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Research article

A study of the spatial network structure of ethnic regions in Northwest China based on multiple factor flows in the context of COVID-19: Evidence from Ningxia

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A R T I C L E I N F O

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Low-income area
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A B S T R A C T

As an underdeveloped and low-income region, the development of minority regions in Northwest China is crucial. As an important part of minority regions, Ningxia Hui Autonomous Region has insufficient endogenous power for stable economic development and high risk of returning to poverty. On the whole, the Ningxia county network shows a spatial pattern of high in the north and low in the south. However, there are great differences in the centrality of different factor flow networks. The factor connections between most counties are weak, and a close innovation network has not yet been formed. There is an obvious administrative clique structure, showing a certain degree of self-enclosure. The factor flows between counties are relatively uniform and greatly affected by geographic distance. From the perspective of integrated flow, the Ningxia county network presents a distinct core-periphery circle structure. Population size and GDP are the main factors affecting the spatial network. The policy implication of this study is that Ningxia Autonomous Prefecture should coordinate the planning of the region's economy, technology, and transportation, so as to reduce the development gap between counties by enhancing the closeness of the county spatial association network, and ultimately realize the region's high-quality development.

1. Introduction

Harsh natural conditions, especially water scarcity, will constrain development [1]. The minority regions of northwestern China

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are the most extensive and deeply underdeveloped regions in China [2]. Breaking the constraints of unbalanced and insufficient development in ethnic areas is a matter of China's national defense security and economic stability [3]. At the same time, ethnic areas are also areas of harsh natural conditions and low income in China [4]. Although the Chinese government has announced the elimination of absolute poverty in 2020, as a low-income area, the ethnic regions in the northwest still suffer from a mismatch between productivity levels and development, the "belt and road" strategy with neighboring developing countries constitutes a "dip" zone, and economic development does not bite into the chain of globalization and is prone to ethnic and religious conflicts. The continued spread of the new crown epidemic has hampered worldwide connectivity [5–12].

Ningxia Hui is an important part of the ethnic region in Northwest China and a core province of the "One Belt, One Road" strategy [13]. The central government has introduced a series of supportive policies to promote the development of the Ningxia. As an important position in the revitalization of China's "One Belt, One Road" strategy, whether Ningxia Hui Autonomous Region can achieve high-quality development is related to whether the "One Belt, One Road" strategy can be successfully promoted. Ningxia has always been a key province for national poverty alleviation [14]. Under the current momentous changes of a scale unseen in a century, this study conducts a deconstructive analysis of the multi-factor flows of Ningxia counties, and thereby provides policy guidance for the development of public health in Ningxia, which is crucial to the development of Ningxia and even the whole country.

With the development of science and technology, researchers worldwide have begun to shift their attention from traditional linear relationships to network relationships [15–18]. Early classical theories, such as location theory, point-axis spatial structure, growth pole, and core-edge, have laid a theoretical foundation for the research on flow space [19–21]. Previous studies have made great achievements in the field of flow space and further demonstrated the superiority of the "flow space" perspective by analyzing the core-edge network structure, network skeleton, and network centrality [22,23] at global, national, regional, and city levels [24–27] using models and methods, such as gravity model, neural network, dynamic urban system model, and social network analysis [28–32] based on data on economics, industry shifts, human mobility, tourist trajectories, commuting, and aviation flow [33–36].

In the context of continuous modernization, counties are an indispensable core unit for China to achieve common prosperity. However, previous studies rarely deconstructed the flow space with the county as a unit. Economic, traffic, and innovation flows are the core of county factor flows. However, previous studies mostly analyzed the network structure from the perspective of single-factor flow, but few have explored and compared the networks of multi-factor flows in counties. In view of this, this study examined and compared the spatial patterns of county networks in Ningxia form the perspectives of economic, traffic, and innovation flows, in order to provide decision support for strengthening the internal connection.

This study can provide important policy insights for high-quality development in Ningxia and China. For Ningxia, since it belongs to the gathering area of ethnic minorities, the development of the north and the south is unbalanced, and the transportation, technology, and economic links are not close, therefore, the links between the southern part of the autonomous region should be increased. For the country as a whole, it is necessary to formulate corresponding regional development strategies.

2. Data and methods

2.1. Samples

Ningxia located in the inland northwest of China, is one of the five major ethnic minority autonomous regions in China. There are 5 prefecture-level cities and 22 counties in the region. Therefore, this paper takes the 22 counties and districts in the region as the research object, and conducts structural and comparative research on the spatial network pattern of counties in Ningxia Autonomous Region. All the 22 counties/districts of Ningxia Autonomous Region were chosen as samples and seen as nodes in the spatial network, as shown in Table 1.

