Spatial Association Network and Influencing Factors of New Quality Productive Forces in the Guanzhong Plain Urban Agglomeration

Shi Yufang, Zhao Yan, Liu Xinyue

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Abstract

An in-depth investigation of the spatial correlation network and influencing factors of new quality productive forces in the Guanzhong Plain urban agglomeration is of great significance for promoting sustainable and coordinated regional development. Based on the entropy method, this study quantitatively evaluates the level of new quality productive forces in 11 prefecture-level cities in the Guanzhong Plain urban agglomeration from 2013 to 2023, and employs social network analysis and the quadratic assignment procedure to explore the structure and influencing factors of its spatial correlation network. The results show that: (1) The overall level of new quality productive forces in the urban agglomeration exhibits steady growth, but there is significant spatial heterogeneity. (2) The network structure of new quality productive forces in the urban agglomeration is relatively stable, showing evident spatial correlations and spillover effects, as well as distinct hierarchical characteristics. (3) The level of new quality productive forces in the urban agglomeration presents a "core-periphery" structure, with Xi' an and Xianyang serving as core nodes and playing key intermediary roles. (4) Industrial robot installation density, higher education level, highway mileage, and energy intensity all significantly affect the spatial network structure of new quality productive forces in the urban agglomeration. Based on these findings, it is recommended to further enhance new quality productive forces in the Guanzhong Plain urban agglomeration by strengthening government support, promoting interregional industrial division of labor and cooperation, and increasing investment in higher education resources and future industries.

Full Text

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Shi Yufang, Zhao Yan, Liu Xinyue

(School of Management, Xi' an University of Science and Technology, Xi' an 710054, Shaanxi)

Abstract: An in-depth exploration of the spatial association network and influencing factors of new quality productive forces in the Guanzhong Plain urban agglomeration is of great significance for promoting sustainable and coordinated regional development. Based on the entropy method, this study quantitatively evaluates the level of new quality productive forces in 11 prefecture-level cities of the Guanzhong Plain urban agglomeration from 2013 to 2023, and applies social network analysis and the quadratic assignment procedure to investigate the structure of its spatial association network and its influencing factors. The results show that: (1) The overall level of new quality productive forces in the urban agglomeration has exhibited steady growth, but significant spatial het-

erogeneity exists. (2) The network structure of new quality productive forces in the urban agglomeration is relatively stable, displaying clear spatial associations and spillover effects, as well as pronounced hierarchical characteristics. (3) The level of new quality productive forces in the urban agglomeration presents a "core-periphery" structure, in which Xi' an and Xianyang serve as core nodes and play a key intermediary role. (4) Industrial robot installation density, the level of higher education, highway mileage, and energy intensity all significantly affect the spatial network structure of new quality productive forces in the urban agglomeration. On this basis, it is recommended that measures such as strengthening government support, promoting interregional industrial division of labor and collaboration, and increasing investment in higher education resources and future industries be adopted to further enhance the new quality productive forces of the Guanzhong Plain urban agglomeration.

Keywords: new quality productive forces; spatial association network; social network analysis; Guanzhong Plain urban agglomeration

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In September 2023, General Secretary Xi Jinping first proposed the concept of "new quality productive forces," emphasizing that scientific and technological innovation should serve as the guide, emerging industries should be expanded, future industries should be cultivated, and the deep integration of technological innovation and industrial innovation should be accelerated. Supported by digital intelligence and networking, and with data as the core production factor, this concept breaks through traditional spatial constraints, promotes the flow of factor resources over a wider range, and gives regions more complex spatial associations. Accelerating the cultivation and formation of new quality productive forces has become an important task for achieving high-quality economic development[1]. The *Three-Year Action Plan for the Coordinated Development of the Guanzhong Plain Urban Agglomeration (2023-2025)* points out that, as an important economic center and transportation hub in Northwest China, the Guanzhong Plain urban agglomeration is a core region for cultivating new quality productive forces and is of key significance for enhancing the overall competitiveness of the region. However, structural contradictions within the Guanzhong Plain urban agglomeration remain prominent, and there are significant differences in the capacity to agglomerate innovation resources and high-end factors, which constrain the development of new quality productive forces. Therefore, an in-depth analysis of the spatial association network characteristics and influencing factors of new quality productive forces in the Guanzhong Plain urban agglomeration is of great significance for promoting the coordinated regional development of new quality productive forces in the Guanzhong Plain urban agglomeration.

