Integrated Development and Interactive Effects of Urban Functions and Rural Functions in Gansu Province

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Abstract

The complementary symbiosis between urban functions and rural functions is not only the core essence of urban-rural integration but also a key pathway to resolving the urban-rural dualistic contradiction. Based on municipal panel data from Gansu Province from 2011 to 2023, this study constructs an evaluation system for urban functions and rural functions, employs the entropy-weighted TOPSIS method and three-dimensional kernel density estimation to analyze the spatiotemporal evolution characteristics of urban and rural functions, uses a coupling coordination degree model to assess the integrated development level of urban and rural functions, and reveals their interactive effects through a simultaneous equation model. The results show that: (1) both urban functions and rural functions in Gansu Province exhibit an upward trend. Urban functions present a spatial pattern of "aggregation along axes and gradient differentiation," while rural functions present a spatial pattern of "east-west differences and belt-like extension." (2) The integrated development level between urban functions and rural functions in Gansu Province has continuously improved and shows spatial convergence with the level of urbanization. (3) There is an interactive reinforcing effect between urban functions and rural functions in Gansu Province. Economic level, government regulation, and technological level promote both urban and rural functions; urban capital factors and urban labor factors have positive effects on urban functions, while rural capital factors and rural labor factors have positive effects on rural functions.

Full Text

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Abstract: The complementary symbiosis between urban functions and rural functions is not only the core meaning of urban-rural integration, but also a key pathway for resolving the urban-rural dualistic contradiction. Based on municipal panel data for Gansu Province from 2011 to 2023, this study constructs an evaluation system for urban functions and rural functions, and uses the entropy-weight TOPSIS method and three-dimensional kernel density estimation to analyze the spatiotemporal evolution characteristics of urban functions and rural functions. It employs a coupling coordination model to analyze the level of integrated development between urban functions and rural functions, and reveals their interactive effects through a simultaneous-equations model. The results show that: (1) Both urban functions and rural functions in Gansu

Province exhibit an upward trend. Urban functions present a spatial pattern of "aggregation along the axis and differentiation by gradient," while rural functions present a spatial pattern of "east-west differences and belt-like extension." (2) The level of integrated development between urban functions and rural functions in Gansu Province has continuously strengthened, and it shows spatial convergence with the level of urbanization. (3) There is an interaction-strengthening effect between urban functions and rural functions in Gansu Province. Economic level, government regulation, and technological level all have promoting effects on both urban functions and rural functions; urban capital factors and urban labor factors have positive effects on urban functions; and rural capital factors and rural labor factors have positive effects on rural functions.

Keywords: urban functions; rural functions; integrated development; interactive effects; Gansu Province

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The integrated development and interactive effects of urban functions and rural functions are not only a process in which urban-rural advantages complement each other and elements reciprocate, but also a scientific issue jointly concerned with new-type urbanization construction and comprehensive rural revitalization[^1]. Because of differences in agglomeration scale and functional division of labor, towns and villages form corresponding urban functions and rural functions. The degree of connection between urban functions and rural functions determines the dynamic characteristics of urban-rural relations[^2]. The integrated development and functional complementarity of urban functions and rural functions are not only key measures for resolving urban-rural antagonistic contradictions, but also the logical foundation for constructing two-way flows of urban-rural elements[^3]. Thus, what is the relationship of integrated development between urban functions and rural functions? Is there an interaction between urban functions and rural functions? By analyzing the spatiotemporal evolution characteristics of urban functions and rural functions, this study reveals their integrated development and interactive effects, providing a theoretical basis for benign mutual promotion between urban functions and rural functions.

Towns and villages are not mutually separated spatial units, but communities that influence each other. Promoting functional complementarity between urban and rural areas is the key to urban-rural integration[^4]. Foreign research has focused on differences in elements between urban and rural areas[^5], mainly involving urban-rural human capital[^6], urban-rural medical services[^7], urban-rural welfare conditions[^8], and so on. Domestic scholars' research on urban-rural relations is embedded in the study of urban-rural integration and mainly includes four aspects: (1) elaborating the theoretical connotations of urban-rural integration from perspectives such as the laws of urban-rural socioeconomic development[^9] and the transformation of urban-rural land use[^10]; (2) selecting economic, population, spatial, social, environmental, and other elements to construct evaluation systems to measure the level of urban-rural integration[^11-13], and using methods such as hotspot analysis[^14], cluster analysis[^15], and landscape analysis[^16] to analyze the spatiotemporal characteristics of urban-rural integration; (3) using methods such as panel data models[^17] and spatial regression models[^18] to analyze the influencing factors of urban-rural integration; and (4) taking urban agglomerations[^19], typical provinces[^20], typical cities[^21], urban-rural interfaces[^22], and other areas as study areas to condense practical models of urban-rural integration. Therefore, eliminating barriers between urban and rural areas and constructing an urban-rural relationship with complementary functions have become an academic consensus.

Urban-rural relations are moving from mutual segmentation toward integrated development, and from one-way dependence toward two-way interaction. This requires two-way flows of production factors and functional complementarity to achieve a dynamic equilibrium between urban functions and rural functions[^23]. On the one hand, the agglomeration effect causes production factors to flow from villages to towns, promoting the development of new-type urbanization and the improvement of urban functions[^24]; on the other hand, the diffusion effect causes production factors to flow from towns to villages, promoting comprehensive rural—

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surface revitalization and the enhancement of rural functions[1]. Under the joint effects of agglomeration and diffusion effects, production factors flow between urban and rural areas; the integrated development and interactive influence of urban functions and rural functions also evolve repeatedly, ultimately realizing urban-rural integration[2]. Urban-rural integration is not homogenization between urban and rural areas; rather, only by achieving mutual complementarity and symbiosis between urban functions and rural functions can the essence of urban-rural integration be realized[3]. Therefore, identifying the development levels of urban functions and rural functions through territorial function theory, and on this basis revealing their integrated development and interactive influence, can both deepen academic research on the restructuring of urban-rural

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relations and refine an urban-rural integration pathway that meets practical needs.

