



Spatial and Temporal Evolution Patterns and Influencing Factors of Logistics Expansion in the Beijing-Tianjin-Hebei-Shanxi Region

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ABSTRACT

The collaborative development of the logistics industry in the Beijing-Tianjin-Hebei-Shanxi region is an important force in promoting regional integration. Based on data from 24 cities in the Beijing-Tianjin-Hebei-Shanxi region on logistics and warehousing land use from 2012 to 2021, the degree of urban logistics expansion was measured using the land use expansion index model. This study, employing methods such as the coefficient of variation, hot and cold spot analysis and weighted standard deviation ellipses, explores the spatial and temporal evolution characteristics and regional differences of urban logistics expansion. Additionally, the study utilises geographic detectors to identify the key influencing factors of urban logistics expansion in the four regions. Findings indicate that most cities in the Beijing-Tianjin-Hebei-Shanxi region experienced moderate to low-speed logistics expansion or no expansion at all, with a “high-low-high” evolutionary trend. Urban logistics expansion displays distinctive spatial differentiation, characterised by a “hot in Beijing-Tianjin, cold in Hebei-Shanxi” distribution. Cities not adjacent to Beijing exhibit higher levels of logistics expansion than those adjacent. Further research reveals that government policies and land use have the greatest impact on urban logistics expansion in the Beijing-Tianjin-Hebei-Shanxi region, particularly in Shanxi Province. It is essential to leverage government functions to provide policy guidance and support in rational urban road planning and economic development. This will not only improve the theory of logistics location and provide a theoretical basis for the coordinated development of regional logistics and economy but also provide a powerful reference for logistics planning, policy making and integrated regional economic development in the Beijing-Tianjin-Hebei-Shanxi region and even nationwide.

KEYWORDS

urban logistics expansion; spatial-temporal evolution; geographic detectors; regional variations.

1. INTRODUCTION

In recent years, with the gradual depletion of resources and the strengthening of environmental protection policies, Shanxi Province, as a resource-based province, urgently needs to develop new economic growth points [1–3]. The logistics demand in the Beijing-Tianjin-Hebei region is huge. With the acceleration of the regional integration process, its radiation-driven effect on the neighbouring areas is becoming increasingly obvious. The geographic location of Shanxi Province determines its unique advantages in connecting the east, middle and west, especially by playing an important role as a bridge in the logistics network [4]. The

development of the logistics industry is an important driving force for the economic growth of Shanxi Province. In May 2023, General Secretary Xi Jinping, in the in-depth promotion of the synergistic development of the Beijing-Tianjin-Hebei Symposium, stressed the need to actively promote the synergistic development of Beijing-Tianjin-Hebei to move to a higher level [5]. All along, Shanxi Province has been actively integrating into major national development strategies, which, coupled with the rapid growth in demand for Beijing's evacuation of non-capital functions, has, to a certain extent, facilitated the spread of Beijing's logistics infrastructure to Shanxi and the surrounding areas [6]. However, logistics and warehousing facilities in Shanxi Province and its connectivity with the Beijing-Tianjin-Hebei region still need to be improved, which limits the overall competitiveness and development potential of its logistics industry. In this context, maintaining a correct perception of the spatial and temporal evolution characteristics of logistics spreading in the cities of Beijing-Tianjin-Hebei-Shanxi¹ is conducive to the integration of Shanxi into the collaborative development of logistics and warehousing in Beijing-Tianjin-Hebei, and is of strong value in guiding the coordinated development of the layout of logistics facilities and urban space [7].

Research on logistics expansion initially gained prominence abroad and gradually spread. Dablanc and Rakotonarivo [8] defined the phenomenon of logistics enterprises and infrastructure shifting from urban centres to the suburbs or even rural areas as logistics sprawl. Aljohani and Thompson [9] endorsed this definition. Logistics sprawl is also referred to as “freight sprawl” [10] or “logistics polarisation” [11]. Subsequent studies have identified varying degrees of logistics sprawl in major cities such as Gothenburg [12], Tokyo [13] and Winnipeg [14]. Analyses of warehouse locations have shown that cities like Atlanta [15] and Los Angeles [16] in the United States have experienced different levels of urban logistics sprawl.

Domestic scholars have shown relatively limited interest in logistics sprawl, primarily using qualitative analysis to explore changes in logistics land use and logistics enterprises, thereby gaining a deeper understanding of the development trends of logistics sprawl. Research on logistics sprawl in Chinese cities has shown that, with the rapid increase in logistics infrastructure needs, most cities in China exhibit varying degrees of logistics sprawl [17]. This situation, to some extent, facilitates the expansion of urban space and promotes the integration and optimisation of urban layout [18]. Regional studies on urban logistics sprawl have found that most cities in the Yangtze River Economic Belt are in a moderate to low-speed logistics sprawl state, with an evolutionary process of “low-high-low” and a clear spatial differentiation, overall displaying a “hot in the west, cold in the east” distribution [19, 20]. Research on logistics sprawl in specific cities has focused on economically developed areas such as Beijing, Chongqing and Hangzhou. Over time, logistics facilities and enterprises in Beijing have gradually shifted to the suburbs, displaying a suburbanisation trend. The degree of logistics enterprise clustering has shown an initial increase followed by a decline, with core logistics enterprises progressively moving to the suburbs and then diffusing and integrating into multiple clustering regions with a lower clustering degree compared to previous periods [21, 22]. Research on logistics sprawl in Chongqing indicates that logistics land use is spreading outward, and wholesale markets in the central urban area are shifting to non-central urban areas, which is considered a necessary stage in urban spatial integration and transformation [23, 24]. Studies on Hangzhou have also identified significant logistics sprawl phenomena in logistics enterprises and warehousing facilities [25, 26], with further analysis conducted on the influencing factors of urban sprawl [27, 28].

After a thorough review and synthesis of relevant domestic and international literature, it was found that research on the spatial and temporal distribution of logistics enterprises primarily focuses on two main areas: first, the in-depth exploration of the distribution patterns of logistics enterprises over time and space; and second, the analysis of key factors affecting the spatial distribution of logistics enterprises and their mechanisms. In the field of spatial and temporal distribution patterns of logistics enterprises, scholars from both domestic and international contexts have examined the spatial distribution patterns of logistics enterprises from various geographic scales, including county, city, provincial, regional and national levels. Their research not only addresses the phenomena of logistics enterprise agglomeration and sprawl but also aims to reveal the underlying spatial-temporal evolution patterns. Research methodologies include geographic techniques such as kernel density estimation, nearest neighbour hierarchical clustering, nearest neighbour index and Ripley's K function, as well as economic methods such as location entropy, ESDA analysis and geographic

¹ Shanxi Province (referred to as Jin) and Hebei Province (referred to as Ji) each contain 11 prefecture-level cities, with Taiyuan, Datong, Yangquan, Changzhi, Jincheng, Shuozhou, Jinzhong, Yuncheng, Xinzhou, Linfen and Luliang belonging to Shanxi Province; and Shijiazhuang, Tangshan, Qinhuangdao, Handan, Xingtai, Baoding, Zhangjiakou, Chengde, Cangzhou, Langfang and Hengshui belonging to Hebei Province. Beijing (Beijing for short) and Tianjin (Tianjin for short) are municipalities directly under the central government.

concentration index. These diverse research methods collectively provide robust tools for uncovering the spatial distribution patterns and dynamic evolution of logistics enterprises [29, 30].

Regarding the factors influencing the spatial distribution of logistics enterprises, current research predominantly focuses on agglomeration or sprawl trends in developed cities or regions, with relatively limited investigation into logistics distribution conditions in less developed areas or cities. Research methods have increasingly shifted from qualitative to more refined quantitative analyses. Researchers are now employing methods such as binomial regression, spatial econometric models and geographically weighted regression (GWR) models to elucidate the relationships between these influencing factors and the spatial distribution of logistics enterprises. However, studies utilising geographic detector models for such analyses remain relatively scarce. This shift and current state reflect the evolution and current status of research methodologies in the field of logistics enterprise spatial distribution.