A review of the existing literature shows that research on new quality productive forces has mainly focused on measurement, spatiotemporal differentiation characteristics, and influencing factors. In terms of measuring new quality productive forces, some scholars have evaluated them from the perspective of their

constituent elements—namely laborers, means of labor, and objects of labor[2]. Others, based on the connotative characteristics of new quality productive forces, have constructed indicator systems from such perspectives as technology, green development, and digitalization[3], as well as input quality, production vitality, and output efficiency[4], in order to measure the level of new quality productive forces. However, measurement can only reveal static differences and has difficulty reflecting the dynamic evolutionary characteristics among regions. For this reason, some scholars have further adopted methods such as the Dagum Gini coefficient[5], Markov chains[6], and convergence models[7] to explore the spatiotemporal evolution and distribution patterns of new quality productive forces. At the same time, relevant scholars have gradually shifted their attention to the analysis of factors influencing new quality productive forces. For example, Ji Xueqiang et al.[8], based on a spatiotemporal geographically weighted regression model, confirmed that economic development, educational investment, and foreign trade have significant effects on the level of new quality productive forces; Miao Chenglin et al.[9], in turn,

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Author biography: Shi Yufang (1980–), female, PhD, professor, mainly engaged in research on urban renewal and sustainable development. E-mail: shiyufang@xust.edu.cn
Corresponding author: Liu Xinyue (2002–), female, master's student, mainly engaged in research on new quality productive forces and urban sustainable development. E-mail: 23202097043@stu.xust.edu.cn

introduced an obstacle-degree model to identify constraining factors in terms of infrastructure and environmental governance, thereby providing directions for improving the path of new quality productive forces in the Yangtze River Delta. Other scholars have found that analyzing only the internal elements of a single region is still insufficient to explain the complex interactive processes of new quality productive forces, and have therefore introduced social network analysis methods. For example, Yang Lihua et al.[10] used social network analysis to examine the spatial association network structure of marine new quality productive forces in 11 coastal provinces of China; Wu Weiping et al.[11], from the perspective of regional enterprises, explored the structural characteristics of the spatial network of new quality productive forces. However, existing studies mostly focus on the development of new quality productive forces at the interprovincial level or among regional enterprises, while studies applying social network analysis to the Guanzhong Plain urban agglomeration remain scarce.

In summary, although the academic community has achieved certain results in research on new quality productive forces, shortcomings still remain. Research objects have mostly focused on the provincial scale, lacking in-depth analysis

of the Guanzhong Plain urban agglomeration, the most economically developed area in Northwest China. Research content has emphasized measurement, spatiotemporal evolution, and influencing factors, but has neglected the potential connections among different cities within the region; discussion of the complexity and characteristics of spatial association networks remains insufficient and urgently needs to be deepened. In view of this, this paper takes the Guanzhong Plain urban agglomeration as the research object, uses a modified gravity model and social network analysis to reveal the characteristics of its spatial association network of new quality productive forces, and identifies key influencing factors through the quadratic assignment procedure (Quadratic Assignment Procedure, QAP), aiming to provide theoretical support and practical reference for improving new quality productive forces in the Guanzhong Plain urban agglomeration.

1 Data and Methods

1.1 Overview of the Study Area

The Guanzhong Plain urban agglomeration is located in the inland area of Northwest China and is a key region for ecological protection and high-quality development in the Yellow River Basin. It covers 11 prefecture-level cities in three provinces—Shaanxi, Shanxi, and Gansu—including Xi' an, Xianyang, Weinan, Tongchuan, Baoji, Tianshui, Shangluo, Qingyang, Pingliang, Yuncheng, and Linfen. Its total area is approximately 10.7×10^4 km^2. At the end of 2023, its permanent resident population was about 4.32×10^7, and its regional gross domestic product was about 2.62×10^{12} yuan. In recent years, construction of the transportation network in the Guanzhong Plain urban agglomeration has accelerated, with the operating mileage of high-speed rail exceeding 1,000 km. The spatiotemporal distance between core cities and surrounding areas has been significantly shortened, providing favorable basic conditions for the flow of regional factors. However, despite improvements in the transportation network, development disparities within the Guanzhong Plain urban agglomeration remain large. Xi' an' s regional GDP accounts for more than 40% of the total for the entire region, and the difference in per capita regional GDP between the highest and lowest cities is nearly threefold, forming a clear development pattern of "one dominant core and distinct gradients." This reflects differences in development potential and competitiveness among cities within the region. Therefore, exploring a development model suited to the characteristics of the Guanzhong Plain urban agglomeration still has important practical significance and research value.

1.2 Data Sources

This study selects the 11 prefecture-level cities of the Guanzhong Plain urban agglomeration as the research objects. The research data mainly come from the *China Statistical Yearbook*, *China City Statistical Yearbook*, *China Energy*

Statistical Yearbook, and the statistical yearbooks of each prefecture-level city for 2013–2023. Some missing data were supplemented using the linear interpolation method.