In summary, it is necessary to conduct research on urban-rural relations from the perspective of the interaction between urban functions and rural functions. However, because of differences in resource endowments and economic development, urban-rural relations exhibit regional differentiation. While attention is paid to the whole country and to the developed eastern regions, research on the development of urban-rural relations in typical provinces of western China helps enrich theoretical research on urban-rural relations in western China[4]. Gansu Province has typical characteristics of urban-rural relations in western China[5]: (1) contradictions in the allocation of urban-rural resources are prominent; the "siphon effect" leads production factors to agglomerate in towns, while the degree to which production factors diffuse from towns to rural areas is relatively weak. (2) Urban-rural socioeconomic development is uneven, and the unbalanced allocation of production factors between urban and rural areas constrains the simultaneous improvement of urban functions and rural functions. (3) Urban-rural interactive development is slow; although the socioeconomic situation is growing, the driving force for urban-rural interactive development is insufficient. Therefore, based on municipal panel data for Gansu Province from 2011 to 2023, and on the basis of analyzing the development levels of urban functions and rural functions, this study uses a coupling coordination degree model and a simultaneous-equations model to reveal the integrated development and interactive influence of urban functions and rural functions.

1 Data and Methods

1.1 Evaluation System

Territorial function theory divides the surface space of human activities into two basic functional units—urban and rural—according to factors such as the scale of economic agglomeration, differences in social functions, land-use patterns, and ecological-cultural landscapes[6]. Towns are the main spatial carriers for advancing new-type urbanization and industrialization, while rural areas are the main spatial carriers for realizing rural revitalization and the production of agricultural and sideline products. Because towns and rural areas carry differentiated economic and social activities, urban functions and rural functions are formed respectively. Both urban functions and rural functions can be concretized as corresponding production functions, living functions, and ecological functions[7]. Therefore, this study measures urban functions and rural functions from three dimensions: production function, living function, and ecological function (Figure 1).

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Urban functions are mainly characterized by economic agglomeration and radiating drive. From the three aspects of production function, living function, and ecological function, 15 indicators are selected to construct an urban function evaluation system[8]. Urban production functions can increase the production of non-agricultural products, improve non-agricultural spatial construction, and realize the allocation of material transportation; thus, the added value of the secondary industry, the added value of the tertiary industry, built-up area, urban population size, and road-network density are used to characterize urban production functions. Urban living functions can provide labor and consumer demand for production activities, and can also raise the income level of urban residents, strengthen consumption capacity, and improve living conditions; thus, per capita disposable income of urban residents, per capita consumption expenditure of urban residents, total retail sales of urban social consumer goods, number of beds in urban hospitals, and urbanization rate are used to characterize urban living functions. Urban ecological functions can improve the ecological environment through energy-conservation and emission-reduction measures, and can also create a suitable living environment by increasing the greening rate; thus, industrial solid-waste generation, industrial waste-gas emissions, industrial wastewater discharge, energy consumption per unit of GDP, and green coverage rate in built-up areas are used to characterize urban ecological functions.

Rural functions are mainly based on factor support and ecological security. From the three aspects of production function, living function, and ecological function, 15 indicators are selected to construct a rural function evaluation system[9]. Rural production functions can create a material basis by providing agricultural and sideline products and improving agricultural production efficiency, and can also provide economic support for ecological restoration; thus, sown area of grain crops, sown area of cash crops, added value of agriculture, forestry, animal husbandry, and fishery, rural population size, and total power of agricultural machinery are used to characterize rural production functions. Rural living functions can provide labor and innovation factors for production activities, and can also improve living conditions and quality of life by raising rural residents' income levels and strengthening consumption capacity; thus, per capita disposable income of rural residents, per capita consumption expenditure of rural residents, total retail sales of rural social consumer goods, number of beds in health centers, and the rural Engel coefficient are used to characterize rural living functions. Rural ecological functions can ensure agricultural production through the organicization of agricultural production, and can also improve the quality of residential environments by enhancing the ecological environment; thus, fertilizer use per unit of cultivated land, grassland area, vegetation coverage index, disaster-affected area in each city/prefecture, and the proportion of days with excellent year-round air quality are used to characterize rural ecological functions.

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In the context of increasingly close urban–rural linkages, urban–rural relations have shifted from one-way dependence to urban–rural interaction. On the one hand, urban–rural integration requires urban functions and rural functions to exert their respective comparative advantages and unique values through factor flows and functional feedback. This study identifies this process through the coupled development between urban and rural functions[10]. On the other hand, the reshaping of the urban–rural symbiotic relationship is reflected in the interactive influence between urban and rural areas: towns extend non-agricultural industries and technical services to rural areas, while ecological products and factor resources from rural areas are transferred to towns, forming functional complementation and transformation between urban and rural areas. This study will examine this through urban–rural

Indicator	Function
U_1: Added value of the secondary industry $(+, 0.246)$ U_2: Added value of the tertiary industry $(+, 0.214)$ U_3: Built-up area $(+, 0.194)$ U_4: Urban population size $(+, 0.181)$ U_5: Road-network density $(+, 0.165)$	Urban production function $(+, 0.382)$
U_6: Per capita disposable income of urban residents $(+, 0.221)$ U_7: Per capita consumption expenditure of urban residents $(+, 0.193)$ U_8: Total retail sales of urban consumer goods $(+, 0.178)$ U_9: Number of beds in urban hospitals $(+, 0.183)$ U_{10}: Population urbanization rate $(+, 0.225)$	Urban living function $(+, 0.317)$
U_{11}: Industrial solid-waste generation $(-, 0.204)$ U_{12}: Industrial waste-gas emissions $(-, 0.206)$ U_{13}: Industrial wastewater discharge $(-, 0.206)$ U_{14}: Energy consumption per unit GDP/tce $(-, 0.213)$ U_{15}: Green coverage rate of built-up areas $(+, 0.176)$	Urban ecological function $(+, 0.301)$

Fusion development; factor flow; functional complementarity; interactive influence; urban function; rural function.