2.2. Methods and data

2.2.1. Economic network

To analyze the economic network of Ningxia counties, it is necessary to construct the relation matrix of economic connection. Calculated as in equation (1).

$$Q_{\mathrm{ij}} = k_{ij} \cdot \left[\left(\sqrt[3]{S_i P_i G} \cdot \sqrt[3]{S_j P_j G_j} \right) \Big/ D_{ij}^2 \right] \tag{1}$$

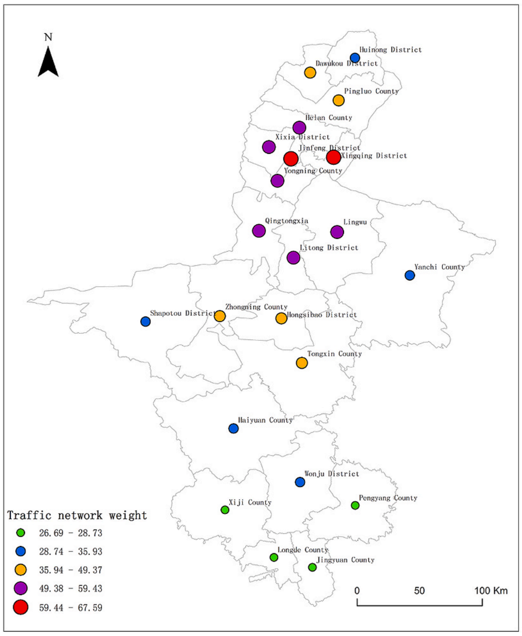
Table 1
Prefecture-level cities and their counties in Ningxia in 2020.

Prefecture-level city	County (district/county-level city)
Yinchuan	Xingqing District, Xixia District, Jinfeng District, Yongning County, Helan County, Lingwu City
Shizuishan	Dawukou District, Huinong District, Pingluo County
Wuzhong	Litong District, Hongsibao District, Yanchi County, Tongxin County, Qingtongxia City
Guyuan	Yuanzhou District, Xiji County, Longde County, Jingyuan County, Pengyang County
Zhongwei	Shapotou District, Zhongning County, Haiyuan County

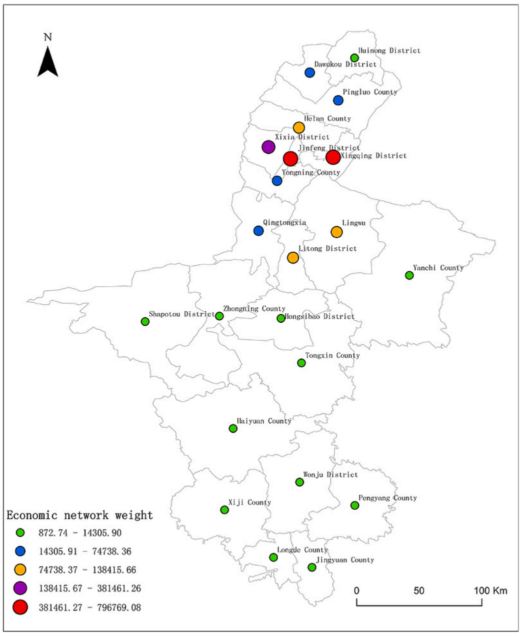
where Q_{ij} is the economic connection strength. S_i, P_i, and P_j are the urban built-up area, population size, and GDP of county i, respectively, and G_j, G_i, and G_j are those of county j, respectively. D_{ij} is the travel distance. We believe that the economic connection between counties with a comparative relation have equal forces. Hence, k_{ij} is set to 1.

2.2.2. *Traffic network*

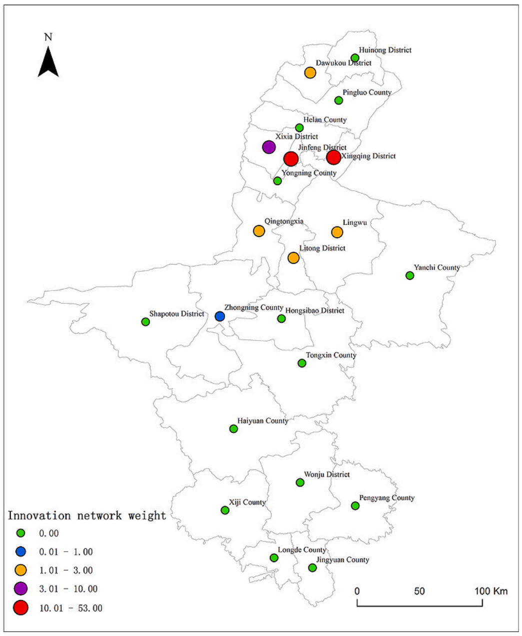
The traffic network is measured by the travel time required between the county-level city people's governments of counties/districts shown by the Baidu Map to form a traffic connection matrix.



A. Traffic network node weight



B. Economic network node weight



C. Innovation network node weight

Fig. 1. Centrality of Ningxia county networks in 2020.

2.2.3. Innovation network

Innovation can stimulate economic growth [37–41]. In this paper, we have selected the patent application data of Ningxia. If a patent is filed by three people, two by two will be recorded as one cooperative patent respectively.

The important role of technological progress has been confirmed by relevant literature [37,40]. The data related to innovation connection are from the Incopat global patent database. Patents registered in Ningxia in 2020 with two or more applicants were retrieved from the Incopat database. In measuring the collaboration of patents, if a patent is applied by A, B, and C at the same time. Then it is considered that there is one collaboration between A and B, A and C, and B and C respectively.