1.3 Construction of the Indicator System

Combining the connotative characteristics of new quality productive forces[12] with related studies[13-14], this paper constructs a comprehensive evaluation indicator system for new quality productive forces from three core dimensions: laborers, means of labor, and objects of labor (Table 1). Laborers determine the development level of new quality productive forces and are measured through secondary indicators including laborer quality, laborer skills, laborer awareness, and laborer output. The selected indicators include higher education level, number of research and experimental development personnel, share of employees in computer services and the software industry, employment concept, entrepreneurial vitality, per capita regional GDP, and per capita income[15-18]. Means of labor reflect the regional level of scientific and technological innovation and the degree of infrastructure development, and are measured through secondary indicators including traditional infrastructure, digital infrastructure, and technological innovation. The selected indicators include highway mileage, road area, Internet penetration rate, mobile phone penetration rate, total telecommunications business volume, green technological innovation, and artificial intelligence technological innovation[19-20]. Objects of labor are the key to promoting a qualitative leap in productivity and forming new quality productive forces, and are measured through secondary indicators including future industries, energy consumption, and green environmental protection. The selected indicators include industrial robot installation density, energy intensity, green space area in built-up areas, and environmental protection intensity[20-22].

1.4 Research Methods

(1) Entropy method

The entropy method is a commonly used objective weighting method. It is suitable for scenario measurement involving multiple periods and multiple indicators, and can avoid the influence of human factors introduced by subjective weighting methods[23]. Therefore, this paper adopts the entropy method to determine the weights of each indicator; the specific calculation process refers to the study by Peng Wenying et al.[24].

(2) Modified gravity model

The modified gravity model has been widely applied in research analysis to measure the connection strength between regions under spatial interaction[25]. Drawing on the study by Zhang et al.[26], this paper uses the average value of each row as the threshold in the modified gravity model. If the interaction force

is greater than the threshold, the value is set to 1, indicating that a correlation exists between the two cities; if it is less than the threshold, the value is set to 0, indicating that no correlation exists between the two cities[27]. The calculation formula is as follows:

$$F_{ij} = K_{ij} \frac{M_i \times M_j}{D_{ij}^r} \tag{1}$$

Table 1 Comprehensive indicator evaluation system for new quality productive forces

Target layer	Criterion layer	Indicator layer	Indicator description	Indicator attribute	Weight
Laborers	Laborer quality	Level of higher education	Number of students enrolled in regular institutions of higher education	Positive	0.1240
Laborers	Laborer quality	Number of R&D personnel	Number of research and experimental development personnel	Positive	0.1247
Laborers	Laborer skills	Share of employees in computer services and software industries	Number of employees in computer services and software industries / total employed persons at year-end	Positive	0.0875

Target layer	Criterion layer	Indicator layer	Indicator description	Indicator attribute	Weight
Laborers	Laborer awareness	Employment concept	Number of employees in the tertiary industry / total employed persons	Positive	0.0142
Laborers	Laborer awareness	Entrepreneurial activity	Number of newly established enterprises per 100 people	Positive	0.0654
Laborers	Laborer output	Per capita gross regional product	Gross regional product / permanent resident population	Positive	0.0230
Laborers	Laborer output	Per capita income	Average wage of on-post employees	Positive	0.0182
Means of labor	Traditional infrastructure	Highway mileage	Total highway mileage	Positive	0.0121
Means of labor	Traditional infrastructure	Road area	Per capita road area	Positive	0.0101
Means of labor	Digital infrastructure	Internet penetration	Number of Internet users per 100 people	Positive	0.0220

Target layer	Criterion layer	Indicator layer	Indicator description	Indicator attribute	Weight
Means of labor	Digital infrastructure	Mobile-phone penetration	Number of mobile-phone users per 100 people	Positive	0.0711
Means of labor	Digital infrastructure	Total volume of telecommunications services	Per capita total volume of telecommunications services	Positive	0.0489
Means of labor	Technological innovation	Green technological innovation	Total number of authorized green invention patents	Positive	0.1725
Means of labor	Technological innovation	Artificial-intelligence technological innovation	Total number of authorized artificial-intelligence patents	Positive	0.0433
Objects of labor	Future industries	Installation density of industrial robots	Number of robots / total population	Positive	0.0386
Objects of labor	Energy consumption	Energy intensity	Energy consumption / gross regional product	Negative	0.0106
Objects of labor	Green environmental protection	Green area in built-up areas	Green area in built-up areas	Positive	0.0969