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Function	Indicator
Rural production function $(+, 0.325)$	R_1: Grain-crop sown area $(+, 0.328)$ R_2: Cash-crop sown area $(+, 0.186)$ R_3: Added value of agriculture, forestry, animal husbandry, and fishery $(+, 0.162)$ R_4: Rural population size $(+, 0.173)$ R_5: Total power of agricultural machinery $(+, 0.151)$
Rural living function $(+, 0.303)$	R_6: Per capita disposable income of rural residents $(+, 0.256)$ R_7: Per capita consumption expenditure of rural residents $(+, 0.193)$ R_8: Total retail sales of rural consumer goods $(+, 0.172)$ R_9: Number of beds in health centers $(+, 0.146)$ R_{10}: Engel coefficient of rural households $(-, 0.223)$
Rural ecological function $(+, 0.372)$	R_{11}: Amount of chemical fertilizer applied per unit cultivated land $(-, 0.189)$ R_{12}: Grassland area $(+, 0.211)$ R_{13}: Vegetation coverage index $(+, 0.212)$ R_{14}: Disaster-affected area of prefectures and prefecture-level cities $(+, 0.175)$ R_{15}: Proportion of days with excellent air quality throughout the year $(+, 0.213)$

Note: "+" indicates a positive indicator; "−" indicates a negative indicator; the values in parentheses are the weights of the respective indicators.

Figure 1 Evaluation system of urban function and rural function

Fig. 1 Evaluation system of urban function and rural function

the identification process of the interactive influence among multiple functions[^39].

1.2 Research methods

1.2.1 Entropy-weight TOPSIS method

The entropy-weight TOPSIS method combines the entropy method with the TOPSIS model, comprehensively considering indicator weights and the degree of proximity to the ideal solution, and can identify the comprehensive influence of multiple indicators[^40]. Therefore, the entropy-weight TOPSIS method is used to measure the development levels of urban function and rural function. First, the range standardization method is used to standardize the original data; second, the entropy method is used to calculate the information entropy of each indicator and determine its objective weight; finally, based on the TOPSIS method, the positive ideal solution and the negative ideal solution are constructed, and the closeness between each evaluation object and the ideal solution is determined[^41].

1.2.2 Three-dimensional kernel density estimation

Three-dimensional kernel density estimation performs kernel-function weighted summation over the neighborhood of each data point in three-dimensional space, so as to reveal the spatial density characteristics and distribution patterns of the research object. This method can avoid estimation errors caused by the specification of the function itself[^42]. Therefore, the three-dimensional kernel density estimation method is adopted to analyze the temporal evolution characteristics of urban function and rural function.

1.2.3 Coupling coordination degree model

The coupling coordination degree model can effectively characterize the interaction relationship between two systems and quantitatively evaluate their coupling-coordination state. The integrated development of urban function and rural function is the coupling-coordination process between urban and rural systems. The higher the coupling coordination degree, the stronger the level of integrated development between urban function and rural function[^43]. Therefore, the coupling coordination degree model is used to measure the integrated development level of urban function and rural function. The calculation formula is as follows:

$$D_{it} = \sqrt{C_{it} \times T_{it}}$$

$$C_{it} = 2\sqrt{(U_{it} \times R_{it})/(U_{it} + R_{it})^2} \qquad (1)$$

$$T_{it} = \alpha \times U_{it} + \beta \times R_{it}$$

where: D_{it} is the integrated development level of urban function and rural function in city i in year t; C_{it} is the coupling degree of urban function and rural function in city i in year t; T_{it} is the coordination degree of urban function and rural function in city i in year t; U_{it} is the urban function of city i in year t; R_{it} is the rural function of city i in year t; α and β are weight coefficients, and their sum is 1. In this study, urban function and rural function are considered equally important; therefore, both α and β are assigned a value of 0.5.

1.2.4 Simultaneous-equation model

Both towns and villages can be regarded as territorial production spaces, in which corresponding urban functions and rural functions are formed through the input and combination of production factors. Therefore, on the basis of the Cobb-Douglas production function, urban function equations[^44] and rural function equations are constructed separately, with the calculation formulas as follows[^45]:

$$U_{it} = \alpha_0 A_{it}^{\alpha_2} G_{it}^{\alpha_3} \mathrm{KU}_{it}^{\alpha_4} \mathrm{LU}_{it}^{\alpha_5} T_{it}^{\alpha_6} \qquad (2)$$

$$R_{it} = \beta_0 A_{it}^{\beta_2} G_{it}^{\beta_3} \mathrm{KR}_{it}^{\beta_4} \mathrm{LR}_{it}^{\beta_5} T_{it}^{\beta_6} \qquad (3)$$

Taking logarithms on both sides of the standard form of the Cobb-Douglas production function yields the empirical form. Rural function is included as an explanatory variable in the urban function equation, and urban function is included as an explanatory variable in the rural function equation. A simultaneous-equation model is constructed to test the interrelationship between urban function and rural function and its influencing factors. In formula (4), urban function is the explained variable, while rural function, economic level, government regulation, urban capital factors, urban labor factors, and technological···

the level of technology is the explained variable; in formula (5), rural function is the explained variable, and urban function, economic level, government regulation, rural capital factor, rural labor factor, and technological level are explanatory variables. Specifically, it is expressed as follows[46]:

$$\ln U_{it} = \alpha_0 + \alpha_1 \ln R_{it} + \alpha_2 \ln A_{it} + \alpha_3 \ln G_{it} + \alpha_4 \ln \mathrm{KU}_{it} + \alpha_5 \ln \mathrm{LU}_{it} + \alpha_6 \ln T_{it} + \theta_i + \nu_t + \varepsilon_{it} \qquad (4)$$

$$\ln R_{it} = \beta_0 + \beta_1 \ln U_{it} + \beta_2 \ln A_{it} + \beta_3 \ln G_{it} + \beta_4 \ln \mathrm{KR}_{it} + \beta_5 \ln \mathrm{LR}_{it} + \beta_6 \ln T_{it} + m_i + n_t + \lambda_{it} \qquad (5)$$