2.2.4. Integrated flow network

The innovation flow, economic flow, and traffic flow are nondimensionalized by averaging to combine the three factor flow matrices into an integrated flow matrix.

2.2.5. Centrality

Drawing on Hu et al. [42], the centrality is calculated as follows equation (2).

$$C_D(n_i) = d(n_i) = \sum_j X_{ij} = \sum_i X_{ji} \tag{2}$$

If j is related to i, then $X_{ij} = 1$, otherwise $X_{ij} = 0$.

2.2.6. External-internal (E-I) index

The E-I index identifies the inter-clique or out-of-clique relationships between nodes according to their relationships in the network. The closer the index is to 1, the stronger the regional openness of the network and the more obvious the clique structure; and if it is close to −1, the opposite is true. The impact of administrative subordination on the factor connections between counties in Ningxia was analyzed by partitioning it into five cliques, i.e., Yinchuan, Shizuishan, Wuzhong, Guyuan, and Zhongwei.

2.2.7. GeoDetector

This paper draws on Sun et al. [43] to explore the influencing factors of spatial network structure in Ningxia. Calculated as in equation (3)

$$q = 1 - \frac{\sum_{h=1}^{L} \sigma_h^2 N_h}{N\sigma^2} \tag{3}$$

where σ^2 is the total variance. σ_h^2 is the variance of the counties. N_h is the number of types. The value range of q is [0, 1].

3. Spatial structure analysis of Ningxia county networks based on multi-factor flows

3.1. Centrality of Ningxia county networks from the perspective of multiple factors

3.1.1. Centrality of traffic network of Ningxia counties/districts

The centrality distribution of the traffic network of Ningxia counties/districts is shown in Fig. 1A. It can be seen that the first- and second-level counties/districts are mainly distributed in Yinchuan and Wuzhong. In particular, Jinfeng District has the largest centrality, and Xingqing District ranks second. The two districts, located in Yinchuan, the capital of Ningxia, are economically developed and the fortresses connecting the north and the south. Thus, they have become the core of the spatial network. The second-level counties/districts are distributed around Jinfeng and Xingqing Districts, namely Yongning County, Xixia District, Helan County, Litong District, Qingtongxia City, and Lingwu City. The third- and fourth-level counties/districts are basically distributed around the first- and second-level counties/districts. The fifth-level counties/districts are concentrated in remote areas in southern Ningxia. Due to the complex terrain, the counties/districts in the southern mountainous area of Ningxia generally have poor transportation.

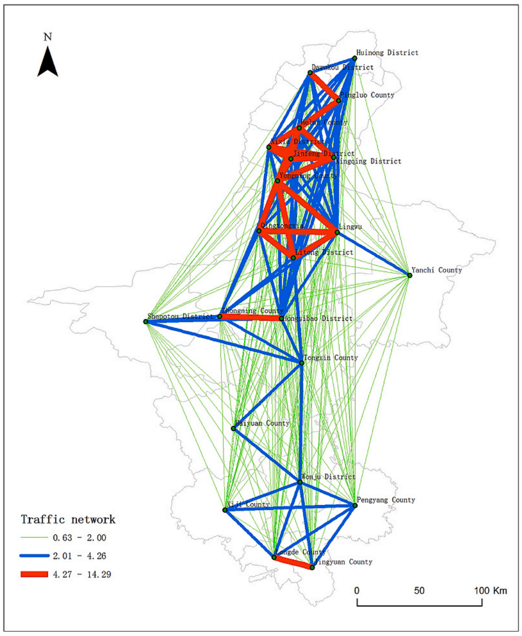
3.1.2. Centrality of economic network of Ningxia counties/districts

The centrality distribution of the economic network of Ningxia counties/districts is shown in Fig. 1B. It can be seen that all the first- and second-level counties/districts of the economic network are located in Yinchuan. The counties/districts of Yinchuan have become the core of the economic network of Ningxia, presenting faster development than other counties/districts. The third- and fourth-level counties/districts are concentrated in the Hetao Plain. Specifically, the third-level counties/districts are Helan County and Lingwu City in Yinchuan and Litong District in Wuzhong. The fourth-level counties/districts are Qingtongxia City, Yongning County, Dawukou District, and Pingluo County. The fifth-level counties/districts are concentrated in the Huinong District on the northern edge of Ningxia and most of the counties/districts in the south. The northern fringe counties/districts are experiencing "labor pains" of economic development due to economic transition. And those in the south are due to economic backwardness [44].

