Postprint: A Multi-flow Perspective on the Network Pattern of Xinjiang Oasis Cities

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Abstract

The spatial flows of various elements continuously reshape inter-city connections. Compared to urban network research from a single-element perspective, studies from a multi-element flow perspective can more comprehensively identify urban spatial patterns and reflect the regional characteristics of urban networks. Taking Xinjiang as the case study area, this study analyzes the structural characteristics of the oasis city network using social network analysis, based on element relationship data reflecting inter-city interactions across aviation, population, railway, logistics, information, and technology flows. The results show that: (1) Influenced by the oasis distribution pattern, the urban network in arid regions exhibits an overall characteristic of "single-core leadership + flat development" centered on core cities. (2) The primacy characteristics are more pronounced in transportation and technology flow networks, while logistics and information flow networks are less influenced by the primate city, with dispersed urban centrality scales and smaller inter-city disparities. (3) Logistics and information flow networks exhibit higher density and are well-developed, displaying a polycentric network structure, whereas transportation, population, and technology flow networks are primarily monocentric, showing a "core-periphery" structure. (4) Accelerating the cultivation of growth poles, guiding the transformation of regional network structures toward polycentricity, and strengthening regional innovation complementarity constitute the primary objectives for the high-quality development of oasis cities and the spatial optimization of urban systems.

Full Text

Network Pattern of Oasis Cities in Xinjiang from the Perspective of Multiple Flows

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Abstract

The spatial flow of various elements continuously reshapes intercity connections. Compared with urban network research from a single-element perspective, analyzing urban networks through a multi-element flow lens provides a more comprehensive identification of urban spatial patterns and better reflects the regional characteristics of these networks. Using Xinjiang as a case study, this paper examines intercity interactions based on relational data related to aviation, population, railway, logistics, information, and technology flows, employing social network analysis to evaluate the structural characteristics of the oasis city network. The findings indicate: (1) Influenced by the distribution pattern of oases, urban networks in arid regions exhibit overall characteristics of "single-core leadership + flat development" centered on core cities. (2) The primacy of traffic flow and technology flow networks is more pronounced, whereas logistics and information flow networks are less dominated by the primate city. Urban centrality is more evenly distributed, and disparities between cities are relatively small. (3) The logistics and information flow networks are dense and mature, exhibiting a multi-center network structure. In contrast, the traffic flow, population flow, and technology flow networks are primarily single-centered, displaying a "core-edge" structure. (4) To achieve high-quality development of Xinjiang' s oasis cities and optimize the urban spatial system, fostering regional growth poles, transitioning to a multi-center network structure, and enhancing regional innovation and complementarity should be prioritized.

Keywords: multiple element flow; urban network; flow space; oasis city; Xinjiang

1. Introduction

Urban interactions and spatial differentiation are rooted in the flow of different elements between cities. With the development of economic globalization and informatization, intercity population mobility, information transmission, material diffusion, and economic-technical cooperation have become increasingly close, forming various element flows in geographical space. These multi-element flows can break through geographical barriers to achieve coordinated development across different regions, prompting the urban system structure to gradually shift toward an open, mobile, and multi-centered networked model. The focus of urban research has also shifted from static structures based on attribute data to dynamic networks based on relational data. As a research hotspot in urban geography in recent years, urban networks represent an extension and expansion of traditional urban and regional spatial structure studies. Examining the point-line combination status of regional urban networks based on intercity element flow data not only reflects external relationships between cities and comprehensively identifies urban spatial pattern characteristics to promote cities to perform their respective functions, but also shapes a regional integrated urban network spatial pattern.

Currently, urban and regional research has gradually shifted to flow space and its mapped urban networks. Scholars have focused on traffic flows, technology flows, and enterprise flows to conduct extensive studies on the node functions and pattern characteristics of urban networks domestically and internationally from perspectives including infrastructure, enterprise organization, knowledge innovation, and population mobility. The Globalization and World Cities Research Network (GaWC) has conducted extensive empirical research on world city networks based on advanced producer services, providing a measurement foundation of "flow" data for intercity connections and pushing this research to a new stage. Taylor proposed the "interlocking network model" in his study of the network characteristics of the world' s top 100 advanced producer service firms, establishing a new perspective for depicting urban connections and providing a methodological foundation for subsequent urban network research. Urban flow space is a complex system of information flow and material circulation, and urban network characteristics differ across various perspectives. Single-element flows cannot reflect the comprehensiveness and complexity of urban network structure characteristics, making it necessary to understand urban network functions, connections, and structures more comprehensively from a multi-element flow perspective.