In the formulas: A_{it} is the economic level of city i in year t, expressed by per capita regional gross domestic product; G_{it} is the government regulation of city i in year t, expressed by general government budget expenditure; KU_{it} is the urban capital factor of city i in year t, expressed by the amount of urban fixed-asset investment; KR_{it} is the rural capital factor of city i in year t, expressed by the amount of rural fixed-asset investment; LU_{it} is the urban labor factor of city i in year t, expressed by the number of employed persons in urban units; LR_{it} is the rural labor factor of city i in year t, expressed by the number of employed persons in rural areas; T_{it} is the technological level of city i in year t, expressed by expenditure on experiments and research. The descriptive statistics of the above variables are shown in Table 1. θ_i and ν_t are the spatial fixed effect and time fixed effect of urban function, respectively; ε_{it} is the residual disturbance term; m_i and n_t are the spatial fixed effect and time fixed effect of rural function, respectively; λ_{it} is the residual disturbance term[47]; α_0 is the constant term, and α_1, α_2, α_3, α_4, α_5, and α_6 are the influence coefficients of rural function, economic level, government regulation, urban capital factor, urban labor factor, and technological level on urban function, respectively; β_0 is the constant term, and β_1, β_2, β_3, β_4, β_5, and β_6 are the influence coefficients of urban function, economic level, government regulation, rural capital factor, rural labor factor, and technological level on rural function, respectively.

1.3 Data Sources

Socioeconomic data and ecological environment data are from the *Gansu Development Yearbook* for 2012–2024; grassland area extraction is based on the 2011–2023 China 30 m land-cover data developed and publicly shared by Yang Jie and Huang Xin of Wuhan University; vegetation coverage index data come from the MOD13A2 data product provided by the National Aeronautics and Space Administration of the United States; land-use data are based on the 30 m spatial-resolution Gansu Province land-use raster data provided by the Geospatial Data Cloud (https://www.gis5g.com/), extracted and calculated using ArcGIS software; administrative division data come from the standard maps on the Standard Map Service website of the Ministry of Natural Resources.

Table 1 Descriptive statistics of variables

Tab. 1 Descriptive statistics of variables

Variable	Meaning	Observations	Standard deviation	Minimum	Maximum
U	Urban function	182	0.174	0.078	0.685
R	Rural function	182	0.196	0.157	0.521
A	Economic level/10^4 yuan · person^{-1}	182	2.619	0.656	13.142
G	Government regulation/10^8 yuan	182	104.351	16.784	502.917

Variable	Meaning	Observations	Standard deviation	Minimum	Maximum
KU	Urban capital factor/10^8 yuan	182	361.775	62.481	1954.269
KR	Rural capital factor/10^8 yuan	182	31.517	4.171	177.579
LU	Urban labor factor/10^4 persons	182	15.501	5.510	79.040
LR	Rural labor factor/10^4 persons	182	48.080	1.250	168.550
T	Technological level/10^8 yuan	182	14.268	0.431	86.338

2 Results and Analysis

2.1 Spatiotemporal Pattern and Integrated Development Characteristics of Urban Function and Rural Function

2.1.1 Temporal evolution characteristics of urban function and rural function MATLAB R2024a software was used to draw three-dimensional kernel density maps of urban function and rural function in Gansu Province, and the temporal evolution characteristics of urban function and rural function were analyzed. The temporal evolution characteristics of urban function in Gansu Province are shown in Fig. 2a: in terms of distribution position, the kernel density curve of urban function shows a rightward shift of the center of gravity, indicating that the urban function of the 14 cities and prefectures

(a) Urban function

(b) Rural function

Fig. 2 Kernel density estimation analysis of urban function and rural function in Gansu Province

horizontally, it generally shows an upward trend; in terms of waveform morphology, it presents a double-peak structure, but the difference between the main peak and the secondary peak is relatively large, indicating that the urban functions of the 14 prefecture-level cities show a trend of polarization. In terms of the tails of the curve, the right tail is longer than the left tail, indicating that the urban functions of the 14 prefecture-level cities are distributed in a clustered pattern and that there is a phenomenon of low-value clustering. The temporal evolution characteristics of rural functions in Gansu Province are as follows (Fig. 2b): in terms of distribution position, the center of gravity of the kernel-density curve for rural functions shifts from left to right, indicating that the rural functions of the 14 prefecture-level cities all show an upward trend. In terms of waveform morphology, it remains a single-peak form, but the waveform gradually becomes wider, indicating that the polarization trend of rural functions among the 14 prefecture-level cities slows over time. In terms of the tails of the curve, the width of the main peak gradually expands, and the left tail is more pronounced than the right tail, indicating that the rural functions of the 14 prefecture-level cities show a dispersed distribution pattern.

2.1.2 Spatial pattern characteristics of urban functions and rural functions The spatial visualization of urban functions in Gansu Province in 2011, 2015, 2020, and 2023 (Fig. 3) shows that the spatial pattern characteristics of urban functions are as follows: (1) Urban functions exhibit a spatial pattern of "aggregation along axes." On the one hand, the Longhai–Lanxin transport axis drives the industrial development and enhancement of urban functions in towns along the line. As an important transportation hub in Northwest China, Lanzhou; Tianshui, as a node city on the Longhai transport axis; and Wuwei and Jiayuguan, as node cities on the Lanxin transport axis, have all benefited in their urban-function improvement from the corridor effect of transport axes. On the other hand, Lanzhou and Tianshui, as traditional industrial bases, are high-value areas of urban functions; Jiuquan and Jiayuguan, where industry is dominated by energy and metallurgy, are medium-value areas of urban functions; and Linxia Hui Autonomous Prefecture (Linxia Prefecture) and Gannan Tibetan Autonomous Prefecture (Gannan Prefecture), where the level of urbanization and industrialization is relatively low, are low-value areas of urban functions. (2) The level of urban functions shows spatial characteristics of "gradient differentiation." In 2011, the urban functions of the prefecture-level cities in Gansu Province ranged from 0.078 to 0.473; in 2023, they ranged from 0.127 to 0.685. Lanzhou has abundant political and economic [[unclear: continuation not visible on this page]].