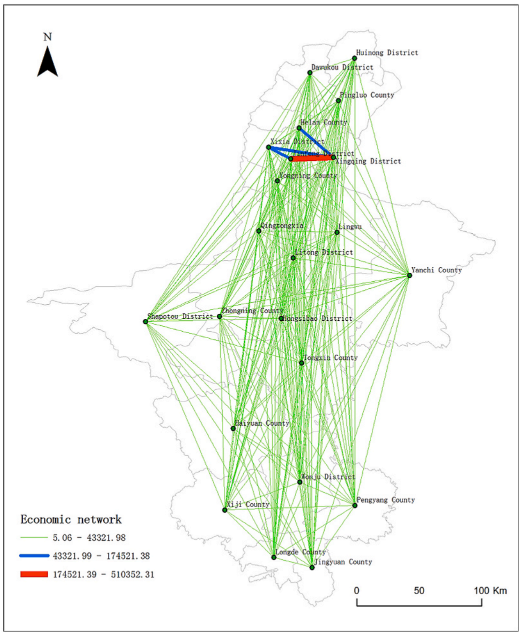
3.1.3. Centrality of innovation network of Ningxia counties/districts

The centrality distribution of the innovation network of Ningxia counties/districts is shown in Fig. 1C. It can be seen that only 8 counties/districts are involved in the innovation network. It is worth noting that most of these innovative connections are cooperation in the field of energy or power. State Grid Ningxia Electric Power Co., Ltd. and its subsidiaries or branches play an important role in the network. However, no innovation connection is present between other counties/districts. Therefore, there is an urgent need to strengthen innovation connections among districts/counties in Ningxia.

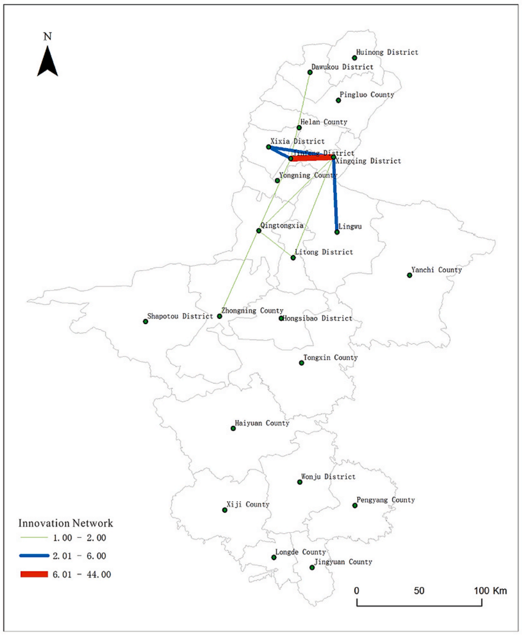
On the whole, in terms of primacy, the primary counties/districts in Ningxia from the perspective of multi-factor flows are always Xingqing District and Jinfeng District. In terms of spatial pattern, the centrality of Ningxia county networks gradually decreases from the north to the south. In particular, in term of overall difference, the innovation network has the largest difference in centrality, followed by the economic network and lastly the traffic network. In term of regional differences, the differences between northern counties/districts are significantly greater than those between southern counties/districts in terms of innovation, economy, and traffic.



A. Traffic network



B. Economic network



C. Innovation network

Fig. 2. Spatial pattern of Ningxia county networks in 2020.

3.2. Spatial pattern of Ningxia county networks from the perspective of multiple factors

3.2.1. Spatial pattern of traffic network of Ningxia counties/districts

The first-level traffic connections between counties/districts in Ningxia mainly rely on national highways and expressways, forming a skeleton network with Yinchuan and Wuzhong as the core, which communicates all counties/districts in Ningxia. As shown in Fig. 2A and Table 3, there are a total of 231 county pairs of traffic connections, and only 19 pairs at the first level. In particular, the connection strength of Jinfeng District with Xingqing District and Xixia District is far greater than that of other connections at the first level. There are 15 connections related to counties/districts in Yinchuan, accounting for more than 60% of the first-level connections. At the second level, the connections of counties/districts in Yinchuan with those in Shizuishan and Wuzhong are not only the largest in number. There are 150 pairs of general-level traffic connections, accounting for more than half of all traffic connections. It shows that the traffic connections between most counties/districts are weak. Moreover, most of the connections are between the northern and southern counties/districts.

3.2.2. Spatial pattern of economic network of Ningxia counties/districts

The economic network linkages are shown in Fig. 2B and Table 3. There are a total of 231 county pairs of economic connections. Specifically, the first level of economic connections include only Jinfeng District Xixia District – Xingqing District. It forms an interconnected skeleton network with the first-level counties/districts as nodes, and its strength far exceeds that of second-level connections. There are three pairs of second-level economic connections, namely Xixia District – Jinfeng District, Xixia District – Xingqing District, and Xingqing District – Helan County. All the first- and the second-level economic connections occur in Yinchuan, demonstrating the close economic connections within Yinchuan as the provincial capital. General-level economic connections account for more than 98% of all economic connections, indicating that the economic connections between most counties/districts in Ningxia are weak and need to be strengthened urgently.

3.2.3. Spatial pattern of innovation network of Ningxia counties/districts

The innovation network linkages are shown in Fig. 2C and Table 3. There are only 9 county pairs of innovation connections in Ningxia, and only one pair of first-level connection, which is Jinfeng District – Xingqing District. Second-level innovation connections all occur between counties/districts in Yinchuan. General-level innovation connections mostly occur between counties/districts in Yinchuan and those in Wuzhong, Zhongwei, and Shizuishan. It can be found that all these connections occur between the northern counties/districts of Ningxia. The innovation network is immature.