Scholars have conducted comparative and comprehensive analyses of urban networks from traffic flow, information flow, and enterprise flow perspectives. For instance, Ma Liya et al. analyzed urban network characteristics in Northeast China using railway passenger 班次, Baidu Index, and listed parent-subsidiary enterprise data, finding that urban interactions under information and traffic flows were more pronounced, yet a cross-provincial connection pattern had not formed under multi-flow perspectives. Zhao Jinli et al. studied the spatial network structure of cities in the Yellow River Basin based on financial enterprises, railway 班次, and Baidu Index, revealing significant differences in node city centrality within the transportation network and the most mature development of the financial network. Overall, research on urban networks from single-element flow perspectives is quite rich, while multi-element flow studies remain limited. There is a lack of comprehensive research incorporating technology and logistics elements into urban networks, and comparative analysis of different network types and their combined effects on urban network structure characteristics needs further deepening. Meanwhile, existing research primarily focuses on well-developed regions such as the Yangtze River Delta and Pearl River Delta, with relatively insufficient studies on central and western regions, particularly at the provincial scale.

Xinjiang serves as the core area of China' s "Belt and Road" initiative and a bridgehead for opening up to the outside world, playing important roles in national food security, energy security, and supply of key agricultural products. Xinjiang' s high-quality development concerns China' s reform, development, and social stability. Significant differences in resource endowments, ecological quality, and economic development across Xinjiang' s regions pose substantial challenges to regional integration and high-quality development. As the main carrier for promoting regional development and new productive forces, cities are the core force for implementing national strategies and promoting regional stability and development in Xinjiang. Identifying the actual level and shortcomings of high-quality urban development from internal regional differentiation and interaction, and examining the functional positioning and correlation relationships of oasis cities in arid regions from a "flow space" perspective, are of great significance for promoting the formation of a new high-quality development pattern with complementary advantages. Xinjiang' s towns, influenced by the natural geographical pattern, feature distinctive oasis characteristics, showing regional particularities such as small scale, clustered layout, and high primacy. Existing scholars have pointed out, based on highway passenger 班次, that Xinjiang' s urban network is dominated by short-distance connections, with prominent hierarchical characteristics and node polarization, where urban hierarchy and geographical distance interact spatially. Beyond highway passenger 班次, intercity population, material, information, and technology connections in Xinjiang are also becoming increasingly close. Air passenger transport also plays an important role in urban interactions. Exploring the network pattern of Xinjiang' s oasis cities from a multi-element flow perspective not only enriches regional research findings on China' s urban networks but also compensates for the limitations of single-perspective studies, enabling more comprehensive and accurate analysis of Xinjiang' s urban network characteristics and spatial organization structure, with the aim of providing theoretical support for Xinjiang' s high-quality urban development and spatial structure optimization.

2. Study Area and Methods

2.1 Study Area Overview

The Xinjiang Uygur Autonomous Region is located in the heart of the Eurasian continent, forming China' s northwestern frontier and the forefront of opening up to the west. Mountains, deserts, and the embedded belt-like and bead-like oases constitute the main components of Xinjiang' s "two basins between three mountains" natural geographical pattern. Oases with favorable water and soil conditions are the primary distribution areas for agriculture and towns. The region covers an area of 166.49$\times10^{4}$ km^{2}. As of the end of 2022, the total permanent population was 2587$\times10^{4}$, with an urbanization rate of 57.90%. The study area includes 14 prefecture-level administrative units (hereinafter referred to as cities). Considering data availability, newly established corps cities including Kunyu, Beitun, Shuanghe, Huyanghe, Tiemenguan, Xinxing, and Kokdala were not included in the study scope (Fig. 1).

