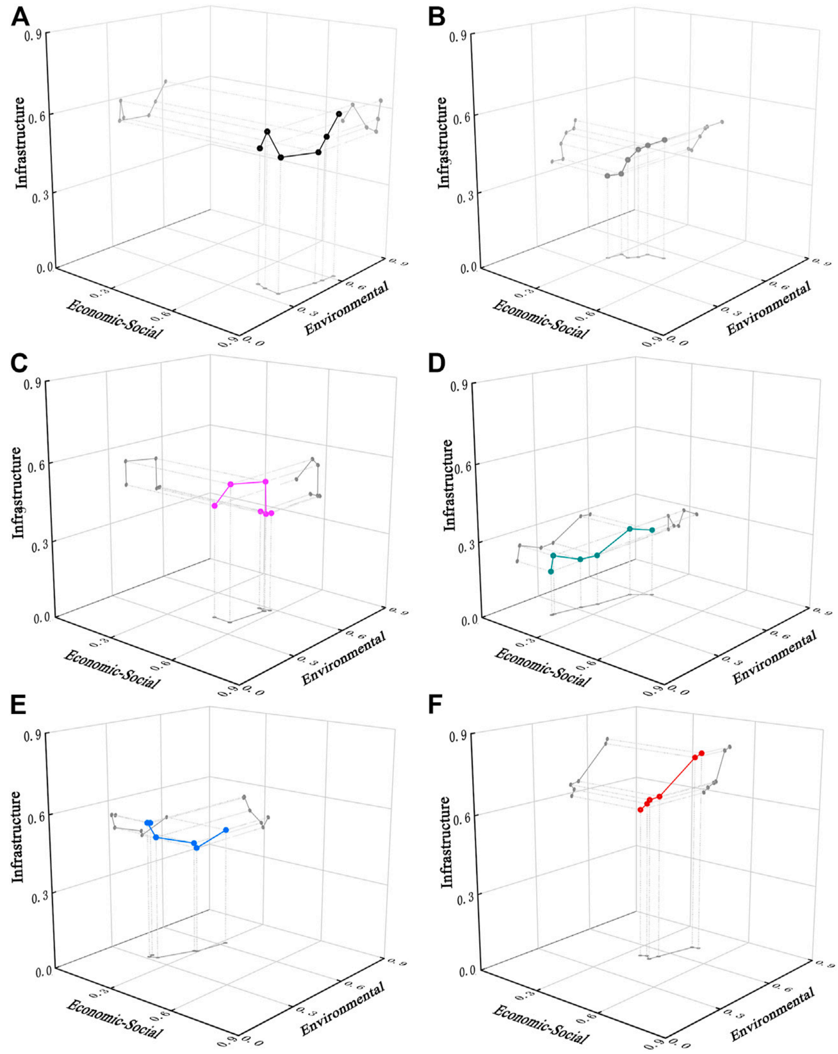

FIGURE 10
Evolutionary paths of urban resilience of each object. **(A)** Lhasa. **(B)** Lhoka. **(C)** Nyingchi. **(D)** Qamdo. **(E)** Garzê. **(F)** Ya'an.

(2) Lhoka remains at the medium resilience development level, with balanced development of all aspects and progressive overall improvement, and moves gradually to the high resilience development level.
(3) Nyingchi's resilience in all dimensions has plateaued after an early period of strong growth, and it is difficult to break past the bottleneck of medium resilience development; the city urgently needs new external development momentum.
(4) Qamdo's urban resilience level exhibits a gradual progression from low resilience to medium resilience, but the resilience foundation is weak and the deficiencies of urban infrastructure construction are evident.
(5) In Garzê, the construction of infrastructure has resulted in the improvement of economic, social, and environmental resilience, but its infrastructure resilience is limited and requires future infrastructure construction improvement to maintain the urban growth trend.
(6) Ya'an's urban resilience demonstrates an opposite evolutionary path to that of Lhasa, with slow growth in economic and social resilience, while environmental and infrastructure resilience has increased significantly, further driving economic and social development and assisting the city in shifting to a high resilience development level.

