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Measuring Urban–Rural Integration and Its Driving Mechanisms in the Chengdu–Chongqing Economic Circle

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Abstract

As urban agglomerations reshape China's urban–rural relations, existing evaluations still focus mainly on development levels within administrative units, with limited attention to spatial interactions between urban and rural territorial systems. Taking the Chengdu–Chongqing Economic Circle (CCEC) as a case, this study develops a spatial interaction-based framework for measuring urban–rural integration. The framework integrates population, land and economic factors to characterize urban–rural development status, orientation, coordination and interaction intensity. The Geographical Detector is further employed to identify the driving mechanisms. Compared with conventional within-unit assessments, this framework captures the direction, intensity, and cross-regional dependence of urban–rural linkages, thereby providing a more relational understanding of urban–rural integration. The results show that the CCEC experienced a transition from factor differentiation toward functional restructuring, characterized by continued urban concentration of population and land factors and a relative balancing of economic factors between urban and rural areas. Urban–rural integration exhibited clear directional and spatial dependence: urban-to-rural interactions were mainly concentrated around the Chengdu–Chongqing dual cores and major development corridors, whereas rural-to-urban interactions formed a more dispersed support network. The driving mechanisms were not dominated by individual factors but emerged from the interaction of economic foundations, spatial conditions, policy environments and regional linkages, with different factors playing varying roles across development stages. This study provides new insights into the evolution mechanisms of urban–rural integration in emerging urban agglomerations characterized by strong core–periphery disparities, highlighting the importance of spatial interactions, policy guidance and regional development conditions.

Keywords: urban–rural integration; spatial interaction; urban agglomeration; driving mechanism; Chengdu–Chongqing Economic Circle

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1. Introduction

Urban–rural integration is an important issue in regional geography. It refers to a process of interaction, coupling and restructuring across the whole regional space, urban–rural systems and multiple development factors. It is reflected not only in the bidirectional

flow of urban and rural factors, but also in functional complementarity, spatial coordination and institutional coordination [1,2].

Urban–rural integration has long been discussed in relation to changing urban–rural relations. Early theories often treated cities and the countryside as separate systems. They emphasized the transfer of surplus rural labour to the industrial sector and the spillover effects of urban growth poles on rural areas. This logic is reflected in the dual-sector model [3], growth pole theory [4] and core–periphery theory [5]. Later studies moved beyond this dichotomy and focused more on urban–rural linkages and the urban–rural continuum. In this view, cities and rural areas are connected through population mobility, industrial linkages, land-use change and information flows. Urban expansion also reshapes rural land-use structures. For example, long-term remote-sensing evidence shows that urban sprawl can lead to substantial agricultural land loss and is closely associated with socioeconomic transformation [6]. These connections form complex regional networks. The Desakota model [7], regional network theory [8], and work on urban–rural linkages and sustainable development [9] all challenge the traditional urban–rural divide and emphasize functional complementarity and spatial interaction between the urban and rural systems.

In China, urban–rural integration has gained additional meanings related to regional coordination and spatial governance. Liu et al. regard it as an advanced stage of urban–rural transformation [10]. They emphasize integration across population, land, industry and values. Fang et al. trace the policy evolution of China's urban–rural relations, from dualistic separation to coordination, integration and, eventually, urban–rural integration [11]. Luo et al. further highlight the role of market-based factor allocation, multi-level spatial coordination and adaptive governance from institutional, spatial and governance perspectives [12]. Overall, urban–rural integration is not a one-way process of urbanization. It is a dynamic process in which urban and rural systems are jointly reorganized through factor flows, functional complementarity and spatial restructuring.

Urban–rural integration is a key policy direction in China's new urbanization, rural revitalization and regional coordination agendas. As urban agglomerations have become major spaces for population concentration, industrial organization and spatial governance, urban–rural relations are no longer confined to development gaps within single administrative units. They are increasingly shaped by factor flows and spatial linkages among different units within urban agglomerations, and between core cities and peripheral areas. The Chengdu–Chongqing Economic Circle (CCEC) is a typical dual-core urban agglomeration in western China. Its urban–rural integration is shaped by core-city spillovers, regional coordination and mountainous spatial constraints. It therefore provides an important case for examining the restructuring of urban–rural relations in western Chinese urban agglomerations and also offers a reference for other emerging urban agglomerations characterized by strong core–periphery disparities, limited peripheral integration capacity and spatial constraints. It measures the spatiotemporal evolution of urban–rural integration from 2007 to 2023 and further identifies its driving mechanisms, aiming to reveal the spatial organization logic of urban–rural integration in a western dual-core urban agglomeration.

2. Literature Review

2.1. Measurement of Urban–Rural Integration

Measuring urban–rural integration provides an empirical basis for identifying the evolution of urban–rural relations and their spatial heterogeneity. Existing studies have approached this issue from several angles, including urban–rural linkages, urban–rural classification and urban–rural development gradients. International studies have paid early attention to population migration, flows of goods and services, environmental pressure and commuting linkages between urban and rural areas. These studies generally found that

urban and rural areas are increasingly connected through commuting, market exchange, service provision and land-use transformation, but such linkages are spatially uneven and often weaken with increasing distance from urban centres [13]. Peri-urban and metropolitan fringe areas usually show stronger functional connections with cities, whereas more remote rural areas tend to face weaker accessibility, limited service provision and stronger development constraints [14]. Peri-urban studies further show that land strategies and urbanization jointly shape rural land pressures, suggesting the need for more integrated urban and rural planning [15].

Compared with international studies that emphasize functional linkages, commuting zones and urban–rural gradients, Chinese studies have paid greater attention to comprehensive evaluation, policy targets and the coordination of multiple subsystems. Scholars have developed multidimensional evaluation systems covering population, economy, land, society, ecology and public services [16,17]. Methods such as the global entropy method [18], coupling coordination models, projection pursuit models, kernel density estimation and exploratory spatial analysis [19] have also been used to examine the spatiotemporal evolution and spatial differentiation of urban–rural integration.

Research on urban–rural integration has shifted from single economic indicators to multidimensional evaluations that include social, ecological and resource-related dimensions. It has also developed multi-scale frameworks covering national, regional and county levels [20,21]. Existing studies show that the overall level of urban–rural integration in China has increased, and that urban–rural relations have gradually moved from dualistic separation towards factor flows and functional complementarity. However, this process has not been spatially even. Marked spatial heterogeneity remains across regions, scales and types of areas [22–24].

Urban–rural integration within urban agglomerations is not only shaped by local development conditions but also by linkages among different areas. Existing studies have often treated each area as an independent evaluation unit [25,26]. They tend to measure internal development levels or system coordination, while paying less attention to spatial linkages among areas within urban agglomerations. In practice, urban–rural integration depends not only on local population, land, economic and public service conditions, but also on spillovers from core cities, connections with surrounding areas and the structure of regional networks. Studies on new urban communities also indicate that population redistribution and functional autonomy are closely related to balanced regional development and core–periphery relationships [27]. It is therefore necessary to examine urban-to-rural radiation, rural-to-urban support and their role in shaping urban–rural integration from the perspective of spatial interaction among different areas within urban agglomerations.

2.2. Spatial Interaction and Urban–Rural Linkages

Spatial interaction is essential for understanding urban–rural integration because urban and rural systems are connected not only by their internal development levels, but also by the flows, linkages and mutual support between them. It provides a relational perspective that captures how factor scale, functional differences and spatial distance shape the intensity and direction of connections between urban and rural territorial systems. In quantitative studies, spatial interaction is often measured using gravity models and distance-decay functions to capture population, land, economic and resource linkages between regions [2]. Incorporating spatial interaction into urban–rural integration research extends evaluation from internal state measurement to relational measurement between urban and rural systems.

Some studies have examined urban–rural relations through population migration, resource flows and commuting linkages [28,29]. These studies show that urban and rural areas are not separate systems, but interact through population, land, industry, capital and technology. Within urban agglomerations, urban–rural integration often shows a core–periphery pattern. Core cities generate spillover effects on surrounding rural areas, while rural areas support urban systems through labour, agricultural products, ecological space and land resources. Taking the Changsha–Zhuzhou–Xiangtan urban agglomeration as an example, Cui et al. developed an urban–rural integration measurement model and found that urban-to-rural and rural-to-urban interactions follow different spatial patterns, with clear differences between intra-county and inter-county interactions [2]. This indicates that urban–rural integration has both directionality and scale effects: urban systems radiate towards rural systems, while rural systems provide feedback support to urban systems; these interactions occur both within individual counties and through cross-county linkages at the urban agglomeration scale.

2.3. Driving Mechanisms of Urban–Rural Integration

The driving mechanisms of urban–rural integration are highly complex. Existing studies have explained the evolution of urban–rural relations from the perspectives of economic development, factor flows, institutional arrangements, socio-cultural conditions, digital technologies and spatial governance. Economic development and industrial restructuring affect employment, income distribution and resource allocation between urban and rural areas. However, excessive urban–rural disparities may also lead to resource misallocation and regional imbalance [30]. Socio-cultural factors, local social capital and rural identity can influence rural resilience and urban–rural interactions, thereby shaping the process of urban–rural integration [31,32].

Among these factors, factor mobility is widely seen as a central factor in urban–rural integration. The movement of labour, land, capital and public services between urban and rural areas is closely related to the transformation of the urban–rural dual structure. Existing studies show that reducing labour mobility costs, reforming construction land institutions and improving the equalization of public services can help narrow urban–rural gaps and improve rural attraction. However, different factors do not operate in the same way. Eastern China is more strongly affected by talent mobility, central China is more constrained by capital, and western China is more sensitive to changes in land factors [33,34]. These findings suggest that the driving mechanisms of urban–rural integration are regionally specific. They need to be examined in different regional contexts rather than inferred from a single national or regional pattern.

Institutional arrangements and governance capacity are also important conditions for urban–rural integration. Land institutions, household registration systems and governance structures shape the boundaries and modes of factor flows between urban and rural areas [35,36]. In China, new urbanization, rural revitalization and the market-oriented allocation of urban–rural factors also affect the level and spatial differentiation of urban–rural integration [37,38]. In recent years, the digital economy and information infrastructure have also been incorporated into this field of research. Digital technologies can improve the allocation efficiency of labour, capital and land. They can also support market connections, industrial integration and spatial spillovers between urban and rural areas. However, their effects vary across regions [39,40].

Overall, existing studies suggest that the driving mechanisms of urban–rural integration are multidimensional and are associated with factor flows, institutional governance, digital technologies and socio-cultural conditions. However, much of the existing work still focuses on single-factor effects or broad mechanism interpretation. Less attention has

been paid to interaction effects, nonlinear enhancement and spatial heterogeneity among different driving factors.

2.4. Research Gaps and Analytical Framework

Research Gaps

In summary, existing studies have advanced the understanding of urban–rural integration in terms of theoretical interpretation, measurement, spatial patterns and driving mechanisms. Recent studies have also introduced spatial interaction into urban–rural integration assessment, providing a useful way to move beyond static comparisons of urban and rural development levels. However, the driving mechanisms of urban–rural integration under complex geographical and institutional conditions remain insufficiently examined. Existing studies have mainly explained urban–rural integration through socio-economic development, population mobility, land use, industrial structure and infrastructure conditions, while relatively less attention has been paid to the combined effects of topographic constraints and policy-related factors. In many cases, terrain is treated as a background condition rather than an explicit explanatory factor, while policy-related influences are often discussed qualitatively rather than incorporated into quantitative analyses of driving mechanisms.