Target layer	Criterion layer	Indicator layer	Indicator description	Indicator attribute	Weight
Objects of labor	Green environmental protection	Intensity of environmental protection	Environmental protection expenditure / government public fiscal expenditure	Positive	0.0168

$$K_{ij} = \frac{M_i}{M_i + M_j} \tag{2}$$

where F_{ij} is the strength of the spatial linkage of new quality productive forces between cities i and j; K_{ij} is the gravitational coefficient, indicating the contribution rate of new quality productive forces between cities i and j; M_i and M_j are respectively the levels of new quality productive forces in city i and city j; D_{ij} is the geographical distance between city i and city j; and r is the friction coefficient. It is generally believed that when r takes values of 1 and 2, respectively, the spatial linkage status of the urban system at the national scale and the provincial-regional scale can be approximately revealed

28

. Based on the actual situation of this study, r is set to 2.

(3) Social network analysis

Social network analysis is a method for quantitatively studying the relational structures and characteristics in social networks

29

. This paper examines the new quality productive forces of the Guanzhong Plain urban agglomeration from two aspects: the characteristics of the overall network structure and those of the individual network structure. The overall characteristics are mainly measured by the number of network relations, network hierarchy, network connectedness, network density, and network efficiency; the individual characteristics are measured by degree centrality, betweenness centrality, and closeness centrality. The specific calculation procedures are provided in Reference

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(4) QAP analysis

The internal mechanism of the QAP analysis method can effectively avoid interference from multicollinearity among variables

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. Applying QAP to relational data analysis also yields more robust results

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. Therefore, this paper uses the QAP analysis method to analyze the influencing factors of the spatial association network of new quality productive forces in the Guanzhong Plain urban agglomeration.

2 Results and Analysis

2.1 Spatiotemporal evolution characteristics of the level of new quality productive forces in the Guanzhong Plain urban agglomeration

2.1.1 Temporal evolution characteristics of the level of new quality productive forces Overall, the new quality productive forces of the Guanzhong Plain urban agglomeration show a significant upward trend (Figure 1). The mean value increased from 0.1087 in 2013 to 0.2408 in 2023, an increase of 121.53% over 11 years, indicating that the development of new quality productive forces in this region is relatively good. From the perspective of different dimensions, the indices of all dimensions also show significant upward trends. In terms of the objects of labor, the index has risen rapidly since 2017, with a relatively fast average annual growth rate, and reached its highest level in 2023. In terms of the means of labor, the development level improved markedly after 2018, with a steep growth curve; in particular, it accelerated after 2020 and surpassed the laborer dimension by 2023, indicating that the region' s investment in means of production, scientific and technological equipment, and related areas has increased significantly, providing strong support for new quality productive forces. In terms of laborers, the overall level shows a steady upward trend. Although the increase is relatively moderate and the growth rate tended to stabilize after 2016, it has consistently remained at a relatively high level in all years, indicating that the quality and skill level of human resources in the region have continued to improve, contributing to new quality

Fig. 1 New quality productive forces and the development levels of various dimensions in the Guanzhong Plain Urban Agglomeration

Visible figure labels: y-axis, "Development level" ; x-axis, "Year" ; legend: "New quality productive forces," "Means of labor," "Workers," "Objects of labor."

plays an important supporting role in the development of productive forces.

2.1.2 Spatial Evolution Characteristics of the Level of New Quality Productive Forces

Using the natural breaks method, the development level of new quality productive forces in the Guanzhong Plain Urban Agglomeration was divided into four grades: low level, medium-low level, medium-high level, and high level. Four time points—2013, 2016, 2019, and 2023—were selected, and ArcGIS software was used for visualization analysis (Fig. 2). The results show that the spatial distribution of new quality productive forces is uneven, forming a pattern in which "Xi' an spreads and diffuses outward to the surrounding areas." In 2013, the new quality productive forces of the Guanzhong Plain Urban Agglomeration were mainly at low and medium-low levels; only Xi' an was at a high level, indicating an unbalanced development pattern. In 2016, the development level of new quality productive forces in the region changed little. Linfen and Shangluo rose to the medium-low level, while Tianshui, Pingliang, Qingyang, and Tongchuan remained at the low level. This may be related to their location on the periphery of the Guanzhong Plain Urban Agglomeration, weak transport infrastructure, lagging industrial upgrading, and insufficient R&D investment. In 2019, Baoji and Xianyang jumped to the medium-high level; at the same time, Tianshui, Pingliang, Qingyang, and Tongchuan rose to the medium-low level, possibly affected by spillover effects from neighboring cities. Xi' an remained at the high level during this period. In 2023, medium-low-level areas shrank; Tongchuan, Weinan, Yuncheng, and Shangluo rose to the medium-high level, and Xianyang entered the high-level category. This indicates that a polycentric trend in new quality productive forces in the Guanzhong Plain Urban Agglomeration has begun to emerge. However, medium-low-level cities still account for nearly half of the total, suggesting that overall development remains unbalanced and that there is still considerable room for improvement.