7 Conclusion

Extremely sensitive to external shocks are cities in underdeveloped locations with severe natural environmental limits and insufficient foundations for their own economic and social growth. How to improve the overall urban resilience and boost the resistance, adaptation, and recovery capacity of at-risk cities is one of the development challenges faced by these cities, and the evaluation and characterization of urban resilience serve as the foundation for the related activity. This study proposes a quantitative evaluation framework that combines the TOPSIS entropy method, coupled coordination model, and correlation analysis to determine the evolutionary path and trend of urban resilience by assessing the resilience of underdeveloped cities and analyzing the coupled coordination relationships between their intrinsic factors. The study's results can aid in clarifying urban development strategies and give quantitative evidence for relevant policy ideas and planning activities.

This study's methodology and findings provide a certain reference value for urban planning work, and its originality is demonstrated primarily in the following. Firstly, this study selects cities in underdeveloped regions as the research objects. Although these cities have a weak resilience foundation, the inner system composition is simpler, and the resilience evolution characteristics are more evident than in developed cities, so it is easy to judge their resilience development pattern and evolution direction. Secondly, this study also combines multiple evaluation and analysis methods. Based on the evaluation and analysis results, explore the internal linkages and the degree of coordination of subsystems. Thirdly, this study proposes a three-dimensional model to determine the development state of urban resilience, from which we can analyze the pattern and development direction of each city's resilience evolution to suggest guiding ideas for various cities. Each city's pattern of resilience evolution and development path can be analyzed, allowing us to suggest guiding principles for its qualities.

The city is a complex large-scale system, and urban resilience is influenced by a variety of internal and external elements, as well as dynamic interactions between subsystems. Simultaneously, the key causes of urban resilience vary from city to city, as do the variables that impede urban development in cities in underdeveloped regions. This paper presents a universal framework for assessing urban resilience in underdeveloped locations, although it has certain practical limits. The evaluation indicators of the study have yet to be further enriched to make them more relevant to underdeveloped regions. Moreover, the linear thinking of the TOPSIS model has some limitations in evaluating the non-linear development process of urban resilience. Therefore, we believe that the research based on this evaluation method must further investigate the interactions of various subsystems and determine the dominant factors affecting urban resilience. When assessing and analyzing the resilience of a specific city, appropriate evaluation indicators and methods must be chosen following the city's characteristics, and the effects of climate, ecology, topography, religion, humanities and other factors must be taken into account. It can make evaluation results and strategies for urban development more targeted. Moreover, future study should also focus on urban resilience prediction and proposes strategies for specific construction aspects.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

RZ: Formal analysis, methodology, and writing. YY: Conceptualization, funding acquisition, and supervision. BW and XL: Review and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Ahern, J. (2011). From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. *Landsc. Urban Plan.* 100 (4), 341–343. doi:10.1016/j.landurbplan.2011.02.021

Alberti, M., and Marzluff, J. M. (2004). Ecological resilience in urban ecosystems: Linking urban patterns to human and ecological functions. *Urban Ecosyst.* 7 (3), 241–265. doi:10.1023/B:UECO.0000044038.90173.c6

Alderson, D. L., Brown, G. G., and Carlyle, W. M. (2015). Operational models of infrastructure resilience. *Risk Anal.* 35 (4), 562–586. doi:10.1111/risa.12333

Alizadeh, H., and Sharifi, A. (2020). Assessing resilience of urban critical infrastructure networks: A case study of ahvaz, Iran. *Sustainability* 12, 3691. doi:10.3390/su12093691

Arifin, B. (2022). Do limited-resource hospitals improve medical care utilization in underdeveloped areas: Evidence from mobile hospitals in Indonesia. *Value Health Regional Issues* 30, 67–75. doi:10.1016/j.vhri.2021.12.002

Bao, Z., Shifaw, E., Deng, C., Sha, J., Li, X., Hanchiso, T., et al. (2022). Remote sensing-based assessment of ecosystem health by optimizing vigor-organization-resilience model: A case study in fuzhou city, China. *Ecol. Inf.* 72, 101889. doi:10.1016/j.ecoinf.2022.101889

Bixler, R. P., Yang, E., Richter, S. M., and Coudert, M. (2021). Boundary crossing for urban community resilience: A social vulnerability and multi-hazard approach in austin, Texas, USA. *Int. J. Disaster Risk Reduct.* 66, 102613. doi:10.1016/j.ijdrr.2021.102613