2.2 Data Sources

Intercity connections are primarily realized through flows of transportation, population, material, capital, information, and technology elements, creating economic activity linkages and complementarities between cities to form multi-scale, complex network systems. Considering data quality and availability, this study selected the following flow data to characterize intercity connections (Table 1):

1) **Aviation flow data**: Flight schedules remain relatively stable within a week, and weekly passenger flight numbers are commonly used to measure aviation connection strength in urban network research. Multiple airports within a city were merged, and stopover flight data were processed accordingly.
2) **Population flow data**: To avoid fluctuations in population flows, this study collected long-duration data from non-holiday periods, using the daily average population migration scale index to measure intercity population connections.
3) **Railway flow data**: Except for holidays, railway schedules remain stable. This study used non-holiday daily railway passenger 班次 to reflect intercity railway connections, merging multiple railway stations within the same city.
4) **Logistics flow data**: Logistics routes are relatively fixed, so single-day data were used to reflect intercity logistics connections.
5) **Information flow data**: To avoid the impact of the pandemic on data stability, the daily average search index from January 1 to December 31, 2022 was used to characterize intercity information connections.
6) **Technology flow data**: Intercity technology connections were measured using patent transfer quantities. Since patent transfers within 1-2 years were too few to be representative, the cumulative patent transfer volume from 2018 to 2022 was used to represent intercity technology connections.

2.3 Methods

2.3.1 Social Network Analysis This study primarily employed social network analysis using UCINET 6.0 to analyze the network structure of each element flow perspective, with visualization conducted through ArcGIS 10.8. Measurement indices are shown in Table 2.

Network density reflects the closeness of connections between cities. The greater the network density, the tighter the intercity connections and the more mature the urban network development.

Point centrality 刻画 the importance of nodes in the network. Out-degree measures a node's radiation capacity, while in-degree measures its agglomeration capacity.

Betweenness centrality measures the ability of node cities to control exchanges with other cities. The greater the betweenness centrality, the stronger the city' s resource control capacity.

2.3.2 Zipf Model The Zipf model is commonly used to study the distribution pattern between city rank and city size. This study uses point centrality of urban networks to represent size, ranks the centrality, and forms a correspondence between size and rank, creating a linear regression relationship. A smaller α indicates more balanced size distribution of urban network nodes, while a larger α indicates a tendency toward concentrated primacy distribution. When α 1, the distribution follows the Pareto type most closely, indicating a stable development structure. When $\alpha < 1$, the distribution tends to be dispersed, with high-ranking cities not prominent and medium-ranking node cities more numerous, resulting in smaller gaps between cities.

3. Results

3.1 Characteristics of Single-Factor Urban Networks

3.1.1 Differences in Network Centrality Characteristics Using UCINET 6.0, we calculated the point centrality of urban networks for each element and performed linear fitting between city rank and point centrality using Zipf' s Law (Fig. 2). The α values for technology, aviation, and railway networks are > 1, indicating concentrated centrality distribution where high-ranking cities play significant roles, particularly in the technology network. The α values for population and information networks are < 1, showing that elements are more dispersed within the region, with high-ranking cities not prominent, more medium-ranking node cities, and smaller gaps between cities.

Using ArcGIS 10.8, point centrality was divided into four levels using the natural breaks method. Urumqi' s centrality in all element networks far exceeds other cities, making it the single-core node of the networks. Kashgar Prefecture, Ili Kazakh Autonomous Prefecture (directly-administered counties and cities, hereinafter referred to as Ili Prefecture), Aksu Prefecture, and other large-scale and comprehensively strong cities have relatively high network centrality, while Aral City, Tumshuk City, Wujiaqu City, Kizilsu Kirghiz Autonomous Prefecture (hereinafter referred to as Kezhou), and Altay Prefecture are constrained by geographical location and economic development, ranking in the third and fourth tiers across all element networks.