Under the background of regional economic integration, the spatial layout and development of the logistics industry, as an important support for economic development, are of great significance to regional synergistic development. This study focuses on the phenomenon of logistics spreading in the cities of Beijing-Tianjin-Hebei-Shanxi region and analyses in depth its spatial and temporal evolution patterns and inter-regional differences, and at the same time, with the help of geodetectors as a tool, it explores the key factors affecting logistics spreading. It is found that most of the cities in Beijing-Tianjin-Hebei-Shanxi region are in the state of medium-low logistics spread or even no spread, and the spreading trend shows the evolution process of “high-low-high”; the urban logistics spread shows unique spatial differentiation, which basically manifests the distribution characteristics of “Beijing-Tianjin is hot, Hebei-Shanxi is cold”, and the distribution characteristics of “Beijing-Tianjin is hot, Hebei-Shanxi is cold”, which is not the case in Beijing-Tianjin. The distribution characteristics of the “Beijing-Tianjin hot, Hebei-Shanxi cold” are basically shown, and cities not bordering Beijing have a higher degree of logistics spreading than bordering cities; the government and land use have the greatest influence on the urban logistics spreading in Beijing-Tianjin-Hebei-Shanxi, especially in Shanxi Province. The study not only breaks through the limitations of previous studies on a single province or city but also reveals the characteristics and differences of regional logistics spread as a whole, providing a comprehensive perspective on regional logistics’ synergistic development. At the same time, it comprehensively considers the impact of multi-dimensional factors such as land use, economic development and policies on logistics spread, explains the complexity of regional logistics development more comprehensively, and provides a scientific theoretical framework for regional logistics planning. It aims to provide theoretical support for urban spatial planning and promote the optimal allocation of urban logistics resources in order to achieve the efficient and harmonious development of cities.

2. DATA SOURCES AND RESEARCH METHODS

Based on the data of logistics and warehousing land area in 24 cities in Beijing, Tianjin, Hebei and Shanxi from 2012 to 2021, the land use sprawl index model is used to measure the degree of urban logistics sprawl, and combined with the coefficient of variation and other methods to explore the spatial and temporal characteristics of urban logistics sprawl and regional differences.

2.1 Data sources

The data for this study primarily came from the China City Statistical Yearbook [31] and the China City Construction Statistical Yearbook [32] covering the period from 2012 to 2021. Data on the area of land used for logistics warehousing in 24 cities during the study period and data corresponding to the 12 indicators in the indicator system of factors influencing the spread of urban logistics were obtained and collated from them. Due to incomplete or missing data for some cities, additional data were sourced from relevant provincial and municipal annual statistical yearbooks and statistical bulletins to supplement and correct the records. In specific cases, interpolation methods were employed to ensure data completeness and accuracy.

2.2 Research methods

Based on existing studies at home and abroad, this paper studies the spatial and temporal evolution characteristics and influencing factors of logistics sprawl in 24 cities in the Beijing-Tianjin-Hebei-Shanxi region, using data on the area of logistics warehousing land in these cities from 2012 to 2021. With the help of the land use sprawl index, coefficient of variation, hot spot analysis and standard deviation ellipse, we study

the evolution characteristics of logistics warehousing land use sprawl in time and space. Then, we establish a system of indicators affecting the spatial distribution of logistics warehousing and explore the influence size and interaction of these influencing factors on the urban logistics sprawl with the help of a geodetector model.

Land use expansion index

A unified definition of urban logistics sprawl has not yet been established in the academic community. To address this issue, this study adopted the land use expansion index model from Aquilué et al. [33] to quantify the expansion of logistics land use across various stages in each city. The specific calculation formula is as follows:

$$LSI_i = \frac{S_{i,1} - S_{i,0}}{S_{i,1}} \quad (1)$$

In the formula, LSI_i represents the logistics warehousing land use expansion index for city i from the beginning to the end of the study period; $S_{i,0}$ and $S_{i,1}$ denote the logistics warehousing land areas at the initial and final stages, respectively. A higher LSI_i value indicates a greater level of logistics expansion in the city, while a lower value signifies a lighter degree of logistics sprawl.

The coefficient of variation is a statistical measure of the degree of data dispersion, which can reflect the distribution characteristics of the data. For example, in grey correlation analysis, by combining the coefficient of variation method, subjective bias can be effectively avoided and the accuracy of the model can be improved. However, it is sensitive to outliers and easily affected by outliers, which may lead to biased results; the scope of application is limited, and in some complex data distribution scenarios, relying on the coefficient of variation alone may not be able to fully reflect the data characteristics. Scholars commonly use the coefficient of variation (Cv) to measure spatial differences. This study employs Cv to assess the extent of logistics sprawl and its variance across cities in Shanxi Province compared to cities in the Beijing-Tianjin-Hebei region, including those adjacent to Beijing and those not adjacent.

$$Cv_i = \frac{S_i}{X_i} \times 100\% \quad (2)$$

In the formula, Cv_i , S_i and X_i represent the coefficient of variation, the unbiased estimate of the standard deviation, and the mean value of logistics sprawl for city i , respectively.

Hotspot analysis

Hotspot analysis, as a spatial statistical method, is based on the distance weight matrix to identify the aggregation phenomenon of high or low values in a specific area. In the study of urban logistics sprawl, hotspot analysis is used to quantitatively assess the extent of logistics sprawl in each city by dividing the urban logistics sprawl index and the area of logistics warehouse land according to the similarity in spatial distribution to form cold spot agglomerations and hot spot agglomerations [34]. This approach is achieved through the application of Getis-Ord local statistical formulas, which provide a powerful analytical tool for urban planning and optimisation of logistics resources. These statistics calculate the local sum of an element and the neighbouring elements within its defined range, comparing the result with the local sum to determine whether the element is in a hot or cold spot area and to judge its degree of agglomeration. The Getis-Ord local statistics formula is as follows:

$$G_i^* = \frac{\sum_{j=1}^n w_{i,j} x_j - \bar{X} \sum_{j=1}^n w_{i,j}}{S \sqrt{\frac{n \sum_{j=1}^n w_{i,j}^2 - (\sum_{j=1}^n w_{i,j})^2}{n-1}}} \quad (3)$$

where X_j represents the attribute value of feature j , W_{ij} is the spatial weight between features i and j , n is the number of features and S is the variance of the features.

Geographic detector

Geodetector is a statistical method designed to detect spatial dissimilarities and explore driving forces. Wang et al. [35] made a detailed description of the specific operation and main ideas of the geodetector and the four sub-detectors. In this paper, we mainly use this tool to analyse and identify the key factors affecting the spread of urban logistics. The formula for the factor detector is as follows:

$$q = 1 - \frac{1}{N\sigma^2} \sum_{h=1}^L N_h \sigma_h^2 \quad (4)$$

where q represents the relative influence of factors on the spatial differentiation of urban logistics sprawl. N_h denotes the number of samples within the sub-regional area. N is the total number of samples across the entire region. L is the number of sub-regions. σ_h^2 is the variance of the sprawl index in the sub-region. σ^2 is the variance across the entire region, and q ranges from 0 to 1. The value of q determines the extent of the detected factor's impact on urban logistics sprawl.

Weighted standard deviation ellipse

The standard deviation ellipse is a model for exploring and judging the centre of geographical elements and the direction of their spatial distribution [36]. The change in the centre of mass reflects the change in the centre of gravity of logistics warehousing in Beijing-Tianjin-Hebei-Shanxi region, the long and short axes of the standard deviation ellipse indicate the major and minor trends in the spatial evolution of logistics warehousing, respectively, and the angle of rotation of the ellipse represents the direction of the spatial major distribution of the geographical elements of logistics warehousing [37]. To accurately represent the distribution characteristics of logistics warehousing land in the Beijing-Tianjin-Hebei-Shanxi region, an optimised standard deviation ellipse method is employed, using logistics land area as weights. This approach analyses the distribution direction, range and other aspects. The formula for calculating the weighted standard deviation ellipse is:

$$\bar{X} = \sum_{j=1}^n w_j a_j / \sum_{j=1}^n w_j; \bar{Y} = \sum_{j=1}^n w_j b_j / \sum_{j=1}^n w_j \quad (5)$$

where $\bar{X}$ and $\bar{Y}$ represent the weighted mean centre. j denotes the logistics land data. n is the total number of logistics land parcels. w_j is the area of logistics land j , and a_j and b_j represent the geographic coordinates of logistics land j .