3.3. Cliques in Ningxia county networks based on E-I index from the perspective of multiple factors

As seen from Tables 1 and 2, under the influence of administrative subordination, the administrative clique structure among the five prefecture-level cities, is significant in different factor flows. Specifically, the E-I index of the economic network is 0.342. The network density between subgroups, except that between Yinchuan and Shizuishan, is much smaller than that within the subgroups. The connections between subgroups are not strong. The E-I index of the traffic network is 0.389. The density within and between subgroups is similar to that of the economic network, except for that between Yinchuan and Shizuishan, between Yinchuan and Wuzhong, and between Wuzhong and Zhongwei. The E-I index of the innovation network is −0.111. The density within and between subgroups is similar to that of the economic network. It shows that except for a few prefecture-level cities, the economic, traffic, and innovation connections mostly occur between counties/districts within the same city, and only a few occur between those of different cities. Spatially, cohesive subgroups are formed with the administrative districts of the five cities, i.e., Yinchuan, Shizuishan, Wuzhong, Guyuan, and Zhongwei, as the boundaries. It indicates that the administrative division of prefecture-level cities strengthens the intra-city county connection to a certain extent, and weakens the inter-city county connection. The existence of administrative cliques not only leads to overall uneven development of Ningxia, but also weakens interregional cooperation. On the whole, Ningxia is characteristic of self-enclosure (the E-I index is far less than 1). The factor networks between cities have great potential for development.

3.4. Primary role of Ningxia county networks from the perspective of multiple factors

Fig. 3A–C shows the results of the first place of the network. It can be observed from the membership model that in term of traffic, economic, and innovation connections, most counties do not directly connect with other counties across the in-between counties, but point to the counties that are spatially adjacent and in the same prefecture-level city. On the one hand, it shows that the internal polarization of Ningxia is not significant, and the factor flows are relatively uniform. On the other hand, it can be seen that the factor

Table 2
Cliques in Ningxia county networks based on E-I index in 2020.

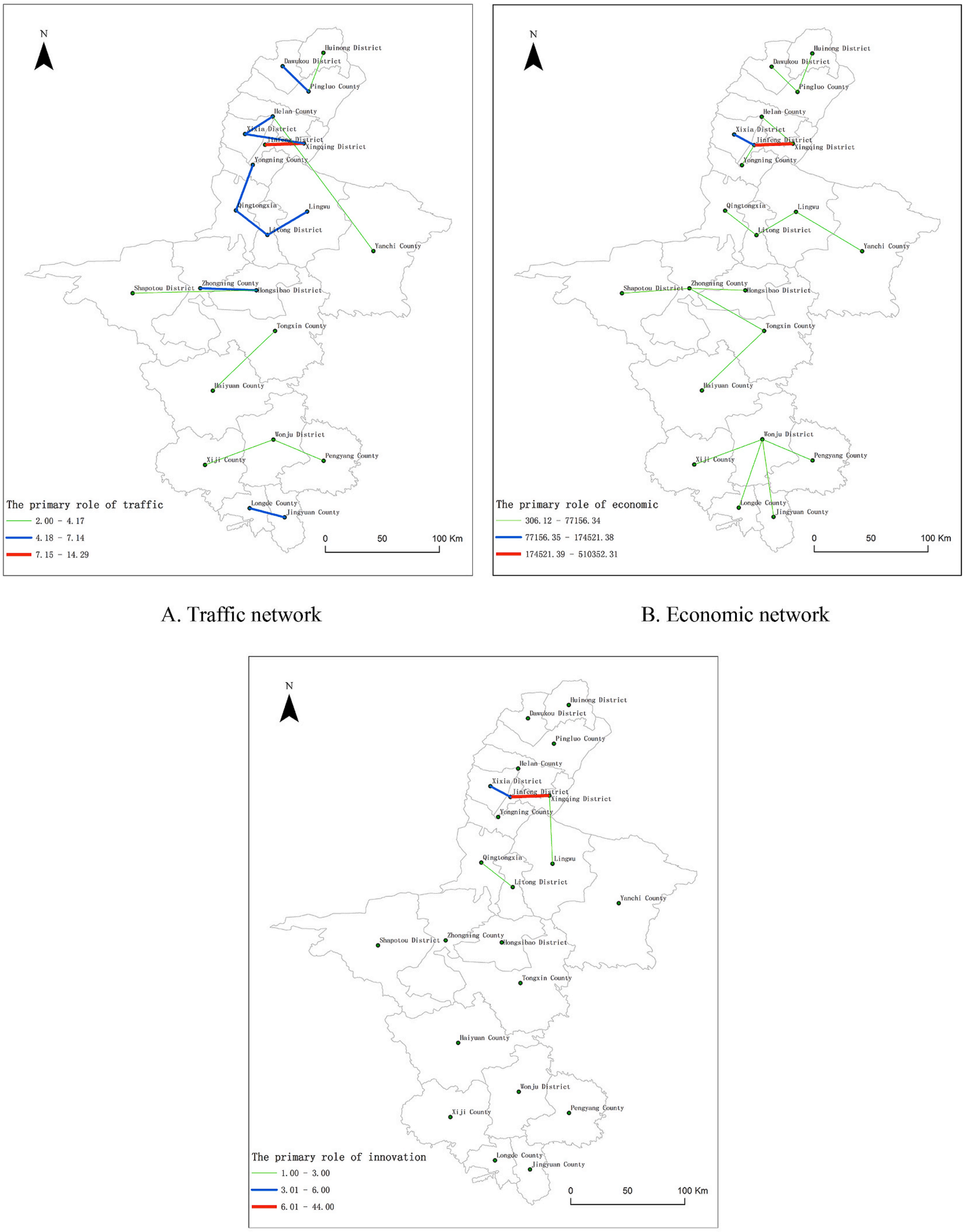
Factor flow	E-I index	Expected E-I index	P
Economy	0.342	0.645	0.000
Traffic	0.389	0.645	0.000
Innovation	−0.111	0.645	0.013