This limitation is particularly relevant to the CCEC. Unlike more mature and relatively flat urban agglomerations such as the Yangtze River Delta, the Chengdu–Chongqing region is characterized by a dual-core structure, extensive mountainous and hilly areas, strong core–periphery differentiation and cross-provincial coordination. These conditions suggest that urban–rural integration in this region may be shaped not only by conventional socio-economic factors but also by terrain-related spatial constraints and policy-related coordination forces. Therefore, it remains necessary to examine how natural geographical conditions and policy-related factors are associated with regional development foundations and spatial interaction relationships in shaping urban–rural integration.

To address this gap, this study applies a spatial interaction-based measurement framework to the CCEC and incorporates terrain and policy-related variables into the analysis of driving mechanisms. By using the geographical detector, this study identifies not only the explanatory power of individual factors but also their interaction effects, thereby providing a more context-sensitive explanation of urban–rural integration in a dual-core mountainous urban agglomeration.

3. Study Design

3.1. Research Questions

Based on the above research gaps, this study addresses the following questions:

1. How did urban–rural integration in the CCEC evolve from 2007 to 2023 from a spatial interaction perspective?
2. How do urban-to-rural and rural-to-urban interactions differ in direction, intensity and spatial organization within and across regions?
3. What factors, especially terrain-related and policy-related factors, explain the spatial heterogeneity of urban–rural integration?

The years 2007, 2015 and 2023 were selected according to the evolution of regional cooperation and national planning in the Chengdu–Chongqing region. The year 2007 represents the initial stage when Sichuan and Chongqing promoted regional cooperation and jointly proposed the construction of the Chengdu–Chongqing Economic Zone [41]. The year 2015 represents the stage when the Chengdu–Chongqing Economic Zone was incorporated into national-level regional planning [42]. The year 2023 represents the development stage after the construction of the CCEC had been elevated to a national strategy and entered substantive implementation [43].

3.2. Analytical Framework

Based on the above research gaps, this study understands urban–rural integration as a process shaped by both regional development foundations and urban–rural spatial interactions. On the one hand, urban–rural integration requires a certain level of regional development as its prerequisite. Population, land and economy correspond respectively to the behavioral subject, spatial carrier and functional support of urban–rural territorial systems, and constitute core elements affecting urban–rural functional differentiation and regional development capacity. With the advancement of urbanization and industrialization, population agglomeration, land development and economic activities are increasingly allocated differently between urban and rural spaces, leading to varying degrees of urbanity and rurality within the same territorial unit.

On the other hand, urban–rural integration is not simply the sum of the separate development levels of urban and rural areas. Rather, it emphasizes factor flows, functional linkages and spatial restructuring between the two. Even if a region has a relatively high level of development, the relational characteristics of urban–rural integration cannot be fully reflected if effective connections between urban and rural areas are lacking. Therefore, beyond regional development foundations, it is necessary to further examine whether interactions occur between urban and rural areas, the direction and intensity of such interactions, and whether they are formed within a region or extended outward through cross-regional linkages.

For the Chengdu–Chongqing dual-core urban agglomeration, urban–rural integration has clear contextual specificity. The region is structured around the dual cores of Chengdu and Chongqing, and exhibits a pronounced core–periphery differentiation. High-value areas of urban–rural integration are mainly concentrated in the core areas of Chengdu and Chongqing and their surrounding areas, while the central and peripheral areas show relatively lower levels of integration. Compared with more mature urban agglomerations such as the Yangtze River Delta, where internal disparities are relatively smaller, the Chengdu–Chongqing region shows more prominent development imbalance. Its urban–rural integration pattern may therefore be more closely associated with dual-core traction, transport corridors and spatial accessibility. Meanwhile, the region is characterized by extensive mountains and hills, with considerable terrain variation, which increases the cost of factor flows and spatial connections. In particular, some mountainous counties and peripheral areas are constrained by transport conditions and insufficient connections with central areas, which may partly explain their relatively slow improvement in urban–rural integration.

Therefore, urban–rural integration in the Chengdu–Chongqing region cannot be understood solely from the perspective of urban–rural development foundations within individual administrative units. It is also necessary to consider cross-regional linkages among the dual cores, development axes and peripheral areas. Accordingly, based on the measurement of urbanity and rurality across the population, land and economic dimensions, this study introduces bidirectional and cross-regional spatial interaction relationships to reveal the characteristics and influencing mechanisms of urban–rural integration in the Chengdu–Chongqing dual-core urban agglomeration. The research workflow is shown in Figure 1.

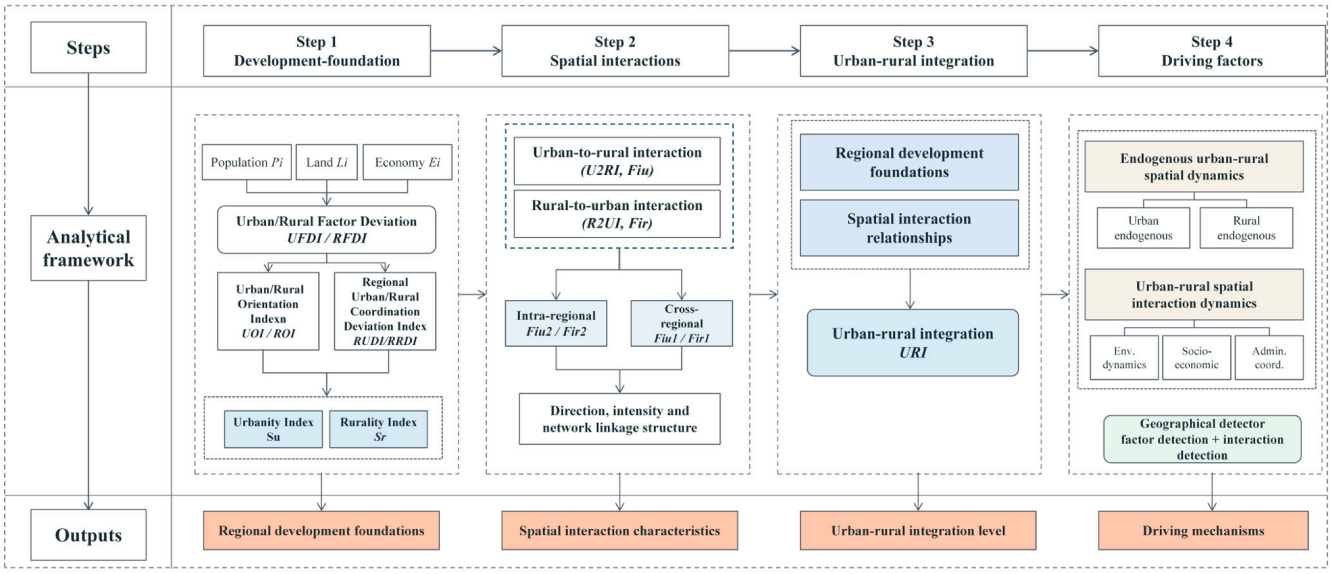


Figure 1. Research process.

4. Study Area and Data Sources

4.1. Study Area

The CCECwas selected as the case study area, as shown in Figure 2. It is located in inland western China and lies at the intersection of the Yangtze River Economic Belt and the Belt and Road Initiative. The study area covers parts of Sichuan Province and Chongqing Municipality, including 44 city(district/county) administrative units. It has a clear dual-core spatial structure. Chengdu and Chongqing were approved as national pilot areas for coordinated urban–rural comprehensive reform, and some parts of the region have been included in national urban–rural integration pilot zones. However, marked core–periphery disparities remain. Peripheral areas are relatively weak in population concentration, industrial foundation, public service provision and transport accessibility.

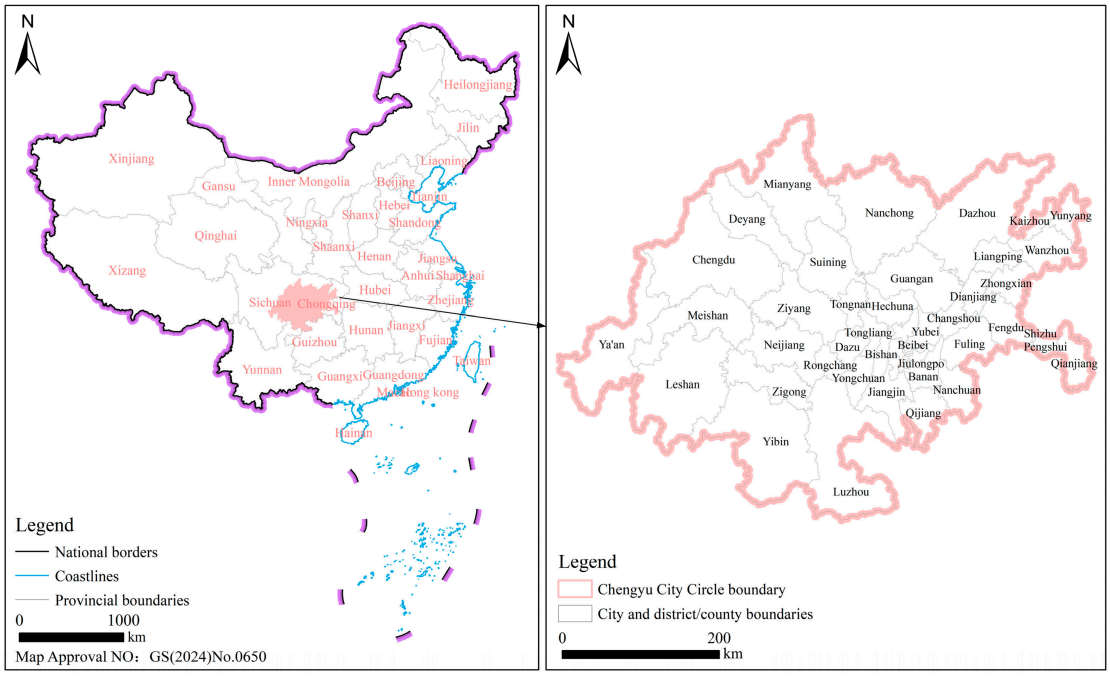


Figure 2. The location of the Chengdu–Chongqing Economic Circle.

4.2. Data Resources

This study uses 44 city (district/county) units in the CCEC as the basic research units. The study period spans 2007 to 2023, with 2007, 2015 and 2023 selected as the main observation years at eight-year intervals. The data used in this study include socioeconomic statistics and spatial data.

The socioeconomic data were mainly obtained from the China County Statistical Yearbook, China Regional Statistical Yearbook, China Rural Statistical Yearbook, China Urban–Rural Construction Statistical Yearbook, relevant statistical yearbooks of Sichuan Province and Chongqing Municipality, and statistical bulletins of cities and counties. These data were used to calculate urban–rural factor deviation, urban and rural attribute indices, urban–rural integration levels and driving factors.