3. SPATIAL AND TEMPORAL EVOLUTION OF URBAN LOGISTICS SPRAWL

This study analyses the temporal evolution of urban logistics sprawl using data on logistics warehousing land area in Beijing, Tianjin, Hebei and Shanxi during the study period. It also explores regional differences in logistics sprawl and examines how its centre of gravity and direction have evolved.

3.1 Temporal evolution of urban logistics sprawl

Combined with the trend of changes in the area of logistics and warehousing land in Beijing-Tianjin-Hebei-Shanxi region between 2012 and 2021 (see Table 1), the entire study period of 9 years was divided into 3 stages on average, 2012-2015, 2015-2018 and 2018-2021, which are denoted by T1, T2 and T3, respectively, and 2012-2021 is recorded as T stage. During the T1 phase, the area of logistics warehousing land in each city generally experienced steady growth. In the T2 phase, there was a reduction in logistics warehousing land area across all four regions. In the T3 phase, the logistics warehousing land area exhibited a fluctuating increase. As indicated in Table 1, the total logistics warehousing land area in the four regions increased by 28.94 km² from 2012 to 2021, with Shanxi accounting for 16.91 km² or 58.43%. From 2018 to 2021, the logistics warehousing land area increased by 26.15 km² in Shanxi and Hebei, reflecting a trend of logistics and infrastructure spillover to these areas.

Table 1 – Logistics warehousing land area (unit: km²)

Year	Shanxi	Beijing	Tianjin	Hebei	Total
2012	36.67	47.58	52.99	57.5	194.74
2013	37.04	48.40	54.98	70.02	210.44
2014	37.07	49.46	57.52	71.47	215.52
2015	39.35	51.64	62.76	60	213.75
2016	38.92	51.51	66.01	64.06	220.50
2017	38.25	51.32	60.12	60.86	210.55
2018	36.28	50.88	52.17	58.7	198.03
2019	51.08	50.88	55.22	54.62	211.80
2020	46.92	50.35	51.19	53.72	202.18
2021	53.58	50.65	51.9	67.55	223.68

Using logistics warehousing land area data from 2012, 2015, 2018 and 2021 for the Beijing-Tianjin-Hebei-Shanxi region, the logistics sprawl extent for each city during each phase was measured based on the aforementioned model (1) (see Table 2). According to Table 2, the land use sprawl index during T2 decreased overall compared to T1, indicating a state of no sprawl (LSI was negative).

In the T1 phase, due to the implementation of the 12th Five-Year Plan², significant progress was made in the logistics industry, particularly in the early and mid-term of T1 (2012-2014). With the release of policies such as the Guiding Opinions on Promoting the Transformation and Upgrading of the Warehousing Industry³, although the area of logistics warehousing land continued to grow, the growth rate slowed significantly. During the T phase, Shanxi emerged as the province with the most severe logistics sprawl in the Beijing-Tianjin-Hebei-Shanxi region, with a logistics warehousing LSI of 0.3156. This was partly due to Shanxi's active engagement in the spillover effects of the Beijing-Tianjin-Hebei collaborative development, accelerating the construction of logistics infrastructure and rapidly expanding logistics warehousing land, thereby driving logistics sprawl.

Table 2 – Spreading index of logistics and warehousing land by stages

Province (municipality)	LSI			
	T ₁	T ₂	T ₃	T
Shanxi	0.0681	-0.0846	0.3229	0.3156
Beijing	0.0786	-0.0149	-0.0045	0.0606
Tianjin	0.1557	-0.2030	-0.0052	-0.0210
Hebei	0.0417	-0.0221	0.1310	0.1488
All cities	0.0889	-0.0794	0.1147	0.1294

According to the LSI calculations, the urban sprawl levels in the Beijing-Tianjin-Hebei-Shanxi region were classified into six categories (see Table 3). When the logistics warehousing land area at the end of the period was lower than at the baseline, such cities were classified as having no sprawl. Using the equal interval classification method in ArcGIS 10.8, the calculated sprawl indices were categorised into five levels: low-speed, lower-speed, medium-speed, higher-speed and high-speed sprawl.

² 12th Five-Year Plan: Outline of the Twelfth Five-Year Plan (2011-2015) for National Economic and Social Development of the People's Republic of China.

³ Guiding Opinions on Promoting the Transformation and Upgrading of the Warehousing Industry: Issued by the Ministry of Commerce of the People's Republic of China in December 2012, it aims to promote the transformation and upgrading of the traditional warehousing industry into a modern logistics industry, in order to reduce the cost of circulation, improve the efficiency of circulation and promote the healthy development of the warehousing industry.

Based on Table 3 and Figure 1, during the T phase, most cities exhibited medium to low-speed sprawl or no sprawl at all, with relatively few cities experiencing higher-speed or high-speed sprawl, notably Shijiazhuang in Hebei Province. This indicates that the urban logistics sprawl in the Beijing-Tianjin-Hebei-Shanxi region was present but remained under control throughout the study period. In the T1 phase, the majority of cities experienced either no sprawl or low-speed sprawl. Cities with lower-speed and medium-speed sprawl were relatively dispersed, while medium-speed and higher-speed sprawl were primarily observed in cities adjacent to Beijing, such as Chengde and Baoding in Hebei Province, indicating severe sprawl during this period. In Shanxi Province, Taiyuan was the only city with lower-speed sprawl, suggesting that logistics development in Shanxi began later and was uneven, with lower-speed sprawl cities possibly in the process of planning and constructing large logistics warehousing bases.

In the T2 phase, the proportion of cities with lower-speed and medium-speed sprawl increased, with no cities experiencing medium-speed sprawl or higher. The number of cities with low-speed sprawl significantly decreased. Cities such as Jinzhong in Shanxi Province and Langfang in Hebei Province exhibited lower-speed sprawl, while Jincheng in Shanxi, Hengshui and Tangshan in Hebei became centres of medium-speed sprawl, indicating accelerated logistics development in Shanxi and Hebei, with an overall intensification of logistics sprawl in Shanxi.

During the T3 phase, the proportion of cities with no sprawl remained high, while the proportion of cities with high-speed sprawl increased, suggesting a moderation in the overall sprawl trend. This could be attributed to government policies adjusting urban construction land use. Several cities in Shanxi Province (Datong, Taiyuan, Lüliang and Yangquan) experienced increased logistics sprawl. The logistics sprawl in the Beijing-Tianjin-Hebei-Shanxi region followed a “high-low-high” pattern across the T1-T3 phases.

Table 3 – Classification of urban logistics sprawl levels

Extent of logistics spread	Classification criteria	Classification method	Percentage of T ₁ cities (%)	Percentage of T ₂ cities (%)	Percentage of T ₃ cities (%)	Percentage of T cities (%)
No spreading	$LSI \leq 0$	Define division	41.67	58.33	41.67	37.5
Low rate of spread	$0 < LSI \leq 0.2$	Equal interval	45.83	20.83	37.5	29.17
Lower rate of spread	$0.2 < LSI \leq 0.4$	Equal interval	4.17	8.33	4.17	4.17
Medium speed spread	$0.4 < LSI \leq 0.6$	Equal interval	4.17	12.5	12.5	25
Higher speed spread	$0.6 < LSI \leq 0.8$	Equal interval	4.17	0	0	4.17
High speed spread	$0.8 < LSI \leq 1$	Equal interval	0	0	4.17	0