Note: If $P < 0.05$, the null hypothesis is accepted, that is, there are cliques.

flows are greatly affected by geographic distance. In addition, the primary factor connections of the counties basically point to the prefecture-level cities to which they belong, echoing the above finding that Ningxia counties are self-enclosed to some extent due to administrative boundaries (see Fig. 4).

3.5. *Spatial hierarchy of Ningxia county networks from the perspective of multiple factors*

Based on the natural break classification method for network centrality above, weights of 5, 4, 3, 2, and 1 are respectively assigned



A. Traffic network

B. Economic network

C. Innovation network

Fig. 3. Primary role of Ningxia county networks in 2020.

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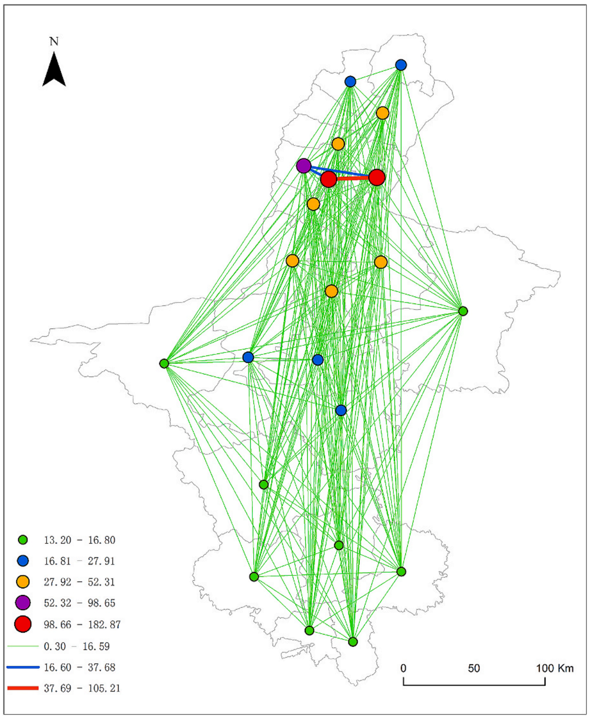

Fig. 4. Integrated flow network of Ningxia counties in 2020.

to the nodes at the first to fifth levels. The sum of the scores of a node for the traffic, economic, and innovation networks is the total score of that node. Counties/districts with a total score of 12–15 are defined as central, 8–10 as sub-central, 4–7 as core, and 3 as radiation-affected.

Table 4 demonstrates the corresponding results. As the central urban areas of the capital city of Ningxia, these three districts not only have political functions, but also have strong advantages in economic development and other aspects, driving the development of the entire Ningxia. In addition, Litong District, Lingwu City, Qingtongxia City, Helan County, and Dawukou District are identified as sub-central counties/districts. These five counties/districts are strongly connected with most counties/districts in Ningxia, and are going gangbusters. Yongning County, Pingluo County, and Zhongning County are identified as core counties. These counties are not strongly connected with other counties/districts, and have not been positively affected by the development of other counties/districts. Finally, Jingyuan County, Pengyang County, Longde County, and Xiji County are identified as radiation-affected counties. These four counties are located in southern Ningxia. Due to the poor locations, they lag behind in traffic, economic, and innovation flows, and become the shackles in the Ningxia county networks.

4. Spatial structure of Ningxia county network from the perspective of integrated flow

The factor connections between counties are often complex. Hence, it is not sufficient to analyze county network from the perspective of single-factor flow. Therefore, it is necessary to show the structure of Ningxia county network in an integrated manner to gain more comprehensive and deeper understanding of its spatial structure.

The spatial pattern of the integrated flow network is significantly different from those of the economic, traffic, and innovation networks. In terms of network centrality, the first- and second-level counties/districts in Ningxia are Jinfeng District, Xingqing District, and Xixia District in Yinchuan, the provincial capital. The third- and fourth-level counties/districts are distributed in the outer layers of the first- and second-level ones. The fifth-level counties/districts are basically located at the southern edge of the province, showing a distinct core-periphery circle structure. In terms of connection strength, there are only 3 pairs of first- and second-level integrated flow connections in the network, all of which are located in Yinchuan. General-level integrated flow connections account for the vast majority. On the whole, the integrated flow network of Ningxia counties shows a radial spatial connection pattern with the first- and second-level counties/districts as the core. Although connections have been established between most counties, they are weak.