Bozza, A., Asprone, D., Parisi, F., and Manfredi, G. (2017). Alternative resilience indices for city ecosystems subjected to natural hazards. *Computer-Aided Civ. Infrastructure Eng.* 32 (7), 527–545. doi:10.1111/mice.12275

Brown, A., Dayal, A., and Rumbaitis Del Rio, C. (2012). From practice to theory: Emerging lessons from asia for building urban climate change resilience. *Environ. Urbanization* 24 (2), 531–556. doi:10.1177/0956247812456490

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., et al. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthq. Spectra* 19 (4), 733–752. doi:10.1193/1.1623497

Capozzo, M., Rizzi, A., Cimellaro, G. P., Domaneschi, M., Barbosa, A., and Cox, D. (2019). Multi-hazard resilience assessment of a coastal community due to offshore earthquakes. *J. Earthq. Tsunami* 13, 1950008. doi:10.1142/S1793431119500088

Cheng, T., Zhao, Y., and Zhao, C. (2022). Exploring the spatio-temporal evolution of economic resilience in Chinese cities during the COVID-19 crisis. *Sustain. Cities Soc.* 84, 103997. doi:10.1016/j.scs.2022.103997

Cimellaro, G. P., Renschler, C., Reinhorn, A. M., and Arendt, L. (2016). Peoples: A framework for evaluating resilience. *J. Struct. Eng.* 142 (10), 04016063. doi:10.1061/(asce)st.1943-541x.0001514

Collier, M. J., Nedović-Budić, Z., Aerts, J., Connop, S., Foley, D., Foley, K., et al. (2013). Transitioning to resilience and sustainability in urban communities. *Cities* 32, S21–S28. doi:10.1016/j.cities.2013.03.010

Datola, G., Bottero, M., De Angelis, E., and Romagnoli, F. (2022). Operationalising resilience: A methodological framework for assessing urban resilience through system dynamics model. *Ecol. Model.* 465, 109851. doi:10.1016/j.ecolmodel.2021.109851

Dianat, H., Wilkinson, S., Williams, P., and Khatibi, H. (2022). Choosing a holistic urban resilience assessment tool. *Int. J. Disaster Risk Reduct.* 71, 102789. doi:10.1016/j.ijdrr.2022.102789

Dobson, S. (2017). Community-driven pathways for implementation of global urban resilience goals in Africa. *Int. J. Disaster risk Reduct.* 26, 78–84. doi:10.1016/j.ijdrr.2017.09.028

Doherty, M., Klima, K., and Hellmann, J. J. (2016). Climate change in the urban environment: Advancing, measuring and achieving resiliency. *Environ. Sci. Policy* 66, 310–313. doi:10.1016/j.envsci.2016.09.001

Faturechi, R., and Miller-Hooks, E. (2015). Measuring the performance of transportation infrastructure systems in disasters: A comprehensive review. *J. Infrastructure Syst.* 21, 04014025. doi:10.1061/(ASCE)IS.1943-555X.0000212

Feldmeyer, D., Wilden, D., Kind, C., Kaiser, T., Goldschmidt, R., Diller, C., et al. (2019). Indicators for monitoring urban climate change resilience and adaptation. *Sustainability* 11, 2931. doi:10.3390/su11102931

Feng, Y., Lee, C. C., and Peng, D. (2023). Does regional integration improve economic resilience? Evidence from urban agglomerations in China. *Sustain. Cities Soc.* 88, 104273. doi:10.1016/j.scs.2022.104273

Graham, L., Debucquoy, W., and Anguelovski, I. (2016). The influence of urban development dynamics on community resilience practice in New York city after superstorm sandy: Experiences from the lower east side and the rockaways. *Glob. Environ. Change* 40, 112–124. doi:10.1016/j.gloenvcha.2016.07.001

Heeks, R., and Ospina, A. V. (2019). Conceptualising the link between information systems and resilience: A developing country field study. *Inf. Syst. J.* 29 (1), 70–96. doi:10.1111/isj.12177