(a) 2011

Legend

Symbol / category	Meaning
—	National boundary

Symbol / category	Meaning
—	Provincial boundary
—	City/prefecture boundary
Urban function	0.078–0.141
Urban function	0.142–0.183
Urban function	0.184–0.223
Urban function	0.224–0.571
Urban function	0.572–1.000

Map labels: Jiuquan City; Zhangye City; Jinchang City; Wuwei City; Baiyin City; Lanzhou City; Linxia Prefecture; Gannan Prefecture; Dingxi City; Tianshui City; Longnan City; Pingliang City; Qingyang City; Jiayuguan City. North arrow; scale: 0–200 km.

(b) 2015

Legend

Symbol / category	Meaning
—	National boundary
—	Provincial boundary
—	City/prefecture boundary
Urban function	0.078–0.141
Urban function	0.142–0.183
Urban function	0.184–0.223
Urban function	0.224–0.571
Urban function	0.572–1.000

Map labels: Jiuquan City; Zhangye City; Jinchang City; Wuwei City; Baiyin City; Lanzhou City; Linxia Prefecture; Gannan Prefecture; Dingxi City; Tianshui City; Longnan City; Pingliang City; Qingyang City; Jiayuguan City. North arrow; scale: 0–200 km.

(c) 2020

Legend

Symbol / category	Meaning
—	National boundary
—	Provincial boundary
—	City/prefecture boundary
Urban function	0.078–0.141
Urban function	0.142–0.183
Urban function	0.184–0.223

Symbol / category	Meaning
Urban function	0.224–0.571
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Map labels: Jiuquan City; Zhangye City; Jinchang City; Wuwei City; Baiyin City; Lanzhou City; Linxia Prefecture; Gannan Prefecture; Dingxi City; Tianshui City; Longnan City; Pingliang City; Qingyang City; Jiayuguan City.
North arrow; scale: 0–200 km.

(d) 2023

Legend

Symbol / category	Meaning
—	National boundary
—	Provincial boundary
—	City/prefecture boundary
Urban function	0.078–0.141
Urban function	0.142–0.183
Urban function	0.184–0.223
Urban function	0.224–0.571
Urban function	0.572–1.000

Map labels: Jiuquan City; Zhangye City; Jinchang City; Wuwei City; Baiyin City; Lanzhou City; Linxia Prefecture; Gannan Prefecture; Dingxi City; Tianshui City; Longnan City; Pingliang City; Qingyang City; Jiayuguan City.
North arrow; scale: 0–200 km.

Note: Based on the standard map with approval number GS(2019)1822 from the Ministry of Natural Resources' standard map service website; the base-map boundaries have not been modified. Linxia Prefecture and Gannan Prefecture are abbreviations for Linxia Hui Autonomous Prefecture and Gannan Tibetan Autonomous Prefecture, respectively. The same below.

Fig. 3 Spatial patterns of urban function in Gansu Province

economic and educational resources, achieving a positive convergence between urban functions and the level of urbanization; Jiuquan City, Jiayuguan City, and Tianshui City, as regional central cities, have formed a positive convergence between urban functions and urban scale. In contrast, Gannan Prefecture and Linxia Prefecture, located on the edge of the Qinghai–Tibet Plateau and with less convenient transportation, both have relatively low levels of urbanization and urban scale, and their corresponding urban functions are also relatively weak.

Fig. 4 Spatial patterns of rural function in Gansu Province

Figure 1: Fig. 4 Spatial patterns of rural function in Gansu Province

Visualizing the spatial distribution of rural functions in Gansu Province in 2011, 2015, 2020, and 2023 (Fig. 4), the spatial pattern characteristics of rural functions are as follows:
(1) Differentiated resource endowments have led rural functions to present an "east-west difference" pattern. Specifically, in the Longdongnan region, Qingyang City, Pingliang City, Longnan City, Tianshui City, and Gannan Prefecture rely on ecological endowments to develop agriculture, forestry, and specialty breeding industries, forming rural functions dominated by agricultural production and ecological conservation; in the Longzhong region, Lanzhou City, Dingxi City, Baiyin City, and Linxia Prefecture make use of the distinctive soil and water resource conditions of the Loess Plateau to form rural functions dominated by specialty agricultural production; in the Hexi region, Jiuquan City, Jiayuguan City, Jinchang City, Zhangye City, and Wuwei City form rural functions in which oasis agriculture and ecological functions are equally emphasized.

(2) Under the combined influence of transportation location conditions and urban radiation effects, rural functions in Gansu Province show a spatial pattern of "belt-like extension." In 2011, the rural function values of the various cities and prefectures in Gansu Province ranged from 0.157 to 0.342; by 2023, they had risen to 0.278–0.485. In areas such as Lanzhou City, Tianshui City, and Jiuquan City, which are distributed along major railways and highways, because urban-rural economic linkages are close and are driven by the radiation of urban functions, rural function levels are relatively high. Affected by differences in production conditions and resource endowments, high-value areas of rural functions are mainly concentrated in Qingyang City, Tianshui City, Dingxi City, Longnan City, and other places with superior agricultural resource endowments. This pattern not only reflects the promoting effect of transportation and urban radiation on rural functions, but also reveals the important influence of resource endowments on the spatial differentiation of rural functions.