Affected by spatial distance, southern Xinjiang cities have higher centrality in the aviation network, while the northern Tianshan slope and Turpan-Hami Basin have lower centrality due to more diverse transportation options. Conversely, in the railway network, Urumqi, Turpan, and Bayingolin Mongol Autonomous Prefecture (hereinafter referred to as Bazhou) have high centrality due to their strong hub and transfer functions, while cities at the ends of railway lines lack transfer opportunities and generally have low centrality. The technology network shows obvious polarization, with Urumqi' s central position far ahead, while other cities mostly rank in the third and fourth tiers, indicating generally weak technology spillover and absorption capacities across node cities.

Population and information network node centrality is influenced by city population size and external communication capacity, with significant differences in agglomeration and diffusion capacities among node cities. Urumqi and Changji Hui Autonomous Prefecture (hereinafter referred to as Changji Prefecture) consistently rank in the top three, while small and remote cities generally have low out-degree and in-degree. Additionally, information network node cities show relatively close connections and a relatively balanced spatial structure. Node cities' out-degree and in-degree centrality differ significantly in the information network, with high-centrality cities generally showing strong information agglomeration capacity and low-centrality cities showing strong information diffusion capacity. In contrast, the logistics network shows smaller gaps in node centrality between first, second, third, and fourth-tier cities, with less obvious hierarchical differentiation.

3.1.2 Differences in Network Connection Characteristics Network density was calculated using UCINET 6.0, and intercity connection strengths were visualized using ArcGIS 10.8 with the natural breaks method dividing them into four levels (Fig. 3). Different element networks show varying densities: logistics (0.87) > information (0.71) > railway (0.32) > population (0.30) > aviation (0.27) > technology (0.11). Logistics and information networks have high networking degrees and are mature, while traffic, population, and technology networks have low development levels, weak connections between node cities, and obvious "core-edge" structures.

The aviation network exhibits a "sparse in the north, dense in the south" structure, with high-intensity connections concentrated between the capital city and remote cities, making air transport the optimal choice for distant cities. The railway network shows obvious axial effects, with strong connections between node cities on railway trunk lines. The population network displays a "sparse in the south, dense in the north" structure, with the strongest connections in the northern Tianshan slope economic belt and obvious spatial proximity effects, as nodes tend to establish connections with neighboring nodes. The information network shows relatively balanced connections among node cities, with Urumqi having the closest connections with other nodes. The logistics network presents a diamond structure, with extensive exchanges among node cities, obvious networking characteristics, and relatively small gaps in connection strength between cities. The technology network shows generally weak intercity connections, forming a radial network structure centered on Urumqi.

3.2 Characteristics of Composite Urban Network

Using the extreme value method, we normalized the connection matrices of five single-factor urban networks, weighted them equally, and summed them to create a composite urban network connection matrix.

3.2.1 Network Centrality We calculated the point centrality and betweenness centrality of the composite network using UCINET 6.0 (Table 3). Urumqi's core position is prominent, lacking secondary growth poles with strong comprehensive capabilities, showing overall characteristics of "core leadership + flat development."

Urumqi demonstrates absolute advantages in resource agglomeration, radiation, and transfer, serving as the single-core node of the network. Kashgar Prefecture, Ili Prefecture, Bazhou, and Aksu Prefecture are also relatively important in the network with point centrality between 28-35, but the overall gap with Urumqi is large, belonging to provincial weak central cities. Other node cities are ordinary cities, primarily driven by the radiation of central cities, with secondary growth poles lacking in the network. Compared with connection capacity, node cities have insufficient transfer capacity. Urumqi, Kashgar Prefecture, and Aksu Prefecture are the main transfer nodes with betweenness centrality > 10, indicating that these cities appear on the shortest connection paths between 10% of all node city pairs. Several cities with betweenness centrality of 0 lack resource transfer capacity and are at the network edge.

3.2.2 Network Association Pattern We visualized intercity connection strengths using ArcGIS 10.8, divided them into four levels using the natural breaks method, and obtained Fig. 4, while calculating hierarchical agglomeration (Table 4). Hierarchical agglomeration reflects the degree to which connection strength concentrates at each level, with larger values indicating higher concentration.