Holling, C. S. (1973). Resilience and stability of ecological systems. *Annu. Rev. Ecol. Syst.* 4, 1–23. doi:10.1146/annurev.es.04.110173.000245

Jin, Q., Luo, Y., Meng, X., Feng, M., and Huang, C. (2023). Short- and long-term impacts of the COVID-19 epidemic on urban PM2.5 variations: Evidence from a megacity, Chengdu, *Atmos. Environ.* 294, 119479. doi:10.1016/j.atmosenv.2022.119479

Joerin, J., Shaw, R., Takeuchi, Y., and Krishnamurthy, R. (2014). The adoption of a climate disaster resilience index in Chennai, India. *Disasters* 38 (3), 540–561. doi:10.1111/disa.12058

Jordan, E., and Javernick-Will, A. (2013). Indicators of community recovery: Content analysis and delphi approach. *Nat. Hazards Rev.* 14 (1), 21–28. doi:10.1061/(ASCE)NH.1527-6996.0000087

Khatibi, H., Wilkinson, S., Eriwata, G., Sweya, L. N., Baghersad, M., Dianat, H., et al. (2022). An integrated framework for assessment of smart city resilience. *Environ. Plan. B* 49 (5), 1556–1577. doi:10.1177/23998083221092422

Kondo, T., and Lizarralde, G. (2021). Maladaptation, fragmentation, and other secondary effects of centralized post-disaster urban planning: The case of the 2011 "cascading" disaster in Japan. *Int. J. Disaster Risk Reduct.* 58, 102219. doi:10.1016/j.ijdrr.2021.102219

Labaka, L., Hernantes, J., and Sarriegi, J. M. (2016). A holistic framework for building critical infrastructure resilience. *Technol. Forecast. Soc. Change* 103, 21–33. doi:10.1016/j.techfore.2015.11.005

Lai, Y. J., Liu, T. Y., and Hwang, C. L. (1994). Topsis for MODM. *Eur. J. Operational Res.* 76 (3), 486–500. doi:10.1016/0377-2217(94)90282-8

Leichenko, R. (2011). Climate change and urban resilience. *Curr. Opin. Environ. Sustain.* 3 (3), 164–168. doi:10.1016/j.cosust.2010.12.014

Li, X., Zheng, J., and Lu, H. (2022). A study on the impact of natural disasters on farmers' relative poverty. *Front. Environ. Sci.* 10, 744. doi:10.3389/fenvs.2022.908744

Liao, K. (2012). A theory on urban resilience to floods—A basis for alternative planning practices. *Ecol. Soc.* 17, art48. doi:10.5751/es-05231-170448

Lin, Y., Peng, C., Chen, P., and Zhang, M. (2022). Conflict or synergy? Analysis of economic-social-infrastructure-ecological resilience and their coupling coordination in the yangtze river economic belt, China. *Ecol. Indic.* 142, 109194. doi:10.1016/j.ecolind.2022.109194

Liu, D., Sun, T., Liu, D., Fu, Q., Zhang, L., Li, X., et al. (2022). A new method to analyze the driving mechanism of flood disaster resilience and its management decision-making. *J. Hydrology* 612, 128134. doi:10.1016/j.jhydrol.2022.128134

Liu, G., and Yu, J. (2007). Gray correlation analysis and prediction models of living refuse generation in Shanghai city. *Waste Manag.* 27 (3), 345–351. doi:10.1016/j.wasman.2006.03.010

Liu, W., and Song, Z. (2020). Review of studies on the resilience of urban critical infrastructure networks. *Reliab. Eng. Syst. Saf.* 193, 106617. doi:10.1016/j.ress.2019.106617

Lu, H., Lu, X., Jiao, L., and Zhang, Y. (2022a). Evaluating urban agglomeration resilience to disaster in the Yangtze Delta city group in China. *Sustain. Cities Soc.* 76, 103464. doi:10.1016/j.scs.2021.103464

Lu, H., Zhang, C., Jiao, L., Wei, Y., and Zhang, Y. (2022b). Analysis on the spatial-temporal evolution of urban agglomeration resilience: A case study in chengdu-chongqing urban agglomeration, China. *Int. J. Disaster Risk Reduct.* 79, 103167. doi:10.1016/j.ijdrr.2022.103167