2.1.3 Characteristics of the integrated development of urban functions and rural functions

From 2011 to 2023, the level of integrated development between urban functions and rural functions showed an upward trend (Fig. 5), indicating that during the study period, the new-type urbanization strategy was effectively implemented, and policies for targeted poverty alleviation and comprehensive rural revitalization continued to exert force; the mutual promotion between urban functions and rural functions continued to increase. Urban

Fig. 4 Spatial patterns of rural function in Gansu Province

Fig. 5 Degree of integrated development of urban function and rural function in Gansu Province

Figure 2: Fig. 5 Degree of integrated development of urban function and rural function in Gansu Province

Figure 5 Integrated development level of urban functions and rural functions in Gansu Province

Fig. 5 Degree of integrated development of urban function and rural function in Gansu Province

The integrated development level of town functions and rural functions shows convergence with the urbanization process in its spatial distribution. As the provincial capital, Lanzhou, relying on its comprehensive advantages as a political, economic, and cultural center, has formed the core leading area for the integrated development of urban and rural functions in the province. As the core city of southeastern Gansu, Tianshui, relying on the advantages of agro-tourism integration and distinctive agriculture, has built a favorable pattern of coordinated urban–rural industrial development, and the integration momentum of town functions and rural functions is strong. Jiuquan and Jiayuguan, supported by the new-energy industry and modern agriculture, and Zhangye, Jinchang, and Wuwei, taking advantage of opportunities in integrated watershed governance, have continuously improved their levels of integrated urban–rural functional development. Longnan, Pingliang, and Qingyang, based on their tourism resources and agricultural-resource advantages, have promoted the bidirectional flow of urban–rural factors, and the integration of urban and rural functions has also improved to a certain extent. By contrast, Gannan Prefecture and Linxia Prefecture, constrained by the alpine climate and ecological protection, together with weak infrastructure, inconvenient transportation, and shortages of public services such as education and medical care, remain at relatively low levels in the integrated development of town functions and rural functions.

2.2 Interactive influence between town functions and rural functions

2.2.1 Test of the simultaneous-equations model

Stata 18.0 was used to conduct the F test, Hausman test, and LM test. The F-test results for the town-function equation and the rural-function equation were 172.856 and 144.320, respectively; both passed the significance test, indicating that the explanatory variables have significant effects on the explained variables[^48]. The Hausman test results for the town-function equation and the rural-function equation were 185.335 and 144.231, respectively; both passed the significance test, indicating that fixed effects rather than random effects are appropriate[^49]. The main estimation methods for the simultaneous-equations model are system estimation methods, which estimate the simultaneous-equations model as a whole; specifically, these include the generalized method of moments and three-stage least squares[^50]. To alleviate endogeneity problems, based on Stata 18.0, the generalized method of moments was used for estimation[^51]. To test the reliability of the estimation results, three-stage least squares was also used for verification. In the estimation results of the two methods, the influence coefficients did not change significantly, indicating that the results are robust (Table 2)[^52].

2.2.2 Analysis of the estimation results of the town-function equation

The influence coefficient of rural functions on town functions is significantly positive, indicating that rural functions promote town functions, mainly through three pathways: (1) factor-resource supply. Relying on agricultural-product production bases such as the Hexi Corridor oasis irrigation agricultural belt, the Longzhong dry-farming agricultural area, and the southeastern Gansu characteristic agricultural area, rural areas provide high-quality agricultural products for towns. At the same time, by transferring the agricultural population to non-agricultural industries, they provide labor resources for towns. (2) Ecological-environmental support. Ecological functional areas such as the Qilian Mountains water-source conservation area, the upper Yellow River Gannan Plateau wetland, and the upper Yangtze River Longnan ecological barrier area provide ecological services for towns and reduce the costs of urban environmental governance. (3) Consumer-market support. Consumption upgrading among rural residents can promote the movement of urban industrial products to the countryside, and the extension of service industries such as cultural tourism to rural areas, thereby providing market support for the improvement of town functions.

The influence coefficient of economic level on town functions is significantly positive, indicating that economic level can promote the flow of production factors to towns, form factor agglomeration and optimize resource allocation, increase factor productivity and reduce production governance costs, thereby improving town functions. The influence coefficient of government regulation on town functions is significantly positive, indicating that government regulation guides the agglomeration of capital, technology, talent, and other factors toward core towns, thereby improving town functions. The influence coefficient of urban capital factors on town functions is significantly positive, indicating that an increase in urban capital factors can not only promote the upgrading of urban industries toward high-end and green development, but also drive the construction of urban infrastructure such as transportation, thereby improving town functions. The influence of urban labor factors on town functions is positive ···

Table 2 Estimation results of the interactive effect between urban function and rural functions in Gansu Province

Variable	Urban function equation	Urban function equation	Rural function equation	Rural function equation
	System generalized moment estimation method	Three-stage least squares method	System generalized moment estimation method	Three-stage least squares method
$\ln U$	–	–	0.195^{**}(3.445)	0.188^{**}(3.316)
$\ln R$	0.227^{**}(5.236)	0.219^{**}(5.627)	–	–
$\ln A$	0.166^{***}(3.625)	0.163^{***}(3.521)	0.185^{***}(3.958)	0.182^{***}(3.425)
$\ln G$	0.220^{*}(4.013)	0.195^{**}(3.785)	0.257^{**}(4.369)	0.221^{**}(4.169)
ln KU	0.219^{**}(4.529)	0.211^{**}(4.412)	–	–
ln KR	–	–	0.144^{**}(3.201)	0.152^{**}(3.314)
ln LU	0.229^{**}(4.126)	0.233^{**}(4.236)	–	–
ln LR	–	–	0.117^{*}(3.195)	0.146^{*}(3.252)
$\ln T$	0.214^{*}(4.332)	0.177^{*}(3.462)	0.233^{**}(4.569)	0.163^{**}(3.795)
Time effect	Controlled	Controlled	Controlled	Controlled
Spatial effect	Controlled	Controlled	Controlled	Controlled
R^2	0.699	0.632	0.710	0.692
Sample size	182	182	182	182

Note: *, **, and* indicate significance at the statistical levels of 10%, 5%, and 1%, respectively; R^2 is the fitted coefficient; values in parentheses are t values. The same below.

The influence coefficient is significantly positive, indicating that the urban labor force is not only the main force in the transformation and upgrading of traditional industries such as petroleum processing and nonferrous metallurgy, but also labor support for the development of emerging industries such as the digital economy and biomedicine. In addition, the urban labor force is both a production group and a consumer group; the consumption demand of the urban labor force can stimulate optimization of the supply of urban services and enhance urban functions. The influence coefficient of technological level on urban functions is significantly positive, indicating that technological level can both improve resource-utilization efficiency and reduce resource waste in the production process, and can also promote the transformation of traditional industries toward high-end and green development, thereby enhancing urban functions.