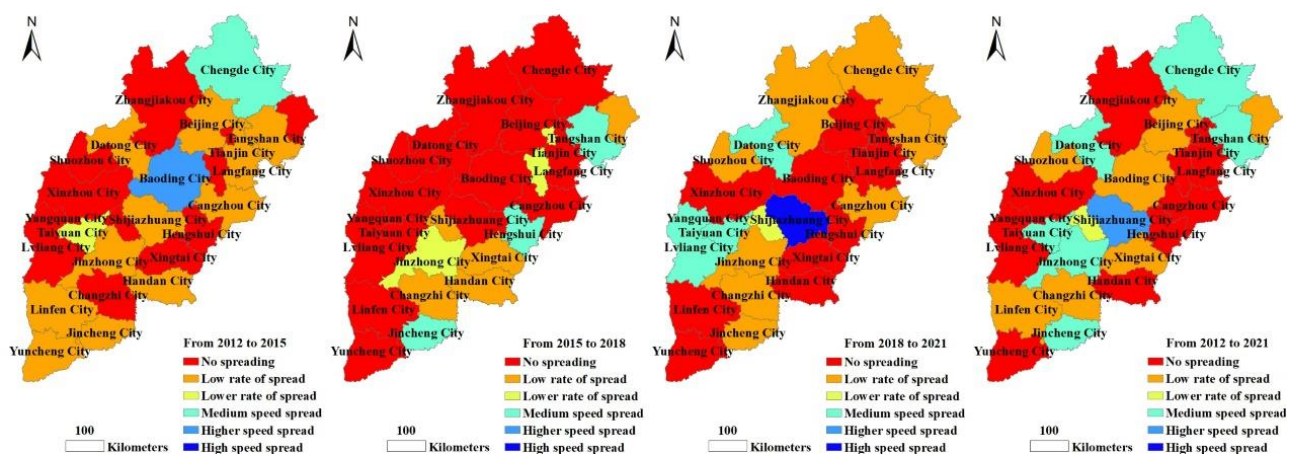


Figure 1 – Degree of logistics sprawl in Beijing-Tianjin-Hebei-Shanxi cities

3.2 Regional differences in urban logistics sprawl

The extent of logistics sprawl is closely associated with regional economic development and urban logistics development levels. To gain a deeper understanding of the differences in logistics sprawl among cities in the Beijing-Tianjin-Hebei-Shanxi region, this study employed the coefficient of variation (Cv) as an analytical tool (see *Table 4*). From a provincial (or municipal) perspective, during the T phase, Beijing had the highest LSI value, while Hebei Province had the lowest and negative average LSI values, reflecting the most severe logistics sprawl in Beijing and relatively low sprawl in Hebei's cities.

In the T1 phase, Tianjin experienced a significant increase in logistics sprawl, becoming the most affected area during this period. In contrast, Shanxi and Beijing did not exhibit noticeable logistics sprawl activity, and only Hebei had a negative average LSI, indicating its relatively lower sprawl level. During the T2 phase, a notable observation was that all cities had negative LSI values, clearly indicating that all cities were in a state of no logistics sprawl, with logistics land use potentially remaining stable or even decreasing. By the T3 phase, the logistics sprawl pattern shifted once more. Shanxi replaced Tianjin as the region with the most severe sprawl. At this stage, the logistics sprawl pattern in the Beijing-Tianjin-Hebei-Shanxi region transitioned from Tianjin to Shanxi, with Hebei's sprawl level remaining unchanged.

Analysis of the data in *Table 4* offers an alternative perspective on the logistics sprawl situation in the Beijing-Tianjin-Hebei-Shanxi region and the differences between cities adjacent to Beijing and those further away. Notably, the average LSI values for cities not adjacent to Beijing were generally higher than those for cities adjacent to Beijing. Especially in the T3 and T phases, these cities had positive LSI values, exceeding the average LSI for all cities. This phenomenon suggests that cities further from Beijing displayed more pronounced logistics sprawl, indicating more severe sprawl activities. This could be due to these cities being less influenced by Beijing's logistics development, allowing them to develop their own sprawl patterns. Conversely, cities adjacent to Beijing had negative average LSI values in the T phase and throughout the T1-T3 phases, reflecting a relatively lower logistics sprawl. This might be attributed to Beijing's strong logistics network and its influence on surrounding cities, leading to more orderly and concentrated logistics development, thereby suppressing sprawl.

Overall, most cities in the Beijing-Tianjin-Hebei-Shanxi region exhibited logistics sprawl, likely related to the region's economic development and growing logistics demand. However, cities adjacent to Beijing experienced relatively lower sprawl due to Beijing's influence, indicating that these cities might place greater emphasis on planning and coordination in logistics development. Shanxi Province also showed a relatively significant logistics sprawl, possibly due to its geographical location, economic development level and logistics infrastructure characteristics. In summary, the logistics sprawl in the Beijing-Tianjin-Hebei-Shanxi region demonstrated notable regional differences, with cities close to Beijing exhibiting lower sprawl, while those further away showed more pronounced sprawl. These differences could be attributed to factors such as geographical location, economic development level, logistics demand and infrastructure development.

As shown in *Table 4*, the distinctiveness of Shanxi Province's logistics sprawl during the T phase is evident. Specifically, the coefficient of variation for Shanxi Province during the T phase was significantly higher than that for the Beijing-Tianjin-Hebei region, reflecting substantial differences in logistics sprawl levels among cities within Shanxi. This indicates that within Shanxi, some cities experienced very high levels of logistics sprawl, while others had relatively lower levels, showing significant divergence. Throughout the T1-T3 phases, the mean LSI values for cities in Beijing-Tianjin-Hebei-Shanxi exhibited a fluctuating trend, decreasing initially, then increasing, and finally decreasing again. Concurrently, the coefficient of variation for the Beijing-Tianjin-Hebei region decreased, showing a trend towards convergence in logistics sprawl levels and a reduction in differences, indicating effective management and control of logistics sprawl in the region. In contrast, Shanxi Province's situation contrasted sharply with Beijing-Tianjin-Hebei. During the T1-T3 phases, the mean LSI for Shanxi Province increased, while its coefficient of variation also continued to rise, suggesting that the differences in logistics sprawl among cities in Shanxi were expanding, with some cities experiencing higher levels of sprawl while others lagged.

Table 4 – Regional differences in logistics sprawl in the Beijing-Tianjin-Hebei-Shanxi region

Province (municipality)	T1		T2		T3		T	
	LSI mean	Cv	LSI mean	Cv	LSI mean	Cv	LSI mean	Cv
Shanxi	0.0003	0.0283	-0.1895	0.0308	0.1920	0.1408	0.0207	0.1483
Beijing	0.0786	0.0309	-0.0149	0.0056	-0.0045	0.0043	0.0606	0.0258
Tianjin	0.1557	0.0641	-0.2030	0.0849	-0.0052	0.0293	-0.0210	0.0846
Hebei	-0.2369	0.0940	-0.0852	0.0325	-0.0207	0.0933	-0.1289	0.0954
Bordering Beijing	-0.3114	0.0646	-0.1563	0.0899	-0.0866	0.0313	-0.4375	0.0927
Not bordering Beijing	-0.0494	0.0716	-0.1357	0.0172	0.1284	0.1144	0.0542	0.0971

The analysis of logistics sprawl hotspots and cold spots (see Figure 2) revealed that during the T1 and T2 phases, there were no prominent hotspot areas, while cold spots shifted from Zhangjiakou in Hebei Province to Jinzhong in Shanxi Province. In the T3 phase, significant logistics sprawl hotspots emerged, primarily concentrated in Shanxi Province, including cities such as Xinzhou, Lüliang, Taiyuan, Jinzhong and Yangquan, with Handan in Hebei Province identified as a cold spot. During the T phase, aside from transitional zones, the main cold spot regions were Datong in Shanxi Province and Zhangjiakou in Hebei Province. Figure 3 indicates that Beijing and Tianjin have consistently been transitional areas in logistics sprawl but have remained hotspots for logistics warehousing land, suggesting a lower degree of sprawl and saturation in logistics park construction. Conversely, Chengde in Hebei Province has been a hotspot for logistics warehousing land across all phases, indicating its role in accommodating the spillover effects of Beijing's logistics development. In terms of logistics warehousing land, Beijing, Tianjin, Chengde, Langfang and Zhangjiakou are hotspots, while most cities in Shanxi Province and Hebei Province are transitional areas, with no cold spots, exhibiting a spatial distribution pattern of “Beijing-Tianjin hot, Hebei-Shanxi cold”.