From level 1 to level 4, the number of node city connections in the composite network gradually increases, showing a pyramid distribution structure, with hierarchical agglomeration decreasing from 0.46 to 0.09. Level 1 connection strength shows characteristics of concentration toward top-level connections. As shown in Fig. 4, connections between Urumqi and regional central cities such as Karamay, Ili Prefecture, Aksu Prefecture, Kashgar Prefecture, Hotan Prefecture, and Bazhou are most significant, showing obvious centripetal connection characteristics. Apart from Urumqi, connections between other cities weaken noticeably, with relatively strong connections between Karamay-Ili Prefecture, Bazhou-Aksu Prefecture, and Aksu Prefecture-Kashgar Prefecture, while connections between Hotan Prefecture and northern Xinjiang cities, and between Tacheng Prefecture and Altay Prefecture with southern and eastern Xinjiang are weak, obviously affected by spatial distance.

4. Discussion

Affected by desert ecosystems, oasis city networks in Xinjiang do not have prominent hierarchies, with central cities playing prominent radiation and driving roles in the network while other cities have limited functions, showing obvious "fault" phenomena in network levels and clear characteristics of small groups and flat development. This differs from urban network structure characteristics in other regions of China. Urban networks in the Yangtze River Basin, Pearl River Delta, and Yellow River Basin mostly show hierarchical progressive structures, with central cities playing prominent roles but not as primate as in arid regions. Building a multi-center, multi-level, and multi-node Xinjiang urban network system is the primary task for promoting high-quality development of oasis cities and an effective measure for optimizing oasis urban spatial system structure.

Under comparative analysis of multiple element flows, information and logistics networks more easily overcome spatial distance friction, forming more mature networks across broader spatial ranges, consistent with findings by Li Yuanjun et al. and Zhao Jinli et al. Compared with developed urban agglomerations like the Yangtze River Delta, spatial distance poses stronger obstacles to population mobility between oasis cities, with "proximity effects" more pronounced in population networks. For technology networks, while Yangtze River Delta cities have evolved from single-center agglomeration to dual-core drive and multi-core radiation patterns, Xinjiang cities remain in the primary stage of single-core agglomeration due to insufficient technology spillover and limited technology absorption capacity. Taking the opportunity of "building eight major industrial clusters," innovation networks should be guided from single-center to multi-center through industrial optimization and upgrading to form complementary advantages in innovation resources, giving full play to the driving role of scientific and technological innovation in regional high-quality development.

Research on China' s urban networks is becoming increasingly in-depth and diversified. Based on intercity traffic, population, logistics, technology, and information connections, this paper depicts Xinjiang' s urban network structure, compensating for limitations of single-element research perspectives to some extent. However, shortcomings remain, as we have not further explored the influencing mechanisms and optimization paths of Xinjiang' s urban network development. Future research should pay more attention to exploring the formation processes and micro-mechanisms of urban networks, and further investigate how urban networks affect urban development, which is important for both theoretical deepening and provincial planning practice. Methodologically, scholars currently mostly use single-element data to represent functional networks, such as using Baidu Index to construct information networks, which cannot fully reveal the real and complex communication and connection systems between cities. New, more realistic, and more diverse data sources, methods, and models should be explored to reveal connection relationships and organizational patterns of urban networks under regional integration.

5. Conclusion

1) Xinjiang's cities are relatively small in scale, with prominent urban network centrality characteristics. Urumqi plays an obvious core role in all element networks, and the urban network overall shows hierarchical characteristics of "core leadership + flat development."Apart from the capital city Urumqi, other city nodes do not fully perform their functions.

2) Attribute characteristics of different element networks show obvious differences. From the perspective of urban nodes, single-core node positions are prominent in aviation, railway, and technology networks, but primacy distribution characteristics are not obvious in information and logistics networks, where cities are relatively closely connected with higher networking degrees. From the perspective of spatial connections, traffic network density is significantly affected by spatial distance and transportation types, with aviation connections most frequent between distant cities, while high-value railway connections occur between railway trunk line node cities. The "spatial proximity" effect of population mobility is prominent, dominated by connections between neighboring cities. The logistics network shows small gaps between cities with unobvious hierarchy, forming a typical networked structure. The information network is less constrained by traditional spatial distance, with extensive and balanced intercity connections. The technology network shows low development levels, forming a radial network pattern centered on central cities.

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