2.2.3 Analysis of the estimation results of the rural function equation

The influence coefficient of urban functions on rural functions is significantly positive, indicating that urban functions promote rural functions, mainly through three pathways: (1) technology transfer. Relying on technology R&D and promotion institutions, advanced agricultural production technologies are extended to rural areas, breaking technological bottlenecks in agricultural production and realizing the transformation of traditional agriculture toward precision and efficiency. (2) Capital input. Through special fiscal support such as fiscal transfer payments, rural infrastructure construction is strengthened, providing material support for the improvement of rural functions; special fiscal funds are also used to promote the intensive processing and extension of characteristic agricultural products, activating endogenous momentum in rural industries. (3) Industrial collaboration. Through the industrial-gradient transfer mechanism, cities are guided to extend and arrange labor-intensive industries and agricultural-product processing links in surrounding rural areas, transforming rural resource advantages into industrial development advantages.

The influence coefficient of economic level on rural functions is significantly positive, indicating that economic level can, through capital investment, technological upgrading, and market expansion, promote the development of characteristic agriculture; it can also attract a large number of migrant workers returning to their hometowns to start businesses and find employment, bringing new development ideas to rural areas and stimulating rural economic vitality. The influence coefficient of government regulation on rural functions is significantly positive, indicating that policy regulation and resource coordination improve rural infrastructure, raise the supply level of rural public services, and enhance rural functions. The influence coefficient of rural capital factors on rural functions is significantly positive, indicating that rural capital factors can both inject financial impetus into the development of characteristic industries such as agricultural-product processing, rural tourism, and rural e-commerce, and also improve the quality of life of rural residents, promoting rural development and the enhancement of rural functions. The influence coefficient of rural labor factors on rural functions is significantly positive, indicating that the rural labor force provides labor support for the development of new business forms such as rural tourism and folk-custom experience; rural local talents represented by "Longyuan craftsmen" and groups of returning "geese" have become a key force in enhancing rural functions. The influence coefficient of technological level on rural functions is significantly positive, indicating that Gansu Province, through technological progress measures such as the promotion of planting and breeding technologies and the construction of digital rural platforms, has promoted the transformation of rural industries toward diversification and high added value, forming a virtuous cycle of technological empowerment and the enhancement of rural functions.

2.2.4 Heterogeneity analysis

Based on factors such as the level of urban–rural development, geographical spatial proximity, and resource endowment, Gansu Province is divided into three types of regions: the Longzhong region (Lanzhou City, Baiyin City, Dingxi City, Linxia Prefecture), the Hexi region (Jiuquan City, Jiayuguan City, Zhangye City, Jinchang City, Wuwei City), and the Longdongnan region (Tianshui City, Pingliang City, Qingyang City, Longnan City, Gannan Prefecture)[53]. Based on Stata 18.0, the system generalized moment estimation method is used to estimate the interactive influence between urban functions and rural functions in the three types of regions, respectively (Table 3). The results show that the urban functions and rural functions in the three types of regions ···

Table 3 Heterogeneity analysis of the interactive effect between urban function and rural function in Gansu Province

Tab. 3 Heterogeneity analysis of interactive effect between urban function and rural function in Gansu Province

Variable	Urban function equation	Urban function equation	Urban function equation	Rural function equation	Rural function equation	Rural function equation
	Longzhong region	Hexi region	Longdongnan region	Longzhong region	Hexi region	Longdongnan region
ln U	–	–	–	0.194^{**}(3.995)	0.142^{**}(3.365)	0.121(3.125)
ln R	0.227^{**}(4.775)	0.170^{**}(3.635)	0.135(3.295)	–	–	–
ln A	0.322^{***}(5.478)	0.317^{**}(5.362)	0.294^{***}(4.965)	0.223^{***}(4.559)	0.215^{***}(4.362)	0.192^{***}(3.578)
ln G	0.226^{*}(4.236)	0.215^{**}(4.162)	0.238^{***}(4.362)	0.311^{**}(5.362)	0.289^{**}(4.362)	0.305^{**}(5.264)
ln KU	0.252^{***}(4.521)	0.239^{***}(4.325)	0.221^{***}(4.113)	–	–	–
ln KR	–	–	–	0.231^{**}(4.859)	0.224^{**}(4.785)	0.254^{**}(4.996)
ln LU	0.274^{**}(4.218)	0.219^{**}(4.117)	0.207^{**}(4.055)	–	–	–
ln LR	–	–	–	0.173^{*}(3.658)	0.125^{*}(3.256)	0.216^{*}(4.147)
ln T	0.255^{*}(4.824)	0.245^{*}(4.785)	0.217^{*}(4.119)	0.287^{**}(4.352)	0.227^{**}(4.334)	0.276^{**}(4.741)
Time effects	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Spatial effects	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
R^2	0.617	0.633	0.698	0.607	0.662	0.669
Sample size	52	65	65	52	65	65

The interactive influence is characterized by both convergence and difference. Relying on the radiating and driving effects of the Lanzhou metropolitan area, with the modern agricultural belt in the Yellow River irrigation area and the central agricultural region as important supports, the Longzhong region has achieved mutual promotion and co-integration between urban function and rural function[^54]. In the Hexi region, the interaction between urban function and rural function shows the characteristics of node concentration and corridor linkage, forming a pattern in which production factors cluster toward node cities and their surrounding oasis irrigation areas. Although urban function and rural function interact with each other, the intensity of interaction between them is weaker than that in the Longzhong region[^55]. In the Longdongnan region, the interaction between urban function and rural function is relatively weak. The possible reasons are as follows: first, the overall development of urban functions is lagging. Except for Tianshui City, most towns in the Longdongnan region have a relatively low level of urbanization, and the radiating and driving effect of towns on rural areas is weak; second, geographical and environmental constraints are significant. Mountains and deeply incised valleys lead to a highly fragmented terrain, and, coupled with the low level of transport infrastructure, the cost of the flow of production factors between urban and rural areas remains high, which restrains the interactive influence between urban and rural functions[^56].