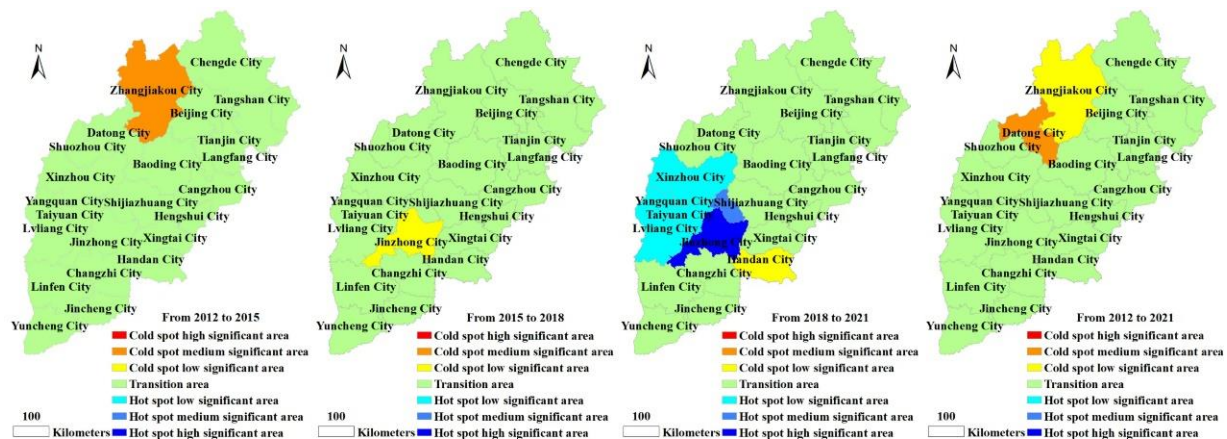


Figure 2 – Urban logistics spreading cold hotspot zoning

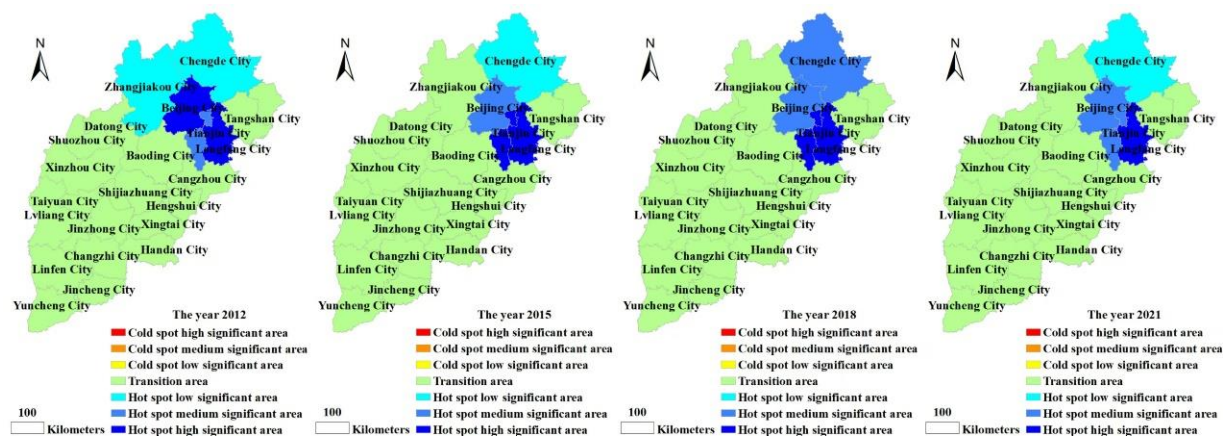


Figure 3 – Cold and hot spot zoning of urban logistics and warehousing land area

3.3 Evolution of logistics sprawl centres and directions

Using the Spatial Analysis tool in ArcGIS 10.8, an in-depth analysis was conducted on the spatial distribution, range and centre of logistics warehousing land in the Beijing-Tianjin-Hebei-Shanxi region, with land area serving as the weight. The results, presented in *Table 5* and *Figure 4*, detail the changes in parameters and the movement trajectories of the centres over the phases.

As can be seen from *Figure 4*, in terms of the trend of moving the centre of gravity of the spread of logistics and warehousing land, the centre of gravity of the spatial distribution of logistics and warehousing land in all stages from 2012-2021 moved from the purple point to yellow, then to blue, and finally to the orange point. In terms of directional movement, the centre of gravity of the spatial distribution of logistics and warehousing land showed a slight movement towards the northeast during 2012-2015, and this centre of gravity shifted slightly towards the southeast during 2015-2018. However, by 2021, the centre of gravity shows a significant shift towards the southwest. Throughout the 2012-2021 trajectory, the centre of gravity of the spatial distribution of logistics and warehousing land in the Beijing-Tianjin-Hebei-Shanxi region as a whole shows a tendency to move towards the west and the south, a change that is to some extent influenced by the significant shift in the centre of gravity during the period 2018-2021. The significant shift of the centre of gravity towards the southwest during the period 2018-2021 may be due to the fact that in 2018, the NDRC issued the Opinions on Supporting Shanxi Province to Strengthen Collaboration with the Beijing-Tianjin-Hebei Region to Achieve Linked Development, which prompted the shift of industrial and logistics resources in the direction of Shanxi, driving the shift in the centre of gravity of logistics and warehousing land. The slight movement towards the northeast in 2012-2015 may be related to the initial stage of the Beijing-Tianjin-Hebei collaborative development at that time, when some industries were transferred to Hebei cities in the northeast, which drove the growth of logistics demand and made the centre of gravity of logistics to shift in that direction; and the movement towards the southeast in 2015-2018 may be related to the further development and opening up of the Binhai New Area of Tianjin, attracting the clustering of logistics enterprises. In terms of the spatial distribution range of logistics warehousing land, there was an overall trend of gradual contraction amidst fluctuations from 2012 to 2021. Specifically, from 2012 to 2015, the area of the ellipsoid representing logistics warehousing land decreased, with a corresponding reduction in the length of the short semi-axis, indicating relatively weak logistics sprawl in Shanxi Province, while logistics activities increasingly concentrated in Beijing and Tianjin. However, from 2015 to 2018, the spatial sprawl trend became most pronounced, with the ellipsoid area increasing by 4.07% and a notable extension in the length of the long semi-axis. Despite the initial contraction, the spatial distribution range of logistics sprawl expanded significantly towards Shanxi Province over the entire period from 2012 to 2021.

From the perspective of the spatial distribution range of the spread of logistics and warehousing land, the overall trend of a gradual contraction in fluctuation is shown during the period of 2012-2021. This is due to the fact that in the process of industrial restructuring in Beijing-Tianjin-Hebei-Shanxi region, some highly polluting and energy-intensive logistics-related industries have gradually shifted to the western part of Hebei and Shanxi, and at the same time, policies have guided the optimal allocation of logistics resources to these areas to achieve regional synergistic development, which has led to the change of the scope of logistics coverage in a specific direction. Specifically, from 2012-2015, the ellipse area of logistics storage land decreased, and the length of the short semi-axis shortened accordingly, indicating that the degree of logistics spreading in Shanxi Province was relatively weak, while logistics activities gradually formed a cluster in the Beijing and Tianjin regions. However, by 2015-2018, the spatial spreading trend of logistics and warehousing land became most significant, with the elliptical area increasing by 4.07%, especially the length of the long semi-axis of the ellipse increased significantly. This may be due to the advancement of logistics infrastructure construction in the region, as well as the adjustment of the industrial layout, which has prompted logistics activities to spread over a wider area. By comparing the magnitude of change at different stages, it can be seen that the change from 2015-2018 is more prominent, reflecting the active level of regional logistics development during this period. From a more macroscopic perspective, the spatial distribution range of logistics spread has expanded to a greater extent towards Shanxi Province throughout the 2012-2021 period, despite experiencing an initial contraction.