Fig. 2 Evolution of spatial patterns of new quality productive forces

Panels: (a) 2013; (b) 2016; (c) 2019; (d) 2023.
Map labels: Tianshui, Pingliang, Qingyang, Baoji, Xianyang, Xi' an, Tongchuan, Weinan, Shangluo, Yuncheng, Linfen.
Legend: provincial boundary; municipal boundary; grades of the level of new quality productive forces: low level, medium-low level, medium-high level, high level.
Scale: 0–100 km.

Note: Prepared based on the standard map from the Standard Map Service website of the Ministry of Natural Resources, with map approval number GS(2023)2767; the base-map boundaries were not modified.

2.2 Spatial Correlation Network Structure of the Level of New Quality Productive Forces in the Guanzhong Plain Urban Agglomeration

2.2.1 Analysis of the Characteristics of the Overall Network Structure

Based on the spatial relationship matrix of new quality productive forces in the Guanzhong Plain urban agglomeration, this paper selects two cross-sections, 2013 and 2023, and uses Netdraw software to draw an evolutionary diagram of the spatial correlation network of new quality productive forces (Fig. 3). The results show that the linkages of new quality productive forces among the 11 cities in the Guanzhong Plain urban agglomeration are multidirectional and interwoven, and that the overall spatial correlation relationship among the cities forms a complex and dense network structure. Xi' an and Xianyang have consistently occupied core positions and exert strong influence on surrounding cities. As the years progress, links among non-adjacent cities increase, breaking through the traditional constraints of spatial proximity. However, differences in the level of intercity association remain significant, and full interconnection among all cities has not yet been achieved.

This paper uses Ucinet software to draw the overall network-structure characteristic diagrams of new quality productive forces in the Guanzhong Plain urban agglomeration from 2013 to 2023 (Figs. 4–5). The results indicate that, from 2013 to 2023, the network characteristics of new quality productive forces in the Guanzhong Plain urban agglomeration exhibit a dynamic evolutionary pattern. In terms of network density and the number of network relationships, both show a fluctuating upward trend, with the overall pattern displaying stage-specific characteristics of "rising first, then falling, rising again, and falling again."Among them, network density ranges from 0.300 to 0.382, indicating a certain degree of closeness among the cities in the region. The number of network relationships ranges from 33 to 42; it reaches its maximum in 2021 and shows short-term peaks in 2017 and 2019, but is generally relatively stable. In terms of network connectedness, the connectedness of the new quality productive forces network in the Guanzhong Plain urban agglomeration remains at 1 throughout, reflecting a relatively stable overall network environment, significant reachability, and a relatively evident spatial spillover effect. Meanwhile, in terms of network hierarchy, the network hierarchy degree remains basically unchanged during the study period, staying at 0.6829. This indicates that the development linkages of new quality productive forces among cities in the Guanzhong Plain urban agglomeration have become tighter and display relatively strong hierarchical characteristics. From the perspective of network efficiency, the overall level of network efficiency is relatively high and shows a slight downward trend, suggesting that interregional connections are strengthening and network stability is gradually improving.

2.2.2 Analysis of the Characteristics of the Individual Network Structure

This paper selects four time nodes—2013, 2016, 2019, and 2023—to analyze the individual network characteristics of new quality productive forces in the Guanzhong Plain urban agglomeration (Table 2).

(1) From the perspective of degree centrality, the degree centrality of each city remains unchanged in 2013, 2016, and 2019. The cities above the average are Xi' an, Baoji, Xianyang, Weinan, and Qingyang. Among them, Xi' an' s degree centrality is consistently 10, indicating that Xi' an occupies a core position as a national central city and a hub of scientific and technological innovation. Driven by "Xi' an-Xianyang integration," Xianyang' s degree centrality rises from 6 to 9, making it a secondary hub. Weinan remains stable at 6, while Baoji and Qingyang remain stable at 5, placing them at the intermediate level. Shangluo, Tianshui, Pingliang, Linfen, and Yuncheng are consistently below the average, indicating that these cities occupy peripheral positions in the network and that their resource-spillover effects in the processes of resource flow and allocation are relatively limited. Overall, the development level of new quality productive forces in the Guanzhong Plain urban agglomeration presents a clear "core-periphery" pattern, with a pronounced siphoning effect from the central cities.