The spatial data include administrative boundaries, government locations, inter-unit distances and intra-unit urban–rural distances. Administrative boundary data were obtained from the National Catalogue Service for Geographic Information. Spatial distances were calculated using GIS. To ensure comparability, administrative divisions and statistical standards were harmonized across the study period. For a small number of missing values, adjacent-year statistical records were used first.

5. Methods

5.1. Method for Measuring Urban–Rural Integration

Based on the existing spatial interaction-based measurement framework [2], this study constructs a method for measuring urban–rural integration. The measurement of urban–rural integration includes six steps: urban/rural factor deviation, urban/rural orientation, regional urban/rural coordination deviation, urbanity/rurality index, urban–rural spatial interaction and urban–rural integration.

The Urban/Rural Factor Deviation Index (UFDI/RFDI) measures the distributional deviation of key factors, including population, land and economy, between urban and rural areas. It reflects whether these factors tend to concentrate in the urban or rural system.

The Urban/Rural Orientation Index (UOI/ROI) identifies the development orientation of a region. It indicates whether regional development tends more towards urban attributes or rural attributes.

The Regional Urban/Rural Coordination Deviation Index (RUDI/RRDI) measures the imbalance in the allocation of population, land and economic factors between urban and rural areas. A higher value indicates a stronger deviation in the urban–rural factor structure.

The Urbanity/Rurality Index (UI/RI) describes the relative strength of urbanity and rurality in each research unit. It reflects the development attributes of urban and rural areas and their changes over time.

The Urban-to-Rural Interaction Index/Rural-to-Urban Interaction Index (U2RI/R2UI) measures the intensity of spatial linkages between urban and rural territorial systems, including urban-to-rural radiation and rural-to-urban support.

The Urban–Rural Integration Index (URI) provides an integrated measure of the degree of integration between urban and rural areas in terms of factor flows, functional linkages and spatial coordination.

ArcGIS 10.8, Python 3.7, SPSS 32.0 and Geodetector 1.0 were employed for spatial analysis, statistical computation, and factor detection.

5.1.1. Urban/Rural Factor Deviation Index (UFDI/RFDI)

Following the principles of scientific validity, data availability and hierarchical structure, this study selects six indicators from the dimensions of population, land and economy

to construct the evaluation indicator system for urban–rural integration [44], as shown in Table 1.

Table 1. Multidimensional urban–rural indicators and formulas for factor deviation.

Dimension	Primary Indicator	Secondary Indicator	Index	Formula	
Population	Population	Urban resident population (UP)	Urban population factor deviation index (P_{iu})	$P_{iu} = \frac{UP}{UP+RP}$	(1)
		Rural resident population (RP)	Rural population factor deviation index (P_{ir})	$P_{ir} = 1 - P_{iu}$	(2)
Land	Land use	Urban built-up area (UBA)	Urban land factor deviation index (L_{iu})	$L_{iu} = \frac{UBA}{UBA+SCA}$	(3)
		Crop sown area (CSA)	Rural land factor deviation index (L_{ir})	$L_{ir} = 1 - L_{iu}$	(4)
Economy	Income	Per capita disposable income of urban residents (UPGD)	Urban economic factor deviation index (E_{iu})	$E_{iu} = \frac{UPGD}{UPGD+RPGD}$	(5)
		Per capita disposable income of rural residents (RPGD)	Rural economic factor deviation index (E_{ir})	$E_{ir} = 1 - E_{iu}$	(6)

5.1.2. Method for Urban/Rural Orientation Index and the Regional Urban/Rural Coordination Deviation Index

Urban and rural orientation degrees and the regional coordination deviation index are calculated from the dimensions of population, land and economy. The model measures urban–rural development status by calculating the gaps between urban and rural systems across the three dimensions of population, land and economy. It can directly reflect the balance of multiple factors between urban and rural systems and is suitable for comparative analysis among city/district/county units within an urban agglomeration [45]. The formulas are given as Equations (7)–(9):

$$d_{i1} = \frac{\sqrt{(P_i - L_i)^2 + (P_i - E_i)^2 + (L_i - E_i)^2}}{3}, \quad (7)$$

$$d_{iu} = \sqrt{P_{iu}^2 + L_{iu}^2 + E_{iu}^2}, \quad (8)$$

$$d_{ir} = \sqrt{P_{ir}^2 + L_{ir}^2 + E_{ir}^2}, \quad (9)$$

where:

i denotes the basic evaluation unit.

P_i, L_i and E_i represent the urban (u) or rural (r) factor deviation of the core factors in the dimensions of population, land and economy, respectively. They reflect the urban–rural spatial allocation status of a unit at a given time.

d_{i1} denotes the regional coordination deviation index. It can be calculated using either urban factor deviation or rural factor deviation. A larger d_{i1} indicates a stronger imbalance among the three dimensions and a greater constraint on urban–rural integration.

d_{iu} and d_{ir} denote the urban orientation degree and rural orientation degree of a unit, respectively. They indicate the potential direction of urban–rural attraction.

5.1.3. Method for Calculating the Urbanity/Rurality Index

Based on the evaluation indicator system for urban–rural integration, the Urbanity/Rurality Index (UI/RI) is calculated using the full permutation polygon synthetic index method. This method does not require subjective weighting and can reduce bias caused by weight assignment. It is suitable for the comprehensive evaluation of multidimensional indicators [46]. The formulas are given as Equations (10)–(13):

$$S_{iu} = \frac{(U_{iu} - L_{iu}) \times (X_{iu} - T_{iu})}{(U_{iu} + L_{iu} - 2T_{iu}) \times X_{iu} + (U_{iu} + L_{iu}) \times T_{iu} - 2U_{iu} \times L_{iu}}, \quad (10)$$

$$S_{ir} = \frac{(U_{ir} - L_{ir}) \times (X_{ir} - T_{ir})}{(U_{ir} + L_{ir} - 2T_{ir}) \times X_{ir} + (U_{ir} + L_{ir}) \times T_{ir} - 2U_{ir} \times L_{ir}}, \quad (11)$$

$$S_u = \sum_{i \neq j}^{i,j} \frac{(S_{iu} + 1) \times (S_{ju} + 1)}{2n \times (n - 1)}, \quad (12)$$

$$S_r = \sum_{i \neq j}^{i,j} \frac{(S_{ir} + 1) \times (S_{jr} + 1)}{2n \times (n - 1)}, \quad (13)$$

where:

U_i is the upper limit of indicator i, determined by its maximum value.

L_i is the lower limit of indicator i, determined by its minimum value.

T_i is the critical value of indicator i, determined by its mean value.

X_i is the actual value of indicator i.

S_{iu} and S_{ju} are the standardized values of the ith and jth sub-indicators of the urban territorial system in an evaluation unit.

S_{ir} and S_{jr} are the standardized values of the ith and jth sub-indicators of the rural territorial system in an evaluation unit.

n is the number of urban or rural indicators. In this study, n equals 3 for both systems.

S_u is the Urbanity Index, and S_r is the Rurality Index. Both values range from 0 to 1.

5.1.4. Calculation of the Urban-to-Rural/Rural-to-Urban Interaction Index (U2RI/R2UI) and Urban–Rural Integration Index (URI)

To quantify urban–rural spatial interaction within units and across city–district/county units, this study uses an extended spatial interaction model with distance attenuation to measure urban–rural integration. The model modifies interaction intensity by incorporating economic distance and spatial distance, and can reflect the potential of urban–rural factor flows and the strength of spatial interaction. The formulas are as follows:

$$R_i = (Max\{d_{i1}\} - d_{i1}) \times \sqrt{F_{iu} d_{iu} F_{ir} d_{ir}} \times 10^5 \quad (14)$$

$$\overline{F}_{iu} = \frac{1}{n-1} F_{iu} = \frac{1}{n-1} \sum_{\substack{j=1 \\ j \neq i}}^{n} \frac{K_{iu} S_{iu} S_{jr}}{\left(E^*_{iujr} D^*_{iujr}\right)^2} \quad (15)$$

$$F_{iu2} = \frac{K_{iu} S_{iu} S_{ir}}{\left(E^*_{iur} D^*_{iur}\right)^2} \quad (16)$$

$$F_{iu} = \overline{F}_{iu1} + F_{iu2} = \frac{1}{n-1} \sum_{\substack{j=1 \\ j \neq i}}^{n} \frac{K_{iu} S_{iu} S_{jr}}{\left(E^*_{iujr} D^*_{iujr}\right)^2} + \frac{K_{iu} S_{iu} S_{ir}}{\left(E^*_{iur} D^*_{iur}\right)^2}, \quad (17)$$

$$\overline{F}_{ir1} = \frac{1}{n-1} F_{ir1} = \frac{1}{n-1} \sum_{\substack{j=1 \\ j \neq i}}^{n} \frac{K_{ir} S_{ir} S_{ju}}{\left(E^*_{irju} D^*_{irju}\right)^2} \quad (18)$$

$$F_{ir2} = \frac{K_{ir} S_{ir} S_{iu}}{\left(E^*_{iru} D^*_{iru}\right)^2}, \tag{19}$$

$$F_{ir} = \overline{F}_{ir1} + F_{ir2} = \frac{1}{n-1} \sum_{\substack{j=1 \\ j \neq i}}^{n} \frac{K_{ir} S_{ir} S_{ju}}{\left(E^*_{irju} D^*_{irju}\right)^2} + \frac{K_{ir} S_{ir} S_{iu}}{\left(E^*_{iru} D^*_{iru}\right)^2}, \tag{20}$$

where:

R denotes the Urban–Rural Integration Index.

i denotes the ith city–district/county unit.

n is the total number of administrative units, n = 44.

d_{i1}, d_{iu} and d_{ir} denote the regional coordination deviation, urban orientation degree and rural orientation degree, respectively.

$Max\{d_{i1}\} - d_{i1}$ reflects the level of regional coordination. It is used as the weight coefficient of urban–rural integration.

S_{iu} and S_{ir} denote the Urbanity Index and Rurality Index, respectively.

K_u is the urban influence coefficient, calculated as the ratio of the Urbanity Index to the sum of the Urbanity Index and Rurality Index. K_r is the rural influence coefficient, calculated as the ratio of the Rurality Index to the sum of the Urbanity Index and Rurality Index.

The urban and rural influence coefficients are calculated as follows, where:

$$K_{iu} = \frac{S_{iu}}{S_{iu} + S_{ir}}, \tag{21}$$

$$K_{ir} = \frac{S_{ir}}{S_{iu} + S_{ir}}, \tag{22}$$

E denotes urban–rural economic distance, measured by the difference between the per capita disposable income of urban and rural residents.

The dimensionless economic distance from urban areas in one unit to rural areas in another unit is calculated as follows:

$$E^*_{iujr} = \frac{2\left|UPGD_i - RPGD_j\right|}{UPGD_i + RPGD_j}, \tag{23}$$

The dimensionless economic distance from rural areas in one unit to urban areas in another unit is calculated as follows:

$$E^*_{irju} = \frac{2\left|RPGD_i - UPGD_j\right|}{RPGD_i + UPGD_j}, \tag{24}$$

For intra-unit interactions, the same urban–rural income disparity is used in both directions:

$$E^*_{iur} = E^*_{iru} = 1 + \frac{2|UPGD_i - RPGD_i|}{UPGD_i + RPGD_i}, \tag{25}$$

D denotes urban–rural spatial distance. In this study, it is defined in two ways.