5. Exploration of influencing factors

5.1. Influencing factors

In this paper, we have selected 10 possible influences. The effect size of each variable is demonstrated in Table 5 using the

Table 3
Density matrix of Ningxia county networks in 2020.

City	Economic network					Traffic network					Innovation network				
	Yinchuan	Shizuishan	Wuzhong	Guyuan	Zhongwei	Yinchuan	Shizuishan	Wuzhong	Guyuan	Zhongwei	Yinchuan	Shizuishan	Wuzhong	Guyuan	Zhongwei
Yinchuan	1.000	0.944	0.533	0.000	0.222	1.000	1.000	0.967	0.000	0.500	0.267	0.056	0.067	0.000	0.056
Shizuishan	0.944	1.000	0.200	0.000	0.000	1.000	1.000	0.667	0.000	0.111	0.056	0.000	0.000	0.000	0.000
Wuzhong	0.533	0.200	0.300	0.000	0.600	0.967	0.667	0.900	0.200	0.867	0.067	0.000	0.100	0.000	0.000
Guyuan	0.000	0.000	0.000	0.200	0.000	0.000	0.000	0.200	1.000	0.400	0.000	0.000	0.000	0.000	0.000
Zhongwei	0.222	0.000	0.600	0.000	0.333	0.500	0.111	0.867	0.400	1.000	0.056	0.000	0.000	0.000	0.000

Table 4
Hierarchy of Ningxia county networks in 2020.

County/district	Traffic score	Economic score	Innovation score	Total score	Hierarchy
Jinfeng District	5	5	5	15	Central
Xingqing District	5	5	5	15	Central
Xixia District	4	4	4	12	Central
Litong District	4	3	3	10	Sub-central
Lingwu City	4	3	3	10	Sub-central
Qingtongxia City	4	2	3	9	Sub-central
Helan County	4	3	1	8	Sub-central
Dawukou District	3	2	3	8	Sub-central
Yongning County	4	2	1	7	Core
Pingluo County	3	2	1	6	Core
Zhongning County	3	1	2	6	Core
Hongsibao District	3	1	1	5	Core
Tongxin County	3	1	1	5	Core
Huinong District	2	1	1	4	Core
Haiyuan County	2	1	1	4	Core
Shapotou District	2	1	1	4	Core
Yuanzhou District	2	1	1	4	Core
Yanchi County	2	1	1	4	Core
Jingyuan County	1	1	1	3	Radiation-affected
Pengyang County	1	1	1	3	Radiation-affected
Longde County	1	1	1	3	Radiation-affected
Xiji County	1	1	1	3	Radiation-affected

geodetector technique mentioned earlier.

5.2. *Result analysis*

From Table 5, it can be found that population size, GDP, urbanization level, industrial structure level and government expenditure can influence the distribution of spatial network structure in Ningxia. Among them, population size and GDP are the two factors that produce the most effect. As can be seen from Table 5, there are five influencing factors with P-values less than 0.1, and these factors are able to influence the spatial network structure of Ningxia. The regression coefficients of these factors are concentrated between 0.4 and 0.7, indicating that these factors are able to explain 40–70% of the spatial network structure of Ningxia.

5.2.1. *County development level*

The correlation with resident population size and GDP ranks first and second among all significant correlations, respectively, indicating that the county development level has a very important influence on the centrality of the county integrated flow network. The regression shows that it has the highest correlation. The resident population size also reflects the attractiveness of a county. The urbanization rate intuitively reflects the county development level.

5.2.2. *County economic quality*

The economic quality of a county is an important reflection of its development. Good economic quality gives greater impetus to the spatial connections of the county. It indicating that a viable county economic structure can be an attractive and radiating factor, thus establishing closer connections with other counties.

Table 5
Correlation coefficients between the centrality of the county integrated flow network and its influencing factors.

Influencing factor	Rank	Detector	Correlation	P
County development level	X1	Urban construction land area	0.1212	0.8644
	X2	Resident population size	0.6225	0.0885
	X3	GDP	0.6799	0.0542
	X4	Total retail sales of consumer goods	0.5451	0.4213
	X5	Number of health facilities	0.2482	0.9046
	X6	Urbanization rate	0.4985	0.0631
County economic quality	X7	GDP per capita	0.2624	0.5237
	X8	Per capita disposable income of all residents	0.5510	0.1305
	X9	Proportion of the output value of the secondary and tertiary industries in the total output value	0.4265	0.0897
Ability of the government to intervene	X10	Local government fiscal expenditure as a percentage of GDP	0.4773	0.0700

5.2.3. Ability of the government to intervene

A moderate ability of the government to intervene can break down the barriers to the free flow of factors, thus creating a good environment for the flow of factors. It can also efficiently allocate factor resources, assist economic development, and provide efficient infrastructure investment, thereby providing macro-control for sound economic development.