(2) From the perspective of closeness centrality, Xi' an' s closeness centrality is consistently 100, indicating that in the development of new quality productive forces in the Guanzhong Plain urban agglomeration it plays the role of a "central actor." It is relatively close to other cities and can rapidly establish connections. Next, Xianyang' s closeness centrality also remains above the average, with close links to other cities. This is mainly due to Xianyang' s geographical proximity to the provincial capital Xi' an, giving it significant

(a) 2013 *(b) 2023*

Fig. 3 Evolution of the spatial correlation network of new quality productive forces

Fig. 4 Network density and number of network relations

Fig. 5 Network efficiency, network hierarchy degree, and network correlation degree

···geographical advantages, and benefits significantly from resource diffusion and spillover effects. The values for Baoji, Weinan, Qingyang, Tongchuan, and Pingliang are close to the average, indicating that these cities are in a relatively stable state and occupy the position of "intermediate actors" in the network. By contrast, the closeness centrality of Shangluo, Tianshui, Linfen, and Yuncheng is far below the average, indicating that these cities are relatively "distant" from the other cities in the Guanzhong Plain urban agglomeration and occupy the

position of "peripheral actors" in the network. The main reason is that these cities are relatively economically underdeveloped and lack their own resources.

(3) From the perspective of betweenness centrality, the differences in centrality are pronounced, with a range reaching 20.17. Xi' an' s betweenness centrality is far greater than that of other areas. As the capital of Shaanxi Province and the central city of Northwest China, Xi' an occupies a key intermediary position in node interactions. In addition, the betweenness centrality of Xianyang and Weinan ranks among the highest in different years, mainly benefiting from their geographical location and the superimposed effects of policies. The betweenness centrality of Baoji, Qingyang, Tongchuan, and Pingliang is relatively low; because of factors such as a single industrial structure, a relatively large share of traditional industries, and insufficient development of emerging industries, these cities may be unable to effectively connect with other cities. The betweenness centrality of Shangluo and Linfen has remained 0, indicating that, in the spatial association network of new quality productive forces in the Guanzhong Plain urban agglomeration, they occupy a "dominated" peripheral position and have weak control over, and influence on, network relations.

2.3 Analysis of Factors Influencing the Spatial Association Network of New Quality Productive Forces in the Guanzhong Plain Urban Agglomeration

2.3.1 Selection of influencing factors

To further explore the factors influencing the development level of new quality productive forces in the Guanzhong Plain urban agglomeration, this paper, based on the comprehensive indicator evaluation system for new quality productive forces constructed above, starts from laborers,

Tab. 2 Centrality analysis of spatial association networks

City	Degree centrality 2013	Degree centrality 2016	Degree centrality 2019	Degree centrality 2023	Closeness centrality 2013	Closeness centrality 2016	Closeness centrality 2019	Closeness centrality 2023	Betweenness centrality 2013	Betweenness centrality 2016	Betweenness centrality 2019	Betweenness centrality 2023
Xi' an	10	10	10	10	100.00	100.00	100.00	100.00	20.17	20.17	20.17	17.17
Tongchuan	4	4	4	6	62.50	62.50	62.50	62.50	0.33	0.33	0.33	0.33
Baoji	5	5	5	5	66.67	66.67	66.67	66.67	1.17	1.17	1.17	0.50
Xianyang	6	6	6	9	71.43	71.43	71.43	83.33	2.50	2.50	2.50	6.42
Weinan	6	6	6	6	71.43	71.43	71.43	66.67	3.33	3.33	3.33	1.00
Shangluo	3	3	3	4	58.82	58.82	58.82	58.82	0.00	0.00	0.00	0.00
Tianshui	3	3	3	4	58.82	58.82	58.82	62.50	0.00	0.00	0.00	0.25

City	Degree centrality 2013	Degree centrality 2016	Degree centrality 2019	Degree centrality 2023	Closeness centrality 2013	Closeness centrality 2016	Closeness centrality 2019	Closeness centrality 2023	Betweenness centrality 2013	Betweenness centrality 2016	Betweenness centrality 2019	Betweenness centrality 2023
Pingliang	4	4	4	5	62.50	62.50	62.50	62.50	0.33	0.33	0.33	0.25
Qingyang	5	5	5	5	66.67	66.67	66.67	66.67	1.17	1.17	1.17	1.08
Linfen	3	3	3	3	58.82	58.82	58.82	55.56	0.00	0.00	0.00	0.00
Yuncheng	3	3	3	5	58.82	58.82	58.82	62.50	0.00	0.00	0.00	1.00
Average	4.73	4.73	4.73	5.64	66.95	66.95	66.95	67.97	2.64	2.64	2.64	2.55

representative indicators were selected from the three dimensions of labor materials and labor objects to construct the influencing-factor analysis model. Taking into account the representativeness of the indicators and their core influence pathways on new quality productive forces, the final explanatory variables selected were industrial robot installation density, higher-education level, highway mileage, and energy intensity.