First, building on the von Thünen circle assumption and the approach of Liu et al. [10], the intra-unit urban–rural spatial distances (D_{iur}, D_{iru}) are estimated using an improved method, defined as the difference between the radius of the minimum enclosing circle of the entire urban–rural territorial space and that of the urban development zone within each research unit.

Second, the cross-unit urban–rural spatial distance is measured using the shortest road distance between the government seats of different city–district/county units. The urban and rural land-use data and road network data used for the calculation correspond to the three study years: 2007, 2015, and 2023.

To mitigate the instability in the calculation results caused by extremely large or small values arising from differences between intra-unit and cross-unit spatial distances, the original distance values are transformed before being incorporated into the interaction model:

$$D^* = 1 + ln(1 + D) \quad (26)$$

F_{iu1} denotes the cross-unit urban-dominated interaction intensity. F_{iu2} denotes the intra-unit urban-dominated interaction intensity. F_{ir1} denotes the cross-unit rural-dominated interaction intensity. F_{ir2} denotes the intra-unit rural-dominated interaction intensity. F_{iu} denotes the total urban-dominated urban–rural interaction intensity of a city–district/county unit, while F_{ir} denotes the total rural-dominated rural–urban interaction intensity of a city–district/county unit.

5.2. Methods for Identifying the Driving Mechanisms of Urban–Rural Integration

5.2.1. Selection of Driving Factors

To identify the driving mechanisms of urban–rural integration in the CCEC, this study draws on previous research by Yu et al. [47] and Cui et al. [2]. Based on data availability and the regional development characteristics of the CCEC, 17 indicators were selected from two dimensions: endogenous urban–rural spatial dynamics and urban–rural spatial interaction dynamics, as presented in Table 2.

Table 2. Driving factors of urban–rural integration.

Driving Mechanism	Type of Dynamic	Indicator
Endogenous urban–rural spatial dynamics	Urban endogenous dynamic	X1: Urban resident population X2: Secondary and tertiary sector value added
	Rural endogenous dynamic	X3: Engel coefficient of rural residents X4: Total agricultural machinery power per unit crop sown area
Urban–rural spatial interaction dynamics	Urban–rural environmental dynamic	X5: Green coverage rate of built-up areas X6: Terrain ruggedness index (TRI)
	Socioeconomic dynamic	X7: Shortest road distance to Chengdu or the central urban area of Chongqing X8: Per capita total retail sales of consumer goods X9: Per capita total import and export volume X10: Fixed internet broadband access users per 10,000 people X11: Health institution beds per 10,000 people X12: Classified highway density X13: Number of schools per 10,000 people
	Administrative coordination dynamic	X14: Per capita fixed asset investment X15: Ratio of urban–rural minimum living allowance standards X16: Policy-planning strategic location level X17: Provincial boundary adjacency variable

Considering that the driving mechanism analysis focuses on changes in urban–rural integration across different periods, all indicators, except terrain ruggedness (X6) and the Sichuan–Chongqing provincial boundary adjacency variable (X17), were calculated as the rate of change from the initial year to the final year of each corresponding study period.

Terrain ruggedness (TRI) was calculated with reference to the Terrain Ruggedness Index method proposed by Riley et al. [48], and was used to characterize terrain variation and surface heterogeneity.

The policy-based strategic location level (X16) was assigned according to regional cooperation agreements and planning documents for each corresponding period, in order to characterize the strategic position of each district or county within the spatial development pattern of the Chengdu–Chongqing region [41–43]. The assignment rule was as follows: districts or counties located in the dual-core area or core functional areas were assigned a value of 3; key nodes or regional central cities were assigned a value of 2; and general areas were assigned a value of 1.

The Sichuan–Chongqing provincial boundary adjacency variable (X17) was represented as a binary variable. Districts or counties located along the Sichuan–Chongqing provincial boundary were assigned a value of 1, while all other areas were assigned a value of 0.

5.2.2. Geographical Detector

This study uses the geographical detector model to examine the spatial explanatory power of different factors for changes in urban–rural integration [49]. Considering the limited number of county-level units, continuous variables were discretized into three quantile-based strata before factor detection and interaction detection. This conservative discretization scheme helps maintain relatively balanced strata and reduce the inflation of interaction q values caused by overly fragmented overlay strata. Categorical variables were directly included according to their assigned categories. The model is expressed as Equation (27):

$$q = 1 - \frac{1}{N\sigma^2}\sum_{H=1}^{L} N_h\sigma_h^2 = 1 - \frac{SSW}{SST}, \quad (27)$$

where:

h denotes the stratification of the explanatory variable, namely its classification or zoning.

N_h and N denote the number of units in stratum h and in the whole study area, respectively.

σ^2_h and σ^2 denote the variance of Y in stratum h and in the whole study area, respectively.

SSW and SST denote the within-stratum sum of squares and the total sum of squares, respectively.

q denotes the explanatory power of a factor, with a value range of $[0, 1]$. A larger q value indicates stronger explanatory power for the spatial differentiation of urban–rural integration.

Based on factor detection, this study further used the interaction detection module of the geographical detector. The three-class stratification results of any two explanatory factors were spatially overlaid, and their interaction explanatory power, q(Xi∩Xj), was calculated. By comparing q(Xi), q(Xj), and q(Xi∩Xj), the interaction type between two factors was identified. Considering the limited number of county-level samples, high interaction q values were interpreted as strengthened explanatory associations rather than strict causal effects.

6. Results

6.1. Restructuring of Urban–Rural Factors and Changes in Development Status

Based on Formulas (1)–(20), this study calculates the Urban/Rural Factor Deviation Index (UFDI/RFDI), Urban/Rural Orientation Index (UOI/ROI), Regional Urban/Rural Coordination Deviation Index (RUDI/RRDI), and Urbanity/Rurality Index (UI/RI) for the study area. These results are used to reveal the redistribution of key factors, including population, land and economy, between urban and rural systems, as well as changes in urban–rural development status.

6.1.1. Results of Urban/Rural Factor Deviation

The UFDI/RFDI results show that population, land and economic factors in the CCEC underwent differentiated restructuring from 2007 to 2023, as shown in Figures 3–5. Population and land factors continued to concentrate in urban areas. The mean urban population factor deviation increased from 0.453 to 0.662, and the mean urban land factor deviation increased from 0.103 to 0.287. This indicates that urban population absorption and the expansion of built-up land remained important processes in the evolution of urban–rural relations.

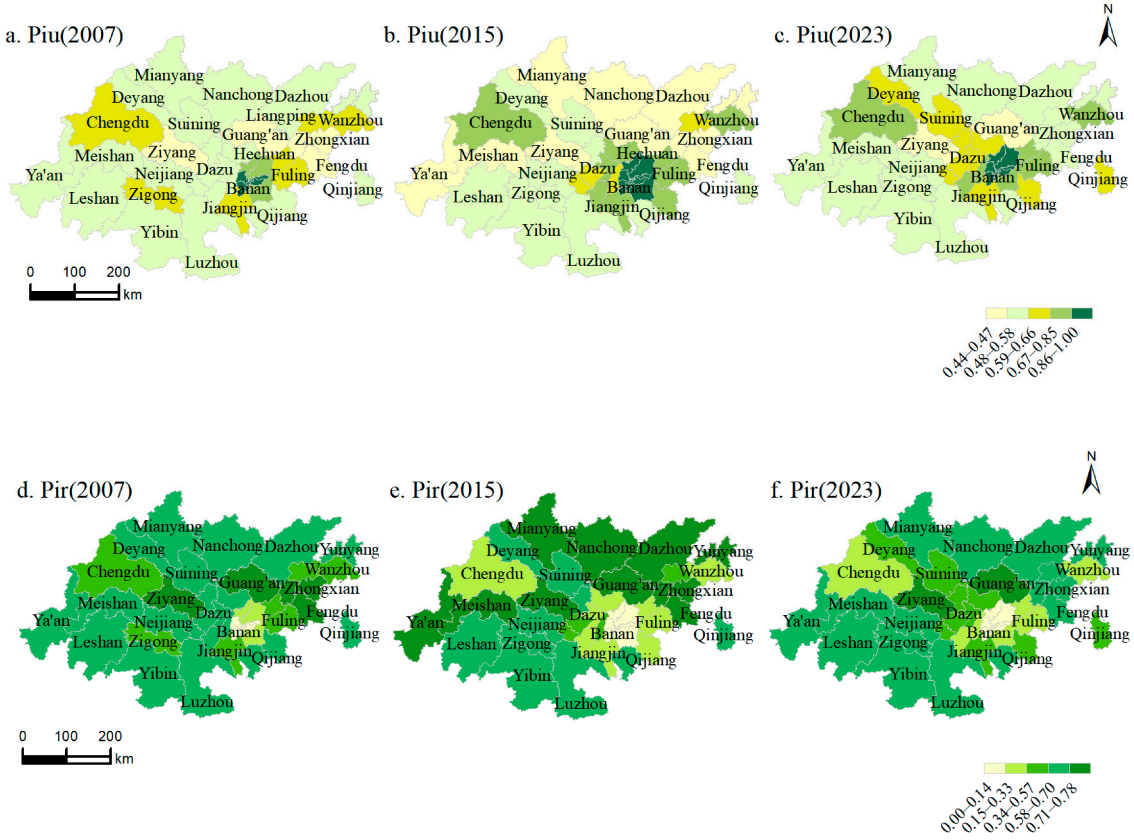


Figure 3. Spatiotemporal evolution of urban/rural population factor deviation.

In contrast, the mean urban economic factor deviation decreased from 0.737 to 0.673. This suggests that the distribution of economic factors between urban and rural areas became relatively more balanced. Spatially, high-value areas of urban population and land factor deviation were initially concentrated around the dual cores of Chengdu and Chongqing, and then gradually expanded towards several prefecture-level cities. This pattern reflects a shift from dual-core concentration to multi-centre diffusion. The multi-centre tendency was more evident for population and economic factors, whereas land factors still showed stronger core concentration.

6.1.2. Urban–Rural Development Status

In terms of development orientation and coordination, the CCEC showed a stronger urban orientation and a weaker rural orientation over time. From 2007 to 2023, the UOI increased by 14.26%, while the ROI decreased by 19.73% (Figure 6). In the dual-core areas, the UOI increased by 16.13%, and the ROI decreased by 41.86%. These changes were much greater than those in peripheral areas, indicating stronger urban concentration in the core-city areas.