In terms of changes in the direction of the spatial distribution of sprawl, the standard deviation ellipse of the spatial distribution of logistics land across the country rotated clockwise by 1.29° from 2012-2015; from 2015-2018, logistics in the cities of Beijing-Tianjin-Hebei-Shanxi region showed a trend of no sprawl, with the standard deviation ellipse rotating counterclockwise by 2.47° ; and by 2021, the standard deviation ellipse rotated clockwise by 4.62° . Overall, it seems that the standard deviation ellipse of logistics land in Beijing-

Tianjin-Hebei-Shanxi rotates clockwise by 3.44° from northeast to southwest, indicating that the logistics spreading trend of cities in Beijing-Tianjin-Hebei is stronger relative to that of Shanxi Province, which reflects the dominant position of Beijing-Tianjin-Hebei region in the regional logistics development, as well as the relative lagging of the logistics development of Shanxi Province in the process of integrating into the Beijing-Tianjin-Hebei coordinated development, and embodies the intra-regional unevenness of logistics development and unique spatial evolution characteristics. The clockwise rotation of 1.29° in 2012-2015 indicates that there is a certain spreading trend of logistics in the cities of Beijing-Tianjin-Hebei in this period, and the direction has changed; the counterclockwise rotation of 2.47° in 2015-2018, when the logistics in the cities of Beijing-Tianjin-Hebei-Shanxi region shows no spreading trend, probably due to the impact of industrial structure adjustment, environmental protection policies and other factors, the development of logistics is subject to certain limitations. The logistics development in Shanxi Province will be limited by the year 2021. In 2021, the clockwise rotation is 4.62° , indicating that the logistics spreading trend of Beijing-Tianjin-Hebei cities is enhanced again in this period. By comparing the rotation angles at different stages, it can be seen that the rotation angle in 2021 is the largest and the change is the most significant, reflecting the obvious changes in the logistics spreading situation of Beijing-Tianjin-Hebei cities in this period.

Table 5 – Various parameters of the weighted standard deviation ellipse

Year	Short half-axis	Long half-axis	Area	Direction angle	Centre of gravity X	Centre of gravity Y
2012	132748.52	282746.18	117904794540.47	43.45	115.74	39.02
2015	123861.65	279119.08	108599322617.38	44.74	115.79	39.02
2018	125871.68	285838.55	113018347218.50	42.27	115.85	39.00
2021	124948.69	286125.35	112301990375.07	46.89	115.55	38.97

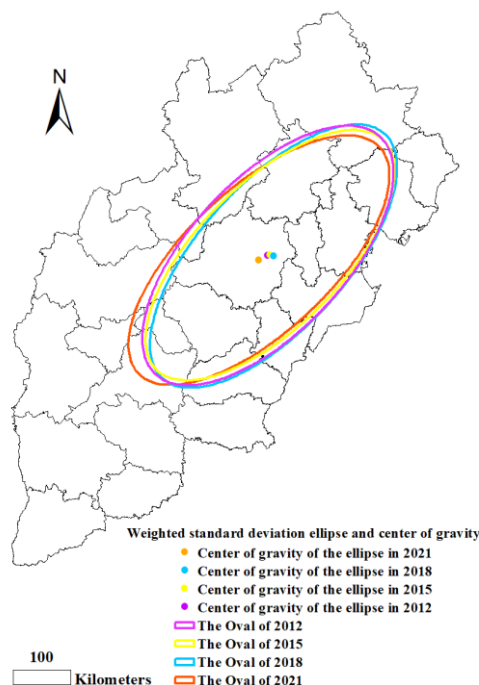


Figure 4 – Weighted standard deviation ellipse and change in the centre of gravity for logistics land, 2012, 2015, 2018, 2021

4. INFLUENCING FACTORS OF URBAN LOGISTICS SPRAWL

Under the guidance of location theory and economy of scale theory, the indicators are screened from three dimensions, including economic development status, and the main factors affecting the spread of logistics in the cities of Beijing, Tianjin, Hebei and Jin and the degree of their influence are examined by geographic detectors.

4.1 Indicator system for logistics sprawl influencing factors

Guided by theories such as location theory and economies of scale, scholars have conducted in-depth analyses of logistics space, encompassing not only logistics [38] and transportation [39, 40] but also economics [41], management [42] and geography [43, 44]. Most empirical studies on urban logistics sprawl focus on its distribution and evolution. However, research on influencing factors often lacks quantitative analysis and typically relies on qualitative discussions based on calculated data on urban logistics sprawl [45]. Given the availability and quantifiability of data, this study adopted previous research findings to select 12 indicators from three dimensions – economic development, logistics development, and government and land use – as shown in *Table 5*. The geographic detector method was used to examine the primary factors affecting logistics sprawl in the Beijing-Tianjin-Hebei-Shanxi region and their impact levels.

Table 6 – Indicator system for influencing factors of urban logistics sprawl

Target level	Indicator level	Unit
Economic development	GDP per capita (X1)	Billions of Yuan
	GDP (X2)	Yuan
	Tertiary sector as a share of GDP (X3)	%
	Total retail sales of consumer goods (X4)	Billions of Yuan
Logistics development	Road density (X5)	Km/km ²
	Fixed internet broadband access subscribers (X6)	Ten thousand persons
	Total postal operations (X7)	Billions of Yuan
	Number of students enrolled in undergraduate programs (X8)	Persons
Government and land use	Public financial expenditures (X9)	Billions of Yuan
	Urban population density (X10)	Persons/km ²
	Land area for urban construction (X11)	Km ²
	Urban road area (X12)	10,000 square metres

Economic development

Regionally coordinated development significantly increases inter-regional transport demand, stimulating the expansion of the logistics industry. Various logistics enterprises began to cluster in cities with advantageous transportation locations and spread to surrounding cities along major transportation corridors and routes. The literature review indicates that urban economic development levels drive logistics sprawl. This study used per capita GDP, total GDP and total retail sales of consumer goods as proxy variables for urban economic development. Additionally, the proportion of the tertiary sector in GDP was included as it can also affect local logistics sprawl.

Logistics development

The core of the logistics business lies in cargo transportation. Before establishing operations, logistics companies thoroughly assess local transportation capabilities. More convenient transportation and significant locational advantages enhance the attractiveness to businesses. Therefore, network density and total postal volume were used to represent urban transportation capabilities. A higher number of internet broadband subscribers reflects a higher level of logistics information technology [46]; thus, this indicator was used to gauge the level of logistics informatisation in cities. As the logistics industry is labour-intensive, labour costs are a key consideration in site selection. The number of university students was used to represent the labour force level in various cities.

Government and land use

The integration and optimisation of urban spatial distribution depend on local government departments. Urban construction land planning relies on government personnel, and public financial expenditure represents the level of local government investment in infrastructure. Thus, public financial expenditure and urban construction land area were selected as proxy indicators for government influence on urban logistics sprawl. Land use also plays a significant role in logistics sprawl, with urban population density and road area used to measure the impact of land use.

4.2 Geographic analysis of factors influencing logistics sprawl in the Beijing-Tianjin-Hebei-Shanxi region

To explore the influence of these three dimensions on urban logistics sprawl, the natural breaks classification method in ArcGIS 10.8 was used to categorise the 12 indicators into five classes. Subsequently, the geographic detector software measured the q-values of each influencing factor, allowing for a quantitative analysis of logistics sprawl in the Beijing-Tianjin-Hebei-Shanxi region.