Maclean, K., Cuthill, M., and Ross, H. (2014). Six attributes of social resilience. *J. Environ. Plan. Manag.* 57 (1), 144–156. doi:10.1080/09640568.2013.763774

Meerow, S., Newell, J. P., and Stults, M. (2016). Defining urban resilience: A review. *Landsc. Urban Plan.* 147, 38–49. doi:10.1016/j.landurbplan.2015.11.011

Mou, Y., Luo, Y., Su, Z., Wang, J., and Liu, T. (2021). Evaluating the dynamic sustainability and resilience of a hybrid urban system: Case of Chengdu, China. *J. Clean. Prod.* 291, 125719. doi:10.1016/j.jclepro.2020.125719

Murgatroyd, A., and Hall, J. W. (2020). The resilience of inter-basin transfers to severe droughts with changing spatial characteristics. *Front. Environ. Sci.* 8, 571647. doi:10.3389/fenvs.2020.571647

Olson, D. L. (2004). Comparison of weights in TOPSIS models. *Math. Comput. Model.* 40 (7-8), 721–727. doi:10.1016/j.mcm.2004.10.003

Parsons, M., and Morley, P. (2017). The Australian natural disaster resilience index. *Aust. J. Emerg. Manag.* 32 (2), 20–22. doi:10.3316/informit.813178575410300

Perrings, C. (2006). Resilience and sustainable development. *Environ. Dev. Econ.* 11 (4), 417–427. doi:10.1017/S1355770X06003020

Pickett, S. T., Cadenasso, M. L., and Grove, J. M. (2004). Resilient cities: Meaning, models, and metaphor for integrating the ecological, socio-economic, and planning realms. *Landsc. Urban Plan.* 69 (4), 369–384. doi:10.1016/j.landurbplan.2003.10.035

Pickett, S. T., McGrath, B., Cadenasso, M. L., and Felson, A. J. (2014). Ecological resilience and resilient cities. *Build. Res. Inf.* 42 (2), 143–157. doi:10.1080/09613218.2014.850600

Sabatino, M. (2016). Economic crisis and resilience: Resilient capacity and competitiveness of the enterprises. *J. Bus. Res.* 69 (5), 1924–1927. doi:10.1016/j.jbusres.2015.10.081

Saja, A. A., Goonetilleke, A., Teo, M., and Ziyath, A. M. (2019). A critical review of social resilience assessment frameworks in disaster management. *Int. J. Disaster Risk Reduct.* 35, 101096. doi:10.1016/j.ijdrr.2019.101096

Sharif, A. (2016). A critical review of selected tools for assessing community resilience. *Ecol. Indic.* 69, 629–647. doi:10.1016/j.ecolind.2016.05.023

Sharifi, A., and Yamagata, Y. (2016). Principles and criteria for assessing urban energy resilience: A literature review. *Renew. Sustain. Energy Rev.* 60, 1654–1677. doi:10.1016/j.rser.2016.03.028

Shen, L., Sun, X., and Suo, W. (2022). A MACBETH-based method for urban resilience evaluation. *Procedia Comput. Sci.* 214, 456–460. doi:10.1016/j.procs.2022.11.199

Snep, R. P., Voeten, J. G., Mol, G., and Van Hattum, T. (2020). Nature based solutions for urban resilience: A distinction between no-tech, low-tech and high-tech solutions. *Front. Environ. Sci.* 8, 599060. doi:10.3389/fenvs.2020.599060

Song, J., Huang, B., and Li, R. (2018). Assessing local resilience to typhoon disasters: A case study in nansha, guangzhou. *PloS one* 13, e0190701. doi:10.1371/journal.pone.0190701

Song, J., Pandey, R., Dong, G., Sharifi, A., and Subedi, B. P. (2022). Urban-rural disparity in community resilience: A multilevel analysis of the relief progress after the 2015 Nepal earthquake. *Sustain. Cities Soc.* 79, 103698. doi:10.1016/j.scs.2022.103698

Talubo, J. P., Morse, S., and Saroj, D. (2022). Whose resilience matters? A socio-ecological systems approach to defining and assessing disaster resilience for small islands. *Environ. Challenges* 7, 100511. doi:10.1016/j.envc.2022.100511