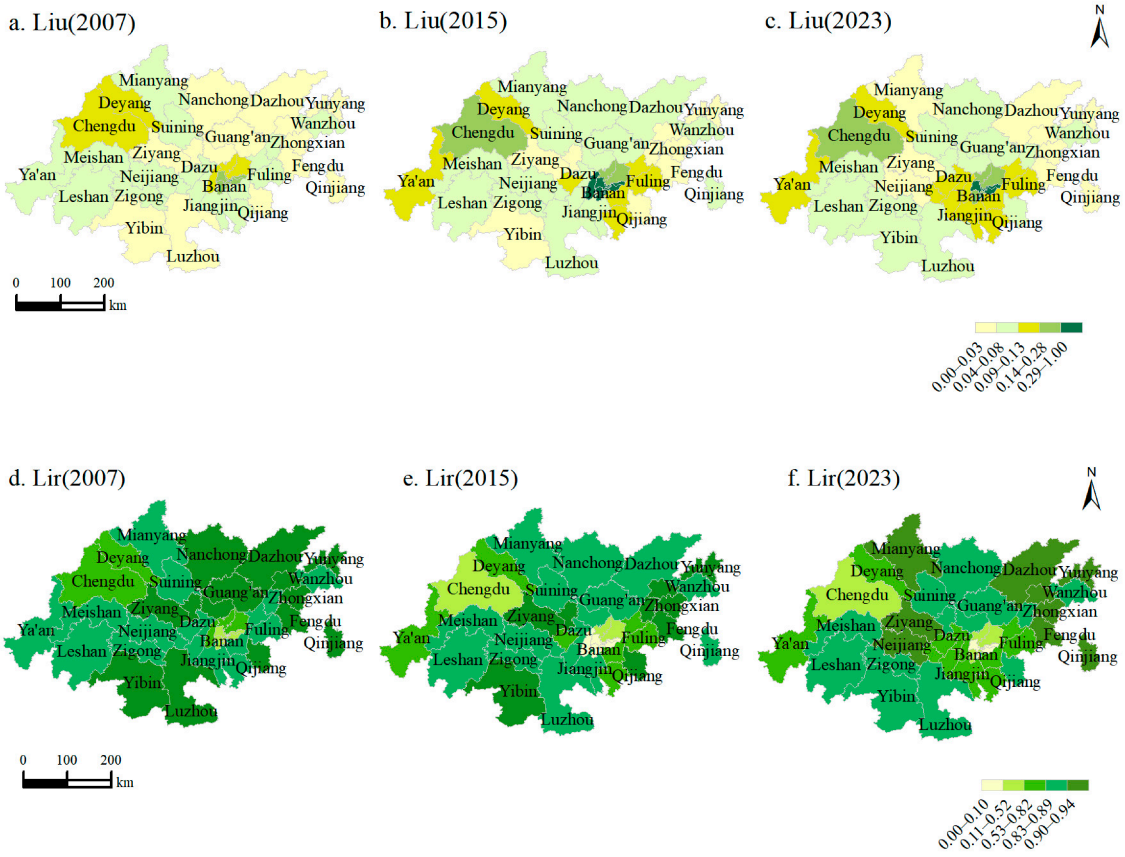


Figure 4. Spatiotemporal evolution of urban/rural land factor deviation.

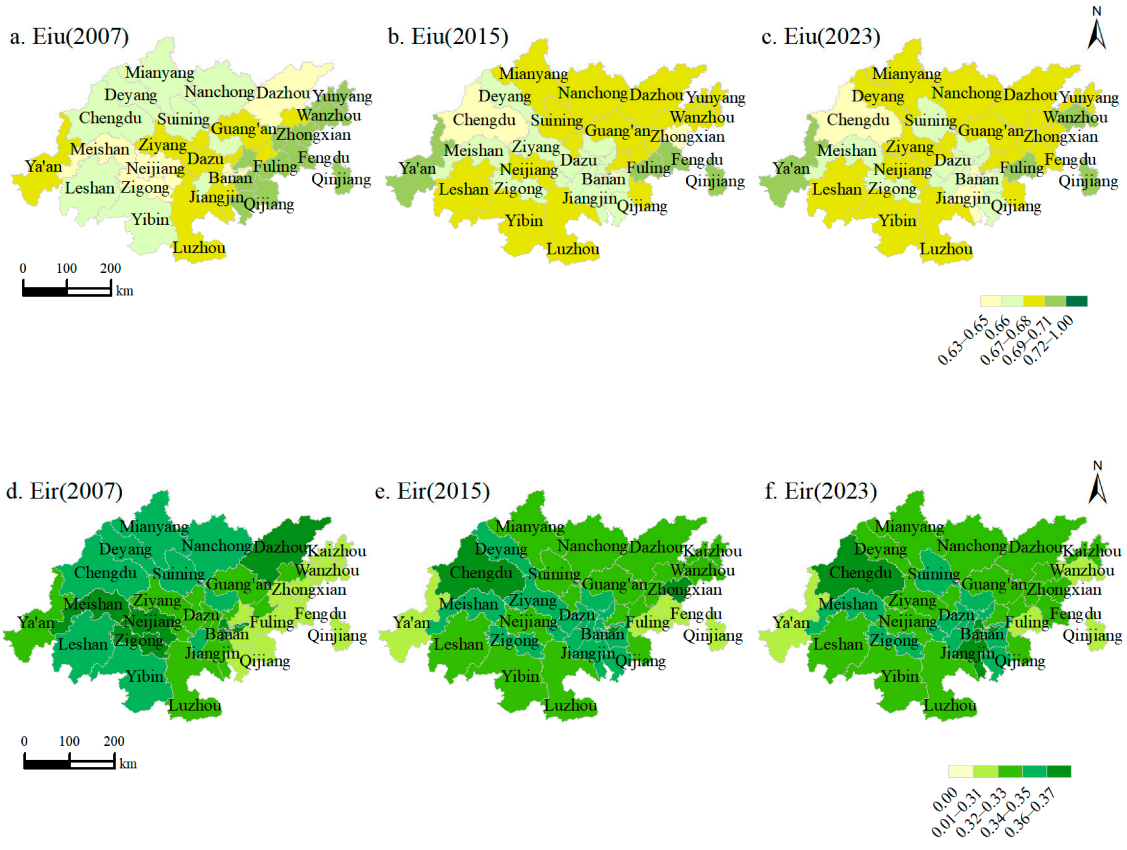


Figure 5. Spatiotemporal evolution of urban/rural economic factor deviation.

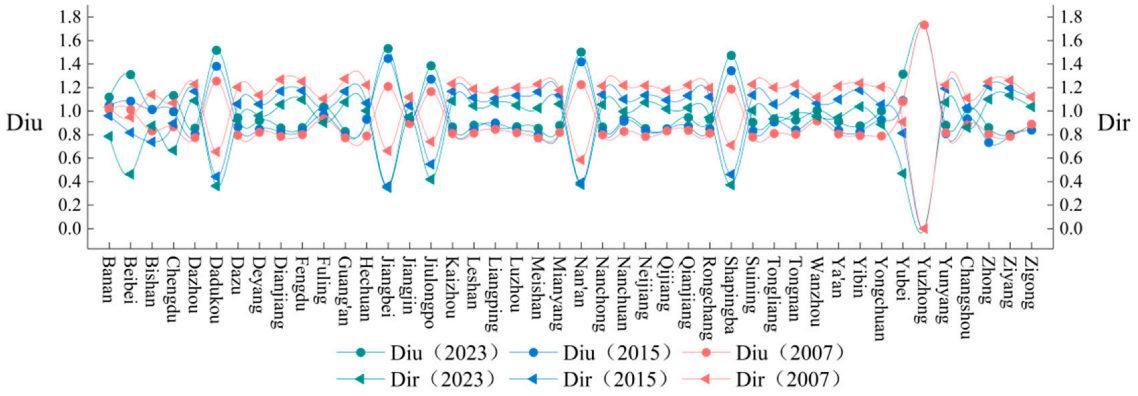


Figure 6. Results of urban/rural orientation index.

At the same time, the gap between the UOI and ROI narrowed from 1.115 to 1.030, suggesting a convergence in development orientation. The RUDI/RRDI, which represents the degree of urban–rural imbalance, also declined (Figure 7). Its mean value decreased from 0.471 to 0.362, with a reduction of 23.14%. The value for central urban areas decreased from 0.361 to 0.222, while that for non-central areas decreased from 0.502 to 0.403. These results indicate that the spatial imbalance of key factors has been eased. Urban–rural development has gradually shifted from a process dominated by urban concentration to a more compound process involving both urban concentration and rural functional improvement.

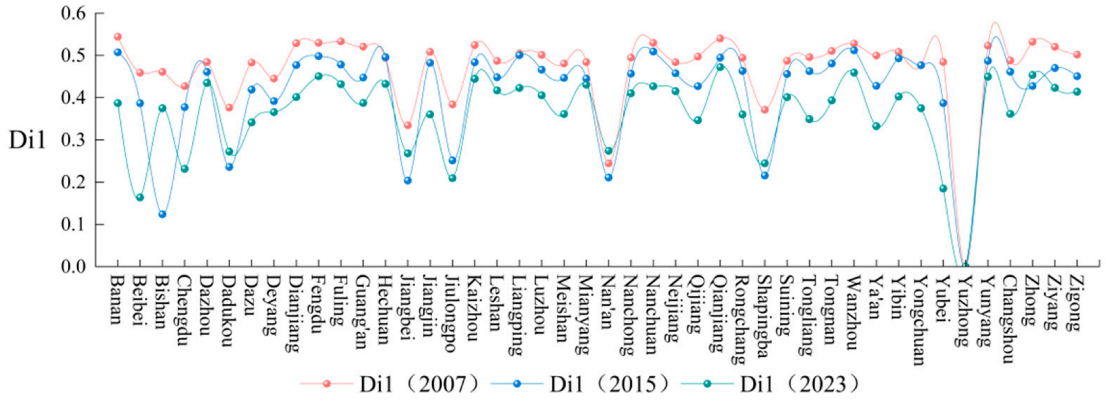


Figure 7. Regional urban/rural coordination deviation index.

6.1.3. Urbanity/Rurality Index

The UI/RI results show that the urban attributes of the study area continued to strengthen (Figures 8 and 9). The number of units with a higher UI than RI increased from 16 to 32, from 38.10% to 76.20%. This indicates that population, land and economic structures dominated by urban attributes have gradually become the main feature of regional development. At the same time, rural attributes did not continue to weaken. After 2015, the RI increased by about 17%, suggesting that some rural areas improved their overall performance in population carrying capacity, agricultural land use and rural income.

Spatially, Chengdu and the central urban area of Chongqing formed the high-value cores of the UI, while peripheral areas retained stronger rural attributes. The expansion of high-value RI areas was greater than that of high-value UI areas, and this expansion was more evident in the Sichuan part than in the Chongqing part.

Overall, the urban and rural attributes of the CCEC show a compound pattern of dual-core concentration, peripheral differentiation and mixed urban–rural characteristics. Urban–rural integration in the region is therefore not a one-way process of urban expansion.

It is shaped by urban concentration, rural functional improvement and the reallocation of urban–rural factors.