2.3.2 Correlation analysis

Ucinet 6.0 was used to conduct a QAP correlation analysis on the 2023 data (Table 3). It can be seen that the spatial association network of new quality productive forces in the Guanzhong Plain urban agglomeration is significantly correlated with all independent variables at the 10% level. This indicates that industrial robot installation density, higher-education level, highway mileage, and energy intensity are strongly correlated with the spatial association network of new quality productive forces in the Guanzhong Plain urban agglomeration.

2.3.3 Regression analysis

To further explore the formation mechanism of the spatial association network structure of new quality productive forces in the Guanzhong Plain urban agglomeration, this paper uses the 2023 data and Ucinet 6.0 to conduct a QAP regression analysis. Through 5,000 random permutations, the regression coefficients and their significance levels were obtained. The model R^2 is 0.499, indicating that the selected influencing factors can explain 49.9% of the variation in the spatial network structure of new quality productive forces in the Guanzhong Plain urban agglomeration. The results are shown in Table 4.

As shown in Table 4, higher-education level is significantly positive at the 1% level, indicating that higher education has a significant positive impact on the spatial association of new quality productive forces in the Guanzhong Plain urban agglomeration. Specifically, the agglomeration of higher-education resources across regions helps promote the cross-regional flow and diffusion of knowledge elements, thereby enhancing the coordinated development of new

quality productive forces among cities. Highway mileage is significantly negative at the 10% level, indicating that differences in basic transportation infrastructure have an inhibitory effect on the spatial association of new quality productive forces among cities. Industrial robot installation density and energy intensity are two key indicators for measuring labor objects. Among them, industrial robot installation density is significantly positive at the 1% level, indicating that technology-intensive industries play a positive role in promoting connections among innovation elements between cities. Energy intensity is significantly negative at the 10% level, suggesting that resources related to new quality productive forces are more likely to flow between cities with smaller differences in energy consumption. Therefore, how to reduce interregional differences in energy consumption is an urgent problem to be solved.

3 Discussion

The study finds that the steady growth trend of new quality productive forces in the Guanzhong Plain urban agglomeration is basically consistent with research findings for other regions. With the acceleration of scientific and technological innovation and digital transformation, the improvement of regional new quality productive forces has become a key factor driving high-quality local economic development [33]. However, although the overall level of new quality productive forces in the Guanzhong Plain urban agglomeration has risen, its spatial distribution shows significant regional differences. This is similar to the phenomenon in some regions that rely excessively on traditional industries [34], and it also exhibits a pronounced "core-periphery" structural feature. As core nodes, Xi' an and Xianyang have not only driven the development of surrounding cities, but also highlighted the imbalance of development within the region. To achieve balanced intra-regional development, the government should formulate phased development plans, ensure that resources and policies are tilted toward cities with lower development levels, and promote their transformation toward emerging industries and high-technology fields.

Based on QAP regression analysis, this paper identifies the significant effects of higher-education level, industrial robot installation density, highway mileage, and energy intensity on the spatial network structure of new quality productive forces. In particular, the influence of higher-education level is significant, which is consistent with the study by Ji Xueqiang et al. [8] on the promoting effect of educational resources on new quality productive forces. Specifically, the agglomeration of educational resources helps promote cross-

Table 3 QAP correlation analysis
Tab. 3 QAP correlation analysis

Variable	Correlation coefficient	Significance level	Standard deviation	Minimum value	Maximum value	$P \geq 0$	$P \leq 0$
Industrial robot installation density	0.339	0.007	0.114	−0.309	0.461	0.007	0.996
Higher-education level	0.648	0.094	0.233	−0.191	0.648	0.094	1.000
Highway mileage	−0.244	0.043	0.152	−0.367	0.616	0.986	0.043
Energy intensity	0.501	0.088	0.201	−0.233	0.745	0.088	0.970

Table 4 QAP regression analysis
Tab. 4 QAP regression analysis

Variable	Unstandardized regression coefficient	Standardized regression coefficient	Significance probability	Probability 1	Probability 2
Industrial robot installation density	0.258	0.286	0.002	0.002	0.998
Higher-education level	0.917	0.786	0.000	0.000	1.000
Highway mileage	−0.131	−0.144	0.079	0.969	0.031
Energy intensity	−0.268	−0.246	0.060	0.991	0.009

regional flows, thereby promoting the coordinated development of new-quality productive forces. In addition, the positive effect of industrial robot installation density indicates that technology-intensive industries play an important role in promoting connections among innovation factors. This point is also supported

by the study of Han Jianli et al.[35] on scientific and technological innovation driving the development of new-quality productive forces. Therefore, increasing investment in higher-education resources is key to promoting the coordinated development of new-quality productive forces in the Guanzhong Plain urban agglomeration. In addition, support for intelligent manufacturing and high-tech industries should be strengthened, and the level of industrial technology should be improved, so as to drive an overall increase in the level of regional new-quality productive forces.