- 1) The geographic detector results revealed that seven factors – X1, X4, X6, X8, X9, X11 and X12 – were significant at the 0.01 level, indicating that most of the selected factors could adequately explain the spatial and temporal differentiation of logistics sprawl in the region.
- 2) In the interaction detection, only five pairs of factors enhance the explanation of urban logistics spread, which reveals the complex synergistic relationship between the influencing factors. X3, X5 and X10 interact more significantly with other factors, implying that these factors play the role of “link” in the formation of spatial-temporal differentiation pattern of Beijing-Tianjin-Hebei-Shanxi region urban logistics spread. X3 represents the proportion of tertiary industry in GDP, X5 represents the density of road network and X10 represents the density of urban population. When X3 and X5 interact with each other, the region with a dense road network can connect the region with a high proportion of tertiary industry in GDP more efficiently, realise the rapid transportation of raw materials and products, and greatly promote the development of logistics activities, thus accelerating the spread of logistics. If the road network density of a city is at a high level, and the tertiary industry in the neighbourhood accounts for a high proportion of GDP, its logistics development speed is faster than that of other regions, and the scope of logistics coverage continues to expand, and the construction of logistics parks is more rapid.
- 3) The q-values of the factors in the factor detection results remain in the range of 0.188-0.968, which intuitively reflects that there are significant differences in the factors affecting the spread of logistics in the Beijing-Tianjin-Hebei-Shanxi region. The higher the q-value is, the stronger the explanatory ability of the factor on the spread of logistics. Total retail sales of consumer goods, urban construction land area and urban road area are the top three factors affecting all cities in the Beijing-Tianjin-Hebei-Shanxi region, with q-values above 0.9. Urban construction land area and urban road area have a greater impact on Shanxi Province, of which urban construction land area is the most significant impact factor with a q value as high as 0.974, indicating that the high-quality development of the urban logistics industry cannot be separated from the rational planning of urban construction land area. Factors with lower q-values, such as GDP per capita and the number of fixed internet broadband access subscribers, also have a certain impact on the spread of logistics, but relatively speaking, their degree of effect is weaker, and they are secondary influencing factors in the formation of spatial and temporal differentiation patterns of the spread of logistics.

From the perspective of the main influencing factors, these factors may play a dominant role in different regions and time periods. For example, X11 represents the area of urban construction land in the Beijing-Tianjin-Hebei-Shanxi region. Areas with large urban construction land can often provide sufficient land resources for logistics warehousing, distribution centres, etc., which makes it easier for logistics enterprises to cluster and thus forms an area with obvious logistics spreading dynamics. In some areas of Shanxi where urban construction land is relatively tight, logistics development is restricted by space, and the degree of logistics spread is lower, reflecting the spatial differentiation of the impact of X11. Analysed from the time dimension, with X4 representing the total retail sales of consumer goods, for example, the growth of total retail sales of consumer goods over time implies an increase in market demand, which stimulates the continuous expansion of the logistics industry, the continuous expansion of the coverage of logistics services, and the continuous construction of new logistics parks, which directly contributes to the process of logistics spreading. In the Beijing-Tianjin-Hebei-Shanxi region, the logistics spreading speed is

accelerated during the phase of better economic development and active consumer market, such as the peak consumption period of holidays, and the logistics distribution network in each city is denser, which fully shows the dynamic effect of X4 on logistics spreading in time. To further explore the role of these factors between different regions, in the Beijing-Tianjin-Hebei region, the economy is more developed, X1 represents the level of economic development of the relevant indicators, its impact on the spread of logistics is more prominent, the developed economy to attract more logistics enterprises layout, enhance the level and scale of logistics services. In some resource cities in Jin and Hebei, X12 is an indicator of urban road area, and the rise and fall of the resource industry is directly related to the demand for logistics. During the prosperous period of resource exploitation, logistics transport is frequent, and the city area naturally expands and the logistics spreads rapidly; when the resource industry declines, the development of urban roads is also limited, reflecting the uniqueness of the role of factors in different regions.

- 4) The results of the partition detection show that the explanatory power of the factors influencing the spread of urban logistics does not differ significantly, indicating that there is no major factor among the 12 factors. Some of the influencing factors are significant, reflecting that the phenomenon of urban logistics spreading is not caused by a single factor but is driven by multiple factors.
- 5) The government and land use dimensions play an extremely crucial role in urban logistics spreading in the Beijing-Tianjin-Hebei-Shanxi region, especially in Shanxi Province. In Shanxi Province, local governments play a leading role in the development and formation of urban logistics infrastructure space. On the one hand, the government guides the reasonable concentration and layout of logistics resources by formulating relevant policies, such as logistics park construction planning and preferential land policies. The government designates specific areas as logistics industrial parks and provides policies such as land grant exemption and tax incentives to attract logistics enterprises to move in, thus promoting the centralised construction of logistics infrastructure and the formation of a large-scale logistics development space. On the other hand, in the land use approval process, the government strictly controls the logistics land use index and gives priority to guaranteeing the land demand of logistics projects to ensure that the logistics infrastructure has enough space for expansion and upgrading. This kind of all-around support, from policy guidance to land resource supply, promotes the logistics infrastructure construction in Shanxi Province to be promoted in an orderly manner, and the logistics spreading trend is gradually formed under the influence of the government and land use dimensions.

On the contrary, in Beijing and Tianjin, due to their higher level of urbanisation and better urban development, logistics sprawl activities show a more complex pattern of influence. Two dimensions, economic development status and government land use, have synergistic effects on logistics sprawl in Beijing and Tianjin. In terms of economic development, the highly developed economic system has given rise to a large amount of logistics demand, whether it is the demand for efficient distribution of raw materials and components in high-end manufacturing industries, or the requirement for rapid distribution of goods in prosperous consumer markets, which has led to the continuous expansion of the logistics industry. As the political, cultural and international communication centre of the country, Beijing's large number of business activities and high-end consumption demand have driven the rapid development of cold chain logistics, express courier and express transportation and other niche logistics areas, and logistics enterprises have been expanding their business scope and achieving logistics spread to meet the market demand. Meanwhile, government land use policies play an integral role in Beijing and Tianjin. In the context of more mature urban development, land resources are relatively scarce, and the government optimises the spatial layout of the city through scientific planning of logistics land and guides logistics enterprises to cluster in specific areas.

This situation of different regions being affected by different dimensions fully demonstrates that the spread of urban logistics has obvious stages and regional differences in the development process. In regions with less developed economies and lower levels of urbanisation, such as some cities in Shanxi Province, the government and land use dimensions become the key force to promote the development and spread of logistics, laying the foundation for logistics infrastructure construction. In the Beijing-Tianjin region, which is economically developed and has mature urbanisation, the economic development and the government's land use play a joint role in meeting the market demand while realising the efficient use of the urban space and promoting the logistics industry to a higher level of development. Recognition of this stage and regional differences is of great significance for the formulation of targeted regional logistics development strategies, which can better promote the synergistic development of logistics in the Beijing-Tianjin-Hebei-Shanxi region and enhance the overall competitiveness of the region.

5. CONCLUSIONS AND RECOMMENDATIONS

We analyse and discuss the results of the study from four perspectives, namely, the dynamics and speed of logistics spreading, spatial heterogeneity, the evolution of the centre of gravity and scope of spatial distribution, and the influencing factors, and compare and analyse them with the urban logistics spreading in different regions of China.

5.1 Conclusions and discussion

In-depth research into the spatial-temporal evolution characteristics and regional differences of urban logistics sprawl in the Beijing-Tianjin-Hebei-Shanxi region, using the geographic detector to examine influencing factors, leads to the following conclusions.

First, the logistics spreading situation in Beijing, Tianjin, Hebei and Shanxi is generally in a controllable stage and the spreading speed is not high, some cities in Shanxi Province and Hebei Province are more serious, and the medium and low-speed logistics spreading or even non-spreading state covers most of the cities, and the spreading situation is controllable. In the T1-T3 stage, the logistics spreading situation in the cities of Beijing, Tianjin, Hebei and Shanxi shows the pattern of “high - low – high”. The change rule of Shanxi Province and Hebei Province is the rapid development of the logistics industry. This pattern of change is closely related to the regional industrial transfer, policy adjustment and other factors. In the T1 stage, with the initial promotion of the Beijing-Tianjin-Hebei co-development strategy, some industries are transferred to Hebei Province, which drives the growth of local logistics demand and accelerates the speed of logistics spreading. In the T2 stage, affected by environmental protection policies, industrial structure adjustment and other factors, some logistics projects slow down and the speed of logistics spreading decreases. In the T3 stage, with the strengthening of the collaboration between Shanxi Province and the Beijing-Tianjin-Hebei region and the introduction of new logistics policies, the logistics industry in Shanxi Province and Hebei Province is developing rapidly. Shanxi Province and Hebei Province ushered in new development opportunities for the logistics industry, and the speed of logistics spreading accelerated again.