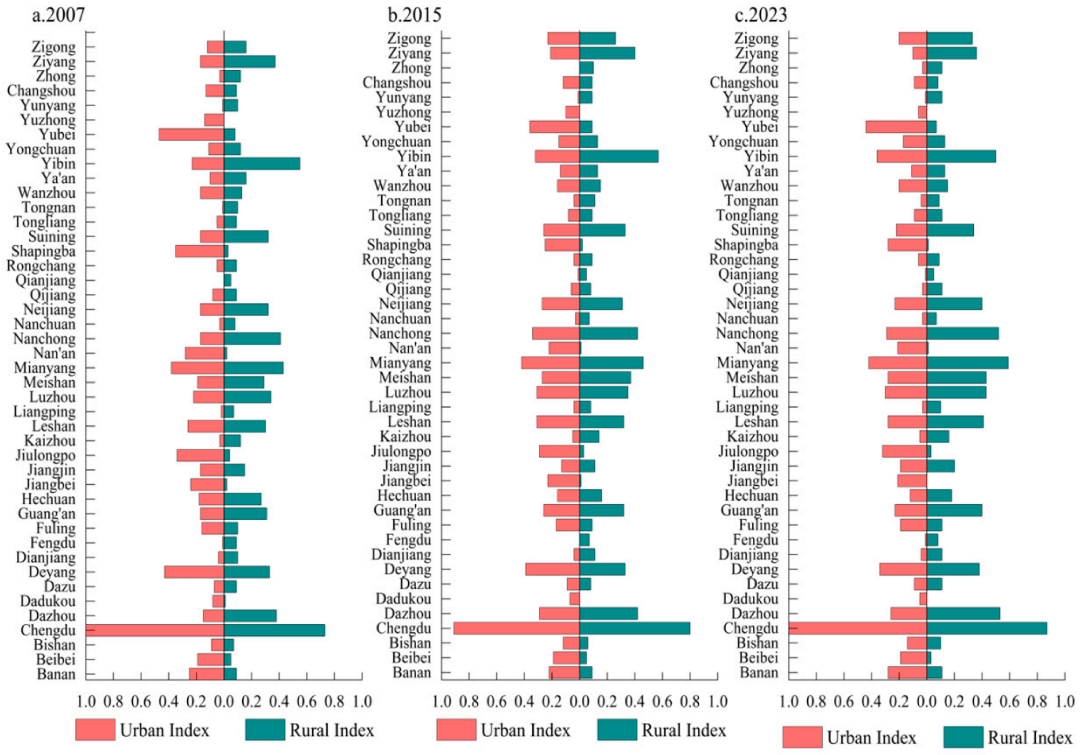


Figure 8. Results of the urbanity/rurality index.

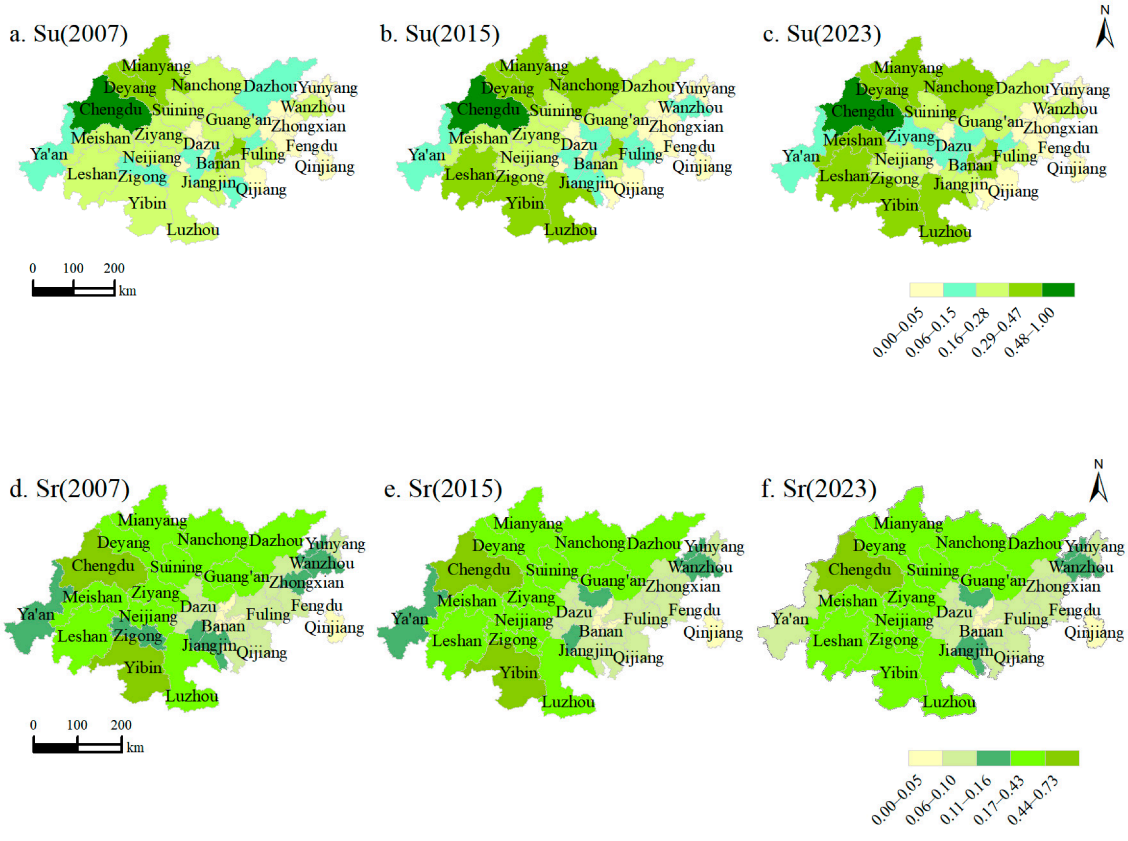


Figure 9. Spatiotemporal evolution of the urbanity/rurality index.

6.2. Spatiotemporal Evolution of Urban–Rural Spatial Interaction and Integration

6.2.1. Urban–Rural Spatial Interaction

The spatiotemporal evolution of urban–rural spatial interaction is presented in Figure 10.

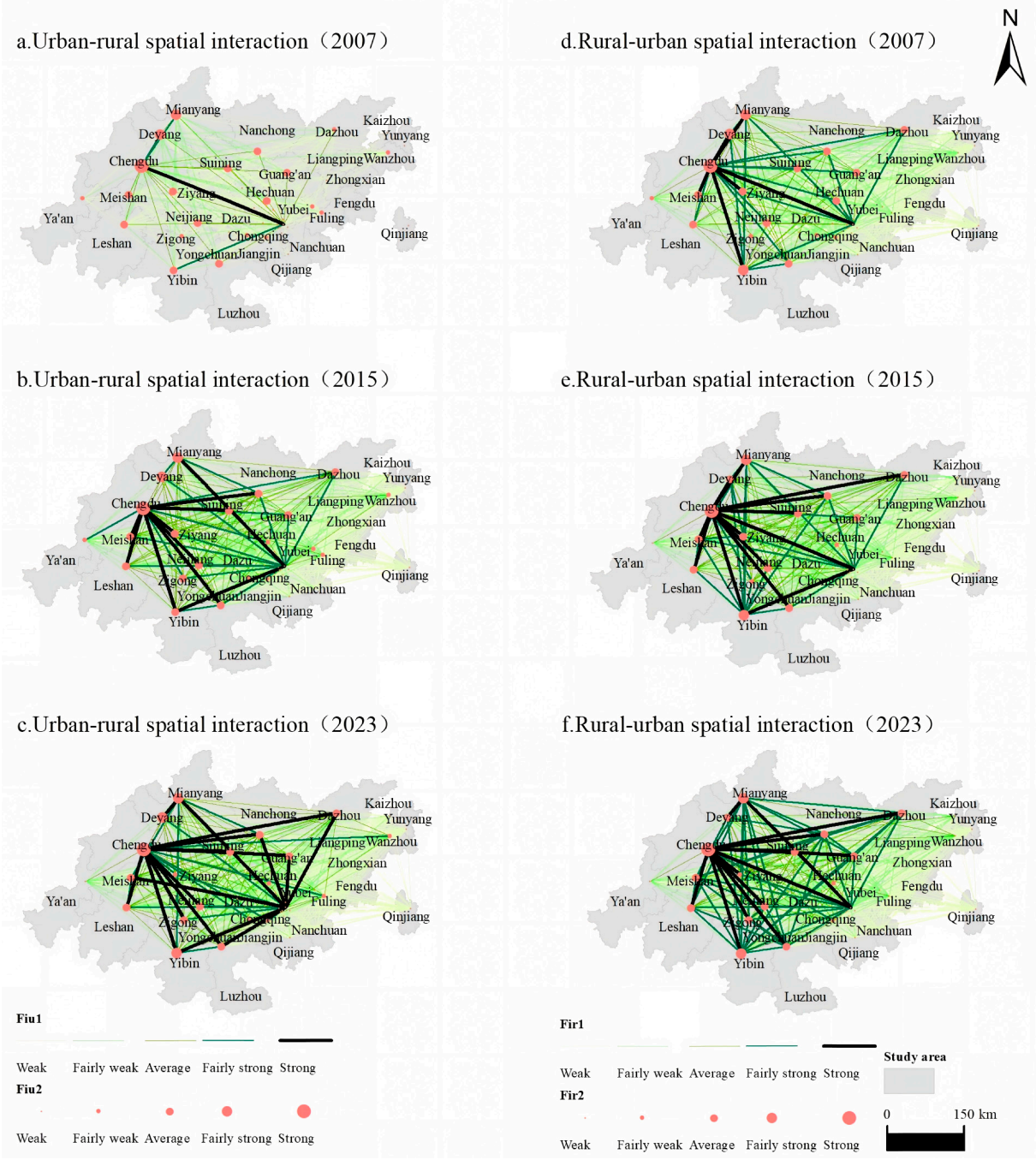


Figure 10. Spatiotemporal evolution of intra-unit and cross-unit urban–rural interaction indices.

1. Urban-to-rural spatial interaction

Urban-to-rural spatial interaction generally shows the characteristics of an emerging corridor effect and increasingly intensified cross-regional connections. From the perspective of intra-regional interaction, the urban-to-rural interaction intensity (Fiu2) presents a stepped distribution pattern decreasing from the northwest to the southeast. From 2007 to 2023, the influence of urban systems on rural systems between the Chengdu–Chongqing

dual cores gradually increased, indicating that cities along the Chengdu–Chongqing development axis played an increasingly stronger role in driving local rural territorial systems.

From the perspective of cross-regional interaction, the urban-to-rural interaction intensity (Fiu1) formed a connection network mainly supported by the Chengdu–Chongqing dual cores and the Chengdu–Chongqing development axis. The network structure became increasingly complex, and the number of connecting lines continued to increase. In 2007, relatively strong connections were mainly concentrated between the Chengdu–Chongqing dual cores and their adjacent areas, and the overall network was relatively sparse. In 2015, the connections further extended along the Chengdu–Chongqing axis, and interactions along the Chengdu–Chongqing corridor were strengthened. By 2023, the cross-regional connection network had further intensified, with high-intensity connections still mainly distributed along the Chengdu–Chongqing corridor and its adjacent areas, showing clear concentration around core nodes and axial areas.

Overall, high-intensity urban-to-rural connections were mainly concentrated in the core areas and along the Chengdu–Chongqing corridor, while peripheral areas generally showed weaker interaction intensity. This indicates that the spatial diffusion of urban-to-rural interaction remained relatively limited.