The core contribution of this study lies in the following: it conducts an in-depth analysis of the structural characteristics of the spatial association network of new-quality productive forces in the Guanzhong Plain urban agglomeration, revealing the spatial distribution patterns and network features of new-quality productive forces across cities. Using the QAP analysis method, it further explores the influencing factors of the association network of new-quality productive forces, such as the driving effects of industrial robot installation density, higher-education level, road mileage, and energy intensity on the spatial association network of new-quality productive forces. At the same time, certain limitations remain: this paper selects only 11 a of data for the Guanzhong Plain urban agglomeration from 2013 to 2023. To analyze the spatial structural characteristics of this region more deeply, future research can conduct analyses over a longer time span to explore the long-term evolutionary patterns of the spatial association network of regional new-quality productive forces. In addition, more variables, such as environmental change and population migration, may be introduced to comprehensively assess the multiple factors influencing the spatial association network of new-quality productive forces in the Guanzhong Plain urban agglomeration.

4 Conclusion

(1) In terms of temporal characteristics, from 2013 to 2023, the overall level of new-quality productive forces in the Guanzhong Plain urban agglomeration showed a steadily increasing trend. In terms of spatial characteristics, the region exhibits significant heterogeneity. Xi' an and Xianyang have the most prominent levels of new-quality productive forces; Baoji, Yuncheng, Weinan, Shangluo, and Tongchuan follow closely, while Tianshui, Pingliang, Linfen, and Qingyang are relatively weak.

(2) In terms of overall network characteristics, during the study period, the network structure of new-quality productive forces in the Guanzhong Plain urban agglomeration was relatively stable. Network density and the number of network relations as a whole exhibited phased characteristics of "rising first, then falling, rising again, and falling again." Network connectedness remained at 1 throughout, indicating relatively obvious spatial association and spillover effects in the level of new-quality productive forces. Network hierarchy was generally high, indicating strong hierarchical characteristics. The overall level of network efficiency was relatively high and

showed a slight downward trend, while the stability of the network among cities gradually improved.

(3) In terms of individual network characteristics, the level of new-quality productive forces in the Guanzhong Plain urban agglomeration presents an obvious "core-periphery" structure, with Xi' an and Xianyang consistently occupying core positions. Shangluo, Tianshui, Linfen, and Yuncheng have relatively few associations with other regions and occupy peripheral positions in the network; their levels of new-quality productive forces are comparatively weak.

(4) From the QAP regression results, industrial robot installation density, higher-education level, road mileage, and energy intensity all significantly affect the spatial network structure of new-quality productive forces in the Guanzhong Plain urban agglomeration. Among them, higher-education level and industrial robot installation density significantly promote connections in the intercity association network of new-quality productive forces, while road mileage and energy intensity exert inhibitory effects on the association network of new-quality productive forces.

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Spatial association network of new quality productive forces and its influencing factors in the Guanzhong Plain urban agglomeration

SHI Yufang, ZHAO Yan, LIU Xinyue

(College of Management, Xi' an University of Science and Technology, Xi' an 710054, Shaanxi, China)

Abstract: Examining the spatial correlation network and drivers of new quality productive forces within the Guanzhong Plain urban agglomeration is essential for promoting sustainable, collaborative regional development. Using the entropy method, this study quantitatively evaluates the levels of new quality productive forces in 11 prefecture-level cities from 2013 to 2023. Social network analysis and secondary assignment procedures are used to examine the spatial association network structure and its determinants. The findings are as follows: (1) Levels of new quality productive forces have grown steadily, though significant spatial heterogeneity persists. (2) The network structure remains stable, exhibiting clear spatial associations, spillover effects, and a pronounced hierarchical pattern. (3) A clear "core-periphery" structure is evident, with Xi' an and Xianyang functioning as key intermediary hubs. (4) Factors such as industrial robot density, higher education attainment, road mileage, and energy intensity significantly shape the spatial network. Based on these findings, it is recommended to strengthen government support, promote regional industrial collaboration and division of labor, and increase investments in higher education and emerging industries to further advance new quality productive forces in the Guanzhong Plain urban agglomeration.

Keywords: new quality productive forces; spatial correlation network; social network analysis; Guanzhong Plain urban agglomeration

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