Tang, J., Heinimann, H., Han, K., Luo, H., and Zhong, B. (2020). Evaluating resilience in urban transportation systems for sustainability: A systems-based bayesian network model. *Transp. Res. Part C Emerg. Technol.* 121, 102840. doi:10.1016/j.trc.2020.102840

Tomao, A., Quaranta, G., Salvia, R., Vinci, S., and Salvati, L. (2021). Revisiting the "southern mood"? Post-Crisis mediterranean urbanities between economic downturns and land-use change. *Land Use Policy* 111, 105740. doi:10.1016/j.landusepol.2021.105740

Ulfarsson, G. F., Steinbrenner, A., Valsson, T., and Kim, S. (2015). Urban household travel behavior in a time of economic crisis: Changes in trip making and transit importance. *J. Transp. Geogr.* 49, 68–75. doi:10.1016/j.jtrangeo.2015.10.012

Wang, L. (2022). Exploring a knowledge map for urban resilience to climate change. *Cities* 131, 104048. doi:10.1016/j.cities.2022.104048

Wang, S., Cui, Z., Lin, J., Xie, J., and Su, K. (2022). The coupling relationship between urbanization and ecological resilience in the Pearl River Delta. *J. Geogr. Sci.* 32 (1), 44–64. doi:10.1007/s11442-022-1935-3

Wang, X., Wang, L., Zhang, X., and Fan, F. (2022). The spatiotemporal evolution of COVID-19 in China and its impact on urban economic resilience. *China Econ. Rev.* 74, 101806. doi:10.1016/j.chieco.2022.101806

Wang, Y., Cai, Y., Xie, Y., Chen, L., and Zhang, P. (2023). An integrated approach for evaluating dynamics of urban eco-resilience in urban agglomerations of China. *Ecol. Indic.* 146, 109859. doi:10.1016/j.ecolind.2023.109859

Wu, S., Zhang, R., Wang, C., and Feng, D. (2022). The impact of natural disasters on rural household wealth: Micro evidence from China. *Front. Environ. Sci.* 10, 1738. doi:10.3389/fenvs.2022.993722

Xia, C., and Zhai, G. (2022). The spatiotemporal evolution pattern of urban resilience in the Yangtze River Delta Urban Agglomeration based on TOPSIS-PSO-ELM. *Sustain. Cities Soc.* 87, 104223. doi:10.1016/j.scs.2022.104223

Xu, W. A., Zhou, J., Yang, L., and Li, L. (2018). The implications of high-speed rail for Chinese cities: Connectivity and accessibility. *Transp. Res. Part A Policy Pract.* 116, 308–326. doi:10.1016/j.tra.2018.06.023

Yang, L., Liang, Y., He, B., Lu, Y., and Gou, Z. (2022). COVID-19 effects on property markets: The pandemic decreases the implicit price of metro accessibility. *Tunn. Undergr. Space Technol.* 125, 104528. doi:10.1016/j.tust.2022.104528

Ye, C., Hu, M., Lu, L., Dong, Q., and Gu, M. (2022). Spatio-temporal evolution and factor explanatory power analysis of urban resilience in the Yangtze River Economic Belt. *Geogr. Sustain.* 3 (4), 299–311. doi:10.1016/j.geosus.2022.09.004

Zhao, R., Fang, C., Liu, J., and Zhang, L. (2022). The evaluation and obstacle analysis of urban resilience from the multidimensional perspective in Chinese cities. *Sustain. Cities Soc.* 86, 104160. doi:10.1016/j.scs.2022.104160

Zhou, S. Y., Huang, A. C., Wu, J., Wang, Y., Wang, L. S., Zhai, J., et al. (2022). Establishment and assessment of urban meteorological disaster emergency response capability based on modeling methods. *Int. J. Disaster Risk Reduct.* 79, 103180. doi:10.1016/j.ijdrr.2022.103180

Zimmerman, R., and Faris, C. (2011). Climate change mitigation and adaptation in North American cities. *Curr. Opin. Environ. Sustain.* 3 (3), 181–187. doi:10.1016/j.cosust.2010.12.004