2. Rural-to-urban spatial interaction

Rural-to-urban spatial interaction generally shows the characteristics of stable intra-regional connections and continuously intensified cross-regional networks. Compared with urban-to-rural interaction, the intra-regional rural-to-urban interaction intensity (Fir2) was generally more stable, with limited changes in its spatial pattern from 2007 to 2023. High-value nodes persisted throughout the study period, indicating that rural territorial systems maintained relatively stable connections with local urban territorial systems and continued to support urban systems.

From the perspective of cross-regional interaction, the rural-to-urban interaction intensity (Fir1) showed a more evident trend of network expansion. In 2007, cross-regional connections were mainly concentrated in the Chengdu–Chongqing dual cores and their adjacent areas. After 2015, cross-regional rural-to-urban connections increased significantly, and the participation of nodes along the Chengdu–Chongqing axis and on the Sichuan side further improved. By 2023, the cross-regional connection lines became more intensive, and Sichuan-side nodes such as Chengdu, Deyang, Suining, Nanchong and Neijiang played a more prominent role in the network. In contrast, except for Chongqing's central urban area and a few nodes along the corridor, some peripheral nodes on the Chongqing side remained at the edge of the network.

Overall, rural-to-urban interaction gradually formed a networked pattern mainly supported by the Chengdu–Chongqing dual cores, the Chengdu–Chongqing development axis and corridor nodes on the Sichuan part.

6.2.2. Urban–Rural Integration

As shown in Figure 11, the urban–rural integration level in the CCEC generally increased from 2007 to 2023, although spatial differentiation remained evident. Because the maps for the three years use a unified classification scheme, the contraction of low-value areas and the expansion of moderate- and high-value areas provide a direct indication of the phased improvement in urban–rural integration. However, this spatial evolution did not take the form of continuous diffusion along the Chengdu–Chongqing axis. Instead, it was characterized by stable core areas, selective node upgrading and local differentiation. High URI values were consistently concentrated in Chengdu, the central urban area of Chongqing, and nearby core nodes such as Deyang and Mianyang, indicating that high-level urban–rural integration mainly relied on regional core cities and their surround-

ing hinterlands. Meanwhile, some areas in southern and northeastern Sichuan showed higher URI levels, suggesting that urban–rural integration improved in certain peripheral nodes and that regional urban–rural factor linkages and functional coordination were strengthened to some extent.

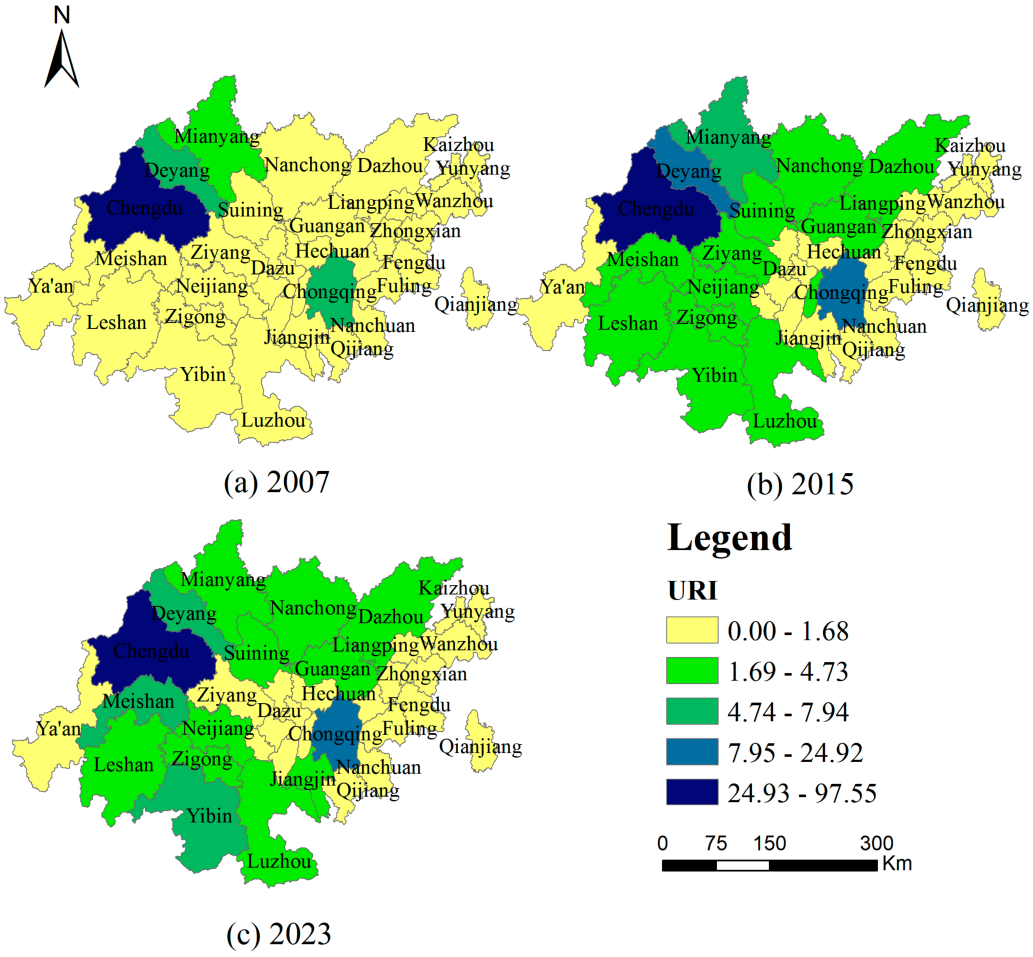


Figure 11. Spatiotemporal evolution of the urban–rural integration index.

It is worth noting that the Chengdu–Chongqing corridor did not form a continuous high-value belt. During 2015–2023, some corridor nodes experienced stagnation or decline in URI, indicating that corridor strengthening does not necessarily lead to a linear improvement in local urban–rural integration. URI is jointly determined by urban–rural coordination deviation, urbanity and rurality, and bidirectional spatial interaction. Although corridor areas may receive stronger regional linkages and factor flows, these flows may primarily serve the expansion of the urban system if rural development capacity and urban–rural factor coordination do not improve simultaneously. This suggests that stronger corridor linkages alone were insufficient to produce a continuous increase in urban–rural integration along the Chengdu–Chongqing axis.

6.3. Driving Mechanisms of Urban–Rural Integration of CCEC

6.3.1. Variable Processing and Multicollinearity Diagnosis

To match the temporal design of this study, the geographical detector analysis was conducted separately for 2007–2015, 2015–2023, and 2007–2023, with 44 county-level units in each period, as in Table 3. The dependent variable was defined as the rate of change in the urban–rural integration index for each period. VIF diagnostics were conducted with

10 as the reference threshold, and X9, X10, X11, X14, and X15 were excluded before the geographical detector analysis.

Table 3. Variance inflation factor results for the retained explanatory variables.

Indicator	2007–2015 VIF	2015–2023 VIF	2007–2023 VIF
X1: Urban resident population	4.57	1.52	3.62
X2: Secondary and tertiary sector value added	1.84	1.12	1.26
X3: Engel coefficient of rural residents	1.34	1.35	1.45
X4: Total agricultural machinery power per unit crop sown area	1.33	7.25	4.36
X5: Green coverage rate of built-up areas	1.49	1.27	1.27
X6: Terrain ruggedness index	1.92	1.78	1.85
X7: Shortest road distance to Chengdu or the central urban area of Chongqing	2.15	2.88	2.52
X8: Total retail sales of consumer goods per capita	5.79	6.48	4.40
X12: Classified highway density	1.72	1.55	1.30
X13: Number of schools per 10,000 people	1.96	1.50	2.40
X16: Policy-planning strategic location level	1.72	1.58	2.37
X17: Provincial boundary adjacency variable	1.80	1.62	1.92

6.3.2. Factor Detection Results

As in Table 4, the factor detection results show that the explanatory power of individual factors was generally limited under the three-class quantile discretization scheme. This indicates that changes in urban–rural integration were not dominated by any single explanatory factor. Nevertheless, some stage-specific differences can still be observed.

Table 4. Factor detection results based on the geographical detector.

Indicator	Indicator Name	2007–2015	2015–2023	2007–2023
X1	Urban resident population	0.068	0.058	0.057 *
X2	Secondary and tertiary sector value added	0.094 *	0.037	0.036
X3	Engel coefficient of rural residents	0.058	0.021	0.047
X4	Total agricultural machinery power per unit crop sown area	0.052	0.133 **	0.042
X5	Green coverage rate of built-up areas	0.011	0.054	0.048
X6	Terrain ruggedness index (TRI)	0.049	0.037	0.042
X7	Shortest road distance to Chengdu or the central urban area of Chongqing	0.048	0.004	0.041
X8	Total retail sales of consumer goods per capita	0.098 *	0.019	0.052
X12	Classified highway density	0.003	0.023	0.050
X13	Number of schools per 10,000 people	0.040	0.100 *	0.057 *
X16	Policy-planning strategic location level	0.019	0.019	0.008
X17	Provincial boundary adjacency variable	0.004	0.020	0.013

Note: Values are q-statistics. * and **, indicate $p < 0.10$ and $p < 0.05$, respectively.

During 2007–2015, economic factors showed relatively higher explanatory power. The q values of total retail sales of consumer goods per capita (X8) and secondary and tertiary sector value added (X2) were 0.098 and 0.094, respectively, ranking highest among all factors in this period. This suggests that, in the early stage, changes in urban–rural integration were more closely associated with local economic vitality and non-agricultural economic development.

During 2015–2023, agricultural production conditions and public service provision became more prominent. Total agricultural machinery power per unit crop sown area (X4)

had the highest q value of 0.133, followed by the number of schools per 10,000 people (X13), with a q value of 0.100. This implies that improvements in agricultural modernization and educational service capacity were more closely related to the spatial differentiation of urban–rural integration changes in this period.

Over the whole period from 2007 to 2023, the q values of individual factors remained relatively low. Urban resident population (X1) and the number of schools per 10,000 people (X13) showed relatively higher explanatory power, with q values of 0.057. This suggests that population urbanization and educational resource allocation maintained a certain association with long-term changes in urban–rural integration, although their individual explanatory power was still limited.

Overall, the factor detection results indicate that no single factor can sufficiently explain the spatial differentiation of urban–rural integration changes. The relatively low q values of individual factors further suggest that urban–rural integration is a complex process shaped by multiple dimensions. Therefore, interaction detection is needed to further examine the compound explanatory effects among different factors.

6.3.3. Interaction Detection Results

The interaction detection results further show that the joint explanatory power of factor pairs was substantially higher than that of individual factors. All reported interactions exhibited nonlinear enhancement, indicating that changes in urban–rural integration were more closely associated with compound factor combinations than with isolated explanatory factors, shown in Table 5.

Table 5. Interaction detection results based on the geographical detector.