6. Impact of spatial networks of multi-factor flows on public health

Rationalization of factor mobility contributes to recovery in the post epidemic era [45,46]. Considering the impact of multi-factor flows on public health crisis management, this study reveals the basic characteristics of factor flows between counties by analyzing the economic, traffic, innovation flows, and provides some suggestions for public health research:

First, it is important to promote factor flows between regions. Since the outbreak of COVID-19, all regions have taken containment measures, which, however, have also caused dysfunction in some aspects of the entire region. Ensuring the flow of factors during the COVID-19 pandemic is an important basis for tackling COVID-19 as soon as possible. Therefore, we suggest that local governments and groups from different regions need to unite and cooperate to reduce unnecessary artificial barriers, so as to promote the rational flow of factors.

Second, efforts should be made to establish a mechanism for guaranteeing factors in public health crisis [47]. The COVID-19 pandemic will probably last for a significant period of time. As far as this study is concerned, there is a need to focus on the guarantee of factors. Therefore, local governments and agencies should guarantee the factors, and provide sufficient factors to support the sustainable development of the region after the COVID-19 outbreak.

Third and lastly, the northern and southern parts of Ningxia Autonomous Region are not closely connected. The traffic, economic, and innovation flows are concentrated along the Yellow River in the north, whereas the south is closed and backward. The outbreak of COVID-19 has further hindered the exchange between the north and the south of Ningxia. Therefore, it is necessary to implement effective screening for individuals under precautions using big data and artificial intelligence, while promoting communication and connection between the north and south of Ningxia.

7. Conclusions and contributions

Based on data from the *Ningxia Statistical Yearbook*, Baidu Map, and the Incopat global patent database, this study developed a matrix of economic, traffic, and innovation flows, and analyzed and compared the spatial networks of Ningxia counties using social network analysis. We find that the first and second levels of the centrality of economic, traffic, and innovation flow networks of Ningxia counties are found in Jinfeng District, Xingqing District, and Xixia District of Yinchuan. There are some differences in centrality distribution between different factor flows. Moreover, the connection strength between most counties is weak, and high-level connections are mainly distributed in northern Ningxia. The E-I index suggests that Ningxia counties are self-enclosed to some extent, showing an obvious administrative clique structure. It is evident from membership analysis that the factor flows between counties are relatively uniform and greatly affected by geographic distance. Second, the spatial pattern of the integrated flow is significantly different from those of the economic, traffic, and innovation flows. But on the whole, it shows a distinct core-periphery circle structure. Although connections have been established between most counties, they are weak. Third, County development level, county economic quality, and ability of the government to intervene are the main factors influencing the centrality of the county integrated flow network.

This study may provide the following marginal contributions. Frist, this study attempts to investigate the county networks in an underdeveloped province, Ningxia, from the perspective of multi-factor flows, i.e., the economic, traffic, and innovation flows, and reveals the network pattern characteristics from different perspectives. It breaks the limitation of the single-factor perspective of traditional factor network research [19–21], and opens up the perspective of combining county and flow space. Second, the use of flow space data to study counties supplements and improves the traditional study of counties with attribute data [35,36,48,49]. The flow space better reflects the nature of interconnection between counties. This study further deepens and expands the theory of flow space. Third, this study investigates the spatial networks of multi-factor flows in Ningxia Hui Autonomous Region, which not only has a profound impact on the comprehensive understanding of the development of various districts and counties in Ningxia from point to line and from line to plane, but also has some implications for effective COVID-19 control in Ningxia.

8. Policy Implications, Limitations, and Directions for Further Research

(1) For Ningxia, the municipal governments should establish a "region-wide chess" perspective, strengthen the links between the south and the north, and eliminate local protectionist thinking and market segmentation between cities.

(2) To enhance the primacy of the central city, Yinchuan, as the capital city of the province, should strengthen cooperation with other prefecture-level cities, expand the radius of the economy, and strengthen exchanges and cooperation in economy, transportation and innovation.

(3) Because the north and south of the Ningxia Autonomous Region are not closely connected, the flow of traffic, economy and innovation is concentrated along the Yellow River in the north, while the southern region is closed and backward. Therefore, the role of "big data and artificial intelligence" should be actively utilized to promote communication and linkage between the north and south of the autonomous region.

This study has some limitations. First, this study only used the data of economic, traffic, and innovation flows to investigate the network of Ningxia counties, which is still insufficient to fully describe the multi-factor network of Ningxia counties. Hence, based on data availability, further research can be carried out with other factors, such as population, investment, information, and tourism flows, to comprehensively describe the spatial pattern of the multi-factor network of Ningxia counties. Second, the article's examination of influencing factors is broad. Third, Based on data availability, further research can compare the networks before and after the COVID-19 outbreak or extend the research period, which may reach different conclusions.

Future research can consider the following: First, other factors, such as population, investment, information, and tourism flows in Ningxia counties, can be included to comprehensively describe the spatial pattern of the multi-factor network of Ningxia counties. Second, field research can be conducted to collect more data to comprehensively analyze the mechanism of the Ningxia county network. Third and lastly, long-term data can be used to comprehensively characterize the evolution of the Ningxia county network.

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Additional information

No additional information is available for this paper.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Feng Hu: Writing – original draft, Project administration. **Qingshan Ma:** Software, Conceptualization. **Hao Hu:** Project administration, Methodology, Investigation. **Kelly Haiyan Zhou:** Writing – review & editing, Validation, Data curation. **Shaobin Wei:** Writing – review & editing, Software, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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