Beijing-Tianjin-Hebei-Shanxi logistics sprawl exhibits a three-stage fluctuation of “high-low-high”, in contrast to the “low-high-low” evolution of sprawl in most of the cities in the Yangtze River Economic Belt [47]. The PRD lacks significant phase fluctuations due to the stable growth supported by the export-oriented economy and industrial upgrading [48]. The policy-sensitive fluctuation characteristics revealed in this study break through the economic determinism framework of the traditional logistics growth theory and validate the dynamic regulation mechanism of policy intervention on logistics spatial reconfiguration [49].

Second, there is obvious spatial heterogeneity in the spread of urban logistics. In terms of logistics and warehousing land, the cities in Shanxi Province and most of the cities in Hebei Province are transition areas, with no cold spots, showing the distribution characteristics of “hot in Beijing and Tianjin, cold in Hebei and Shanxi”. The difference in the level of logistics spread between Beijing, Tianjin and Hebei is gradually narrowing, and the level of logistics spread in cities in Shanxi Province is increasing; compared with cities bordering Beijing, the level of logistics spread in cities not bordering Beijing is higher overall, with a greater difference in the internal part. This may be due to the fact that Beijing and Tianjin have gathered logistics resources by virtue of their infrastructural and policy advantages, while most cities in Shanxi and Hebei lag behind in logistics development due to their economic and industrial structures. Handan, Xingtai and other cities in Hebei that do not share a border with Beijing have strong logistics demand and a high degree of logistics contagion due to their resource-based industries (iron and steel, coal) and their status as transport hubs, but there is still significant spatial variation within these cities due to the differences in their industrial layouts and transport conditions.

The Guangdong-Hong Kong-Macao Greater Bay Area, with Guangzhou, Shenzhen and Hong Kong as its core, forms a balanced and close logistics network [50], with a relatively small gap between the core and peripheral cities in terms of logistics development and efficient allocation of resources. In contrast, Beijing, Tianjin, Hebei and Shanxi show significant imbalance. The spatial pattern of logistics in the Yangtze River Delta has evolved from dual-centre, multi-level to multi-centre, two agglomerations [51], with Shanghai as the core to radiate to the peripheral cities, and the gradient of the logistics level decreases with the increase of the distance from Shanghai, and the difference is relatively smooth [52]. In the Beijing-Tianjin-Hebei-Shanxi region, Hebei's non-bordering cities (e.g. Xingtai and Handan) form logistics islands due to the layout of heavy industry, and the degree of spread is higher than that of the bordering cities, which is in conflict with the spatial assumptions of Friedmann's [53] Core-Edge Theory, suggesting that policy interventions can break the

limitations of geographical proximity. This suggests that policy interventions can break the geographical proximity constraints and provide a new case for regional logistics research.

Third, from 2012 to 2021, the trajectory of the centre of gravity of the spatial distribution of logistics spread in Beijing, Tianjin, Hebei and Shanxi experienced an evolutionary pattern towards the northeast-southeast-southwest direction, in which, influenced by the Opinions on Supporting Strengthened Collaboration between Shanxi Province and the Beijing-Tianjin-Hebei Regions to Achieve Linkage Development issued by the National Development and Reform Commission in 2018, the 2018-2021 trend of the centre of gravity shifting to Shanxi Province is the most obvious. The spatial distribution range of logistics spread in Beijing-Tianjin-Hebei-Shanxi cities shows a shrinking trend in fluctuation, and the spread covers a larger extent mainly in the direction of western Hebei and Shanxi provinces. The standard deviation ellipse of logistics land use in Beijing-Tianjin-Hebei-Shanxi is rotated clockwise by 3.44° , indicating that the trend of logistics spreading in Beijing-Tianjin-Hebei is stronger relative to Shanxi Province.

The centre of gravity of logistics in the Chengdu-Chongqing region fluctuates around the two core cities of Chengdu and Chongqing, driven by topography and regional economic ties [54], and logistics resources spread along the transport corridors. In contrast, the logistics centre of gravity in Beijing-Tianjin-Hebei-Shanxi shows a multi-directional evolution pattern, which is significantly affected by industrial transfer, policy guidance and the adjustment of urban functional positioning. Unlike the city cluster in the middle reaches of the Yangtze River, where the logistics scope expands with economic development [55], the logistics coverage of Beijing-Tianjin-Hebei-Shanxi shrinks to the west of Hebei and Shanxi, mainly due to the transfer of high-pollution, high-energy-consumption industries and policy-guided optimisation of resource allocation. From the standard deviation ellipse rotation, the expansion of logistics land in the Pearl River Delta is stable and driven by transport hubs and industrial clusters [56], while the Beijing-Tianjin-Hebei-Shanxi ellipse rotates clockwise by 3.44° , indicating that the trend of Beijing-Tianjin-Hebei logistics spreading is stronger than that of Shanxi, reflecting its dominant position in regional logistics and the lagging of Shanxi's integration into the Beijing-Tianjin-Hebei collaborative development.

Fourth, urban logistics sprawl is complex and multifactor-driven. The proportion of urban built-up land area is the factor with the most significant overall impact, followed by urban road area and total retail sales of consumer goods. Government and land use are the most important dimensions influencing the spread of logistics in all cities, and the spread of logistics in Beijing and Tianjin is influenced to a greater extent by the dimension of economic development status.

This finding contrasts with studies in the Yangtze River Economic Belt, which point out that public financial expenditure is the primary influencing factor of logistics sprawl in all cities. In addition, unlike the central region where logistics development relies on population density and industrial agglomeration, the Beijing-Tianjin-Hebei-Shanxi region is more influenced by policy guidance and land-use restrictions, highlighting the regional specificity [57]. Beijing, as a mega-city, has scarce land resources, and the restriction on the area of urban construction land directly restricts the expansion of logistics and warehousing land, which makes logistics enterprises have to seek more efficient land use. Logistics development in the Yangtze River Delta region is driven more by technological innovation and high value-added industries, while the Beijing-Tianjin-Hebei-Shanxi region is characterised by the spread of consumption-driven logistics. This policy-economy dual-track driving characteristic contrasts with the transport-oriented logistics development in the Chengdu-Chongqing region [58, 59], which breaks through the single-economy explanatory framework of the traditional logistics location theory.

5.2 Recommendations

First, for cities with limited or low-speed sprawl, improving urbanisation levels can create economies of scale and increase logistics activities between cities, thereby mitigating sprawl. Attention should also be given to managing medium- and high-speed logistics sprawl, which is crucial for reducing the negative impacts of sprawl.

Second, the positions within the logistics industry chain for cities in the Beijing-Tianjin-Hebei-Shanxi region should be rationally allocated, integrating port resources and forming a “multi-centre” logistics development model. This approach will promote regional industry integration and facilitate the spread of resources from Beijing and Tianjin to Shanxi, achieving comprehensive development across the region. Establishing a joint operation mechanism for resource sharing and collaborative distribution will enhance logistics network planning and efficiency, promoting overall development and regional integration.

Third, Shanxi Province should seize opportunities to integrate into national development strategies, break administrative barriers and utilise the spatial spillover effects of the logistics industry in the Beijing-Tianjin-Hebei region. Logistics parks should be consolidated with severe homogenous competition and leverage core cities in the Beijing-Tianjin-Hebei metropolitan area to drive logistics development in Shanxi, ensuring coordinated growth of logistics and urbanisation.

Fourth, government departments should actively formulate policies to promote local road construction and economic development. Accelerating the development of logistics corridors, comprehensively planning and integrating logistics economic channels, and utilising the comprehensive logistics corridors in the Beijing-Tianjin-Hebei region can improve infrastructure service capacity. Optimising the logistics warehousing division of labour and industry layout among the four regions will enhance resource allocation efficiency and rationalise spatial distribution. Supporting the development of modern logistics and increasing total retail sales of consumer goods will inject new vitality into economic development.

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