Period	Interaction	q_i	q_j	q(Xi∩Xj)	Interaction Type	Overlay Strata	Min n
2007–2015	X6 × X16	0.049	0.019	0.501 ***	Nonlinear enhancement	5	2
	X7 × X16	0.048	0.019	0.483 ***	Nonlinear enhancement	5	2
	X4 × X13	0.052	0.040	0.341 **	Nonlinear enhancement	9	3
	X1 × X4	0.068	0.052	0.306 **	Nonlinear enhancement	9	4
	X13 × X16	0.040	0.019	0.269 *	Nonlinear enhancement	6	2
2015–2023	X4 × X13	0.133	0.100	0.344 *	Nonlinear enhancement	9	2
	X4 × X7	0.133	0.004	0.331 *	Nonlinear enhancement	9	2
	X4 × X5	0.133	0.054	0.329 *	Nonlinear enhancement	9	2
	X5 × X13	0.054	0.100	0.324 *	Nonlinear enhancement	9	4
	X4 × X6	0.133	0.037	0.299 *	Nonlinear enhancement	9	3
2007–2023	X7 × X8	0.041	0.052	0.477 **	Nonlinear enhancement	9	2
	X1 × X5	0.057	0.048	0.331 ***	Nonlinear enhancement	9	3
	X6 × X8	0.042	0.052	0.307	Nonlinear enhancement	9	3
	X2 × X8	0.036	0.052	0.307	Nonlinear enhancement	8	3
	X8 × X12	0.052	0.050	0.256 *	Nonlinear enhancement	9	3

Note: The *p*-values for q(Xi∩Xj) were obtained using 9999 permutation tests. *, **, and *** indicate $p < 0.10$, $p < 0.05$, and $p < 0.01$, respectively.

During 2007–2015, the strongest interactions were mainly related to natural conditions, location accessibility, and policy-planning location. The interaction between terrain ruggedness index (X6) and policy-planning strategic location level (X16) showed the highest joint explanatory power, with a q value of 0.501, followed by the interaction between shortest road distance to Chengdu or the central urban area of Chongqing (X7) and X16, with a q value of 0.483. These results suggest that, in the early stage, the spatial differentiation of urban–rural integration changes was closely associated with the combined effects of terrain constraints, core-city accessibility, and policy-planning location. The combinations of X4 × X13 and X1 × X4 also showed relatively high explanatory power, indicating a

joint explanatory relationship between agricultural mechanization, educational resource allocation, and changes in the urban resident population. However, compared with the combinations involving terrain, distance, and policy-planning strategic location, the explanatory power of these county-level internal development factors remained relatively weaker. This suggests that their roles had already emerged in the early stage, but they had not yet become key explanatory factors.

During 2015–2023, the interaction structure clearly shifted toward county-level internal development factors centered on agricultural production conditions. The interaction between X4 and X13 showed the highest explanatory power, indicating that agricultural mechanization and educational public service provision were jointly associated with changes in urban–rural integration. The combinations of X4 × X7, X4 × X5, and X4 × X6 also ranked among the leading interactions, suggesting that the role of agricultural production conditions should be examined together with location accessibility, built-up environmental quality, and terrain conditions. An increase in agricultural mechanization reflects improvements in agricultural production efficiency, while the number of schools and the green coverage rate of built-up areas respectively represent public service provision and urban environmental quality. Meanwhile, the presence of X7 and X6 indicates that accessibility to core cities and terrain conditions still constituted important spatial contexts. Overall, after 2015, the explanatory focus of urban–rural integration changes gradually shifted from policy location and external spatial conditions in the earlier stage to the combined effects of agricultural production efficiency, public service provision, urban carrying capacity, and spatial accessibility.

Over the whole study period from 2007 to 2023, X8 appeared repeatedly in several major interaction combinations, indicating that consumer-market vitality was an important factor associated with long-term changes in urban–rural integration. Among these combinations, X7 × X8 showed the highest explanatory power, suggesting that county-level consumer-market vitality was closely related to road accessibility to the core urban areas of Chengdu and Chongqing, as well as to the broader regional market. In other words, the explanatory role of market vitality in urban–rural integration changes needs to be understood in the context of location accessibility and the strength of regional connections.

Meanwhile, X8 also formed high-explanatory-power combinations with X6, X2, and X12, indicating that long-term changes in urban–rural integration were not merely associated with differences in consumption levels, but were also jointly related to terrain conditions, industrial-economic foundations, and transport infrastructure. Counties with more active consumer markets, stronger industrial support, and better transport connections were more likely to develop flows of people, goods, and services between urban and rural areas. In contrast, in areas with rugged terrain or insufficient transport connectivity, market linkages and urban–rural functional integration may have been constrained to some extent.

In addition, the enhanced interaction between X1 and X5 indicates that long-term changes in urban–rural integration were not only related to urban population agglomeration but also depended on whether urban environmental quality could support population carrying capacity and improvements in living quality.

Overall, changes in urban–rural integration during 2007–2023 reflected a long-term cumulative process shaped by the joint effects of market vitality, transport connections, industrial foundations, population carrying capacity, and urban environmental quality.

7. Discussion

7.1. Urban–Rural Restructuring and Spatial Interaction

Existing studies generally suggest that urban–rural integration is not merely reflected in the reduction of urban–rural development disparities but represents the restructuring of territorial relationships through factor flows, functional complementarity and spatial reorganization. This study further demonstrates that urban–rural integration in the CCEC exhibits significant stage dependence and spatial dependence, resulting from the combined effects of urbanization, urban–rural functional restructuring and regional network transformation.

From the perspective of urban–rural factor restructuring, the CCEC shows a pattern of continuous urban concentration of population and land factors, accompanied by a relatively balanced distribution of economic factors between urban and rural areas. This indicates that urban–rural integration does not imply the equalization of all factors between urban and rural systems, nor does it represent a simple convergence of rural areas toward urban development patterns. Instead, it reflects a dynamic process of reallocating population, land and economic functions during urbanization. The continued concentration of population and land highlights the agglomeration role of urban areas as regional development centers, while the relative balance of economic factors reflects the deepening of urban–rural industrial linkages and regional division of functions. Therefore, urban–rural integration should be understood as a process of restructuring territorial functions rather than merely an improvement in development levels.

From the perspective of spatial interaction, this study further reveals the spatial organization mechanism of urban–rural integration in a dual-core mountainous urban agglomeration. Unlike the relatively compact and multi-node interactive spatial structure of the Changsha–Zhuzhou–Xiangtan urban agglomeration, the CCEC still exhibits a strong core-dependent pattern. Urban-to-rural interactions are mainly concentrated around the Chengdu–Chongqing dual cores and major development corridors, whereas rural-to-urban interactions show a more dispersed network structure. This suggests that dual-core development can enhance regional diffusion capacity but does not automatically generate balanced urban–rural integration. For the CCEC, the transition from dual-core-driven development to multi-node coordination requires not only strengthening the spillover capacity of core cities but also improving the ability of intermediate nodes and peripheral areas to absorb resources and participate in regional networks.

From the perspective of driving mechanisms, this study confirms previous findings that urban–rural integration is jointly influenced by economic development, public services, infrastructure and regional linkages [50]. More importantly, the results show that these factors do not operate independently but generate stage-specific effects through interaction. This finding provides the basis for constructing the mechanism framework discussed below.

7.2. Mechanism Framework

Based on the above analysis, this study further proposes a mechanism framework for urban–rural integration in dual-core mountainous urban agglomerations.

Urban–rural integration is first influenced by county-level endogenous development capacity. Population concentration, industrial development and agricultural production capacity provide the foundation for factor integration and functional transformation between urban and rural areas. Second, spatial conditions affect the formation of urban–rural linkages. Terrain constraints, accessibility and locational advantages determine the ability of different areas to participate in regional networks and receive spillover effects from core cities. Third, the policy environment supports urban–rural factor flows by improving development conditions through spatial planning, infrastructure construction and public resource allocation. Meanwhile, regional network connections strengthen the flows of pop-

ulation, industries, capital and information, promoting closer functional linkages between urban and rural areas.

Overall, urban–rural integration is not driven by a single factor, but results from the combined effects of multiple conditions. For western urban agglomerations with dual-core structures and complex terrain, the key to urban–rural integration is not simply expanding urban scale, but improving the connectivity among core cities, regional nodes and rural areas to promote a more coordinated regional network.

7.3. Policy Implications

First, the construction of development corridors should not be simply equated with improvements in urban–rural integration. Transportation and spatial connections can facilitate factor flows, but only when the development capacity and resource absorption ability of corridor areas are strengthened can these external linkages be transformed into local integration outcomes.

Second, the capacity of peripheral areas to participate in regional networks should be enhanced. For mountainous and marginal areas with weak urban–rural interactions, efforts should focus on improving transportation conditions, optimizing public service allocation and strengthening market connections, thereby enhancing their ability to receive spillover effects from core cities.

Third, integrated policies involving multiple factors should be promoted. The driving mechanism results indicate significant interactions among agricultural modernization, public services, consumer markets and transport infrastructure. Therefore, urban–rural integration requires coordinated efforts to improve agricultural production capacity, enhance public service provision and strengthen urban–rural market connections, rather than relying on a single policy instrument or isolated investment.

8. Conclusions

This study developed a spatial interaction-based framework for measuring urban–rural integration and revealed its evolutionary characteristics and driving mechanisms in the CCEC from 2007 to 2023. The results show that urban–rural relations in the CCEC have gradually shifted from factor differentiation toward functional restructuring. Population and land factors continued to concentrate in urban areas, while economic factors became relatively more balanced between urban and rural systems. Spatial interactions exhibited clear directional and scale effects: urban-to-rural interactions were mainly dependent on the dual cores and development corridors, whereas rural-to-urban interactions formed a more dispersed network structure. However, core–periphery disparities remained evident. The driving mechanism analysis indicates that urban–rural integration is not determined by a single factor but represents a stage-dependent process shaped by the combined effects of economic foundations, spatial conditions, policy environments and regional linkages.

The main contribution of this study is to clarify the explanatory pathways associated with urban–rural integration in dual-core regions that are still in the development stage of urban agglomeration. The results demonstrate that policy-planning location does not directly promote the formation of multi-node networks; instead, it influences the ability of peripheral areas to participate in regional factor flows through interactions with terrain conditions, accessibility to core cities and county-level development capacity. This provides a new perspective for understanding the evolution pathways of urban–rural integration in mountainous urban agglomerations.

In addition, some conventional explanatory variables, such as urbanization rate and industrial structure, were not directly included in the driving mechanism analysis, which may partly explain the relatively limited explanatory power of individual factors. This

is because population, land and economic factors are already core components of the URI measurement system, and including them again as explanatory variables may cause endogenous overlap between measurement outcomes and driving factors. Therefore, this study treats these factors as manifestations of urban–rural integration and focuses on identifying the effects of policy environments, spatial conditions and regional linkages. This approach helps separate the influence of basic development conditions and further reveals the pathways through which policy guidance shapes urban–rural integration.

This study also has several limitations. The URI is calculated by integrating multiple sub-indices. Although this framework can comprehensively capture the restructuring of urban–rural relations, the complexity of the calculation process may introduce uncertainty into the results. Future studies should further examine the robustness of URI under different index specifications. For example, using total values to measure cross-regional spatial interactions may be affected by differences in regional size, thereby exaggerating cross-regional linkages and weakening the identification of intra-regional interactions. Due to limitations in the availability of fine-scale mobility and flow data, urban–rural interaction relationships identified in this study are model-based estimates rather than direct observations of actual factor flows.

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