3 Discussion

The rational flow and efficient allocation of production factors between urban and rural areas can realize complementarity between urban function and rural function. The possible innovations of this study are as follows: first, against the realistic background in which urban–rural relations are shifting from one-way dependence to two-way interaction, an evaluation system for urban–rural functions is constructed from the three dimensions of "production function–living function–ecological function," and urban function and rural function are systematically evaluated, respectively; second, the study reveals the integrated development characteristics and interactive effects of urban function and rural function, which helps to identify the complementary advantages and factor feedbacks between urban and rural areas and enriches the theoretical connotation of urban–rural relationship research. At the same time, it should also be noted that existing research still needs to be expanded in the following aspects. First, although the use of city-level data to measure the three dimensions of "production function–living function–ecological function" can identify the development levels of urban function and rural function, if county-level data could be used, the precision of the research would be effectively improved. Second, although the simultaneous-equations model can identify the interactive influence between urban function and rural function, due to limitations in the number of research units and in research methods, spatial factors are not sufficiently considered. If spatial models could be used to incorporate spatial factors into research on the integrated development and interactive influence of urban function and rural function, the explanatory power of the study could be improved. Third, although statistical data can be used to identify macro-level conclusions regarding the interaction of urban and rural functions, if micro-level data such as household questionnaires and enterprise interviews could be combined to verify the micro logic of the macro conclusions, the contextual adaptability of the research conclusions would be strengthened.

4 Conclusions

(1) The urban function and rural function of Gansu Province both show an upward trend. The spatial distribution of urban function presents a pattern of "aggregation along the axis and gradient differentiation," while rural function presents a pattern of "east-west differences and belt-like extension." Relying on the Longhai-Lanxin transport trunk line, a functional agglomeration belt has formed with node cities such as Lanzhou, Tianshui, and Jiuquan as the core, exhibiting relatively high urban and rural functions; counties such as Gannan Prefecture and Linxia Prefecture, which are located at the ends of the transport network, have relatively low urban and rural functions. Therefore, in promoting integrated urban-rural development in Gansu Province, it is necessary to strengthen the agglomeration of urban functions.

spillover effects, it is also necessary to consolidate the supporting and safeguarding role of rural functions, focus on key areas such as factor flows, economic development, and technological innovation, promote multidimensional interaction among production functions, living functions, and ecological functions, and realize the coordinated advancement of new urbanization and comprehensive rural revitalization.

(2) The level of integrated development between urban functions and rural functions in Gansu Province shows a gradually strengthening trend. Cities such as Lanzhou and Tianshui, which have prominent locational advantages and convenient transportation conditions, have seen a continuous improvement in the level of integrated development between urban functions and rural functions, forming a favorable pattern of mutual promotion between urban and rural areas; places such as Gannan Prefecture and Linxia Prefecture, located in the transition zone between the Qinghai-Tibet Plateau and the Loess Plateau, are affected by geographical environmental constraints and weak foundations for economic development, and the level of integrated development between urban functions and rural functions remains low. Therefore, promoting the simultaneous improvement of urban functions and rural functions, giving play to the economic agglomeration role of towns and the ecological safeguarding role of rural areas, and forming multidimensional linkages among towns, between towns and villages, and among villages are the core requirements for urban-rural integration in Gansu Province.

(3) There is a two-way promoting relationship between urban functions and rural functions in Gansu Province, and the pulling effect of urban functions on rural functions is more prominent. The interactive influence of urban and rural functions exhibits regional differentiation: as the core

area of the provincial capital economy, the Longzhong region relies on the advantages of economic agglomeration and transportation hubs, and the mutual promotion between urban functions and rural functions is the most significant; the Hexi region follows, where the intensity of mutual promotion between urban functions and rural functions is slightly weaker due to the influence of the geographical environment and the pattern of resource distribution; in southeastern Longdong, because of deep mountains and gullies and inconvenient transportation, the interaction between urban functions and rural functions is the weakest. The level of economic development is the basic condition for improving urban and rural functions; government regulation plays a key role by guiding the rational flow of factors and the optimized allocation of resources; and technological level directly empowers urban–rural development by improving production efficiency. Urban capital factors and urban labor factors effectively enhance urban functions, while rural capital factors and rural labor factors significantly improve rural functions. Therefore, constructing locally appropriate pathways for mutual complementation and functional transformation between urban and rural areas is a key route for resolving urban–rural dualistic contradictions.

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Integrated development and interactive influence between urban function and rural function of Gansu Province

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Abstract: The complementary and symbiotic relationship between urban and rural functions is the key to integrated urban–rural development as well as the pathway to alleviating the urban–rural dual contradiction. Panel data at the city scale in Gansu Province from 2011 to 2023 were utilized. First, the evaluation system for urban and rural functions has been constructed. The entropy weight TOPSIS method and three-dimensional kernel density estimation were used to identify the spatiotemporal characteristics of the evolution of urban and rural functions. Second, the coupling coordination model was used to analyze the degree of integration development of urban and rural functions. Finally, the simultaneous equation model was used to reveal the interaction between urban and rural functions. The results show that: (1) Both urban and rural functions exhibit an upward trend in Gansu Province. The spatial distribution of the urban function showed pattern of axis-aligned agglomeration and gradient differentiation, while rural functions showed pattern of east-west disparity and belt-like extension. (2) The integrated development between urban and rural functions is continuously strengthened in Gansu Province, demonstrating spatial congruence with urbanization progress. (3) A positive interaction was observed between urban and rural functions in Gansu Province. The economic level, government regulation, and technical level all had a promoting effect on urban and rural functions, urban capital elements and urban labor factors had a promoting effect on urban functions, and rural capital elements and rural labor factors had a promoting effect on rural functions.

Keywords: urban function; rural function; integrated development; interactive influence; Gansu Province

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