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RESEARCH ARTICLE

Research on grain supply and demand matching in the Beijing-Tianjin-Hebei region based on ecosystem service flows

Jiaxin Miao[1], Peipei Pan[1#], Bingyu Liu[1], XiaowenYuan[1], Zijun Pan[2], Linsi Li[1], Xinyun Wang[3], Yuan Wang[1], Yongqiang Cao[4], Tianyuan Zhang[1]

[1] *School of Geographic Sciences/Hebei Key Laboratory of Environmental Change and Ecological Construction/Hebei Technology Innovation Center for Remote Sensing Identification of Environmental Change, Hebei Normal University, Shijiazhuang 050024, China*
[2] *School of Geographic Sciences, Liaoning Normal University, Dalian 116029, China*
[3] *School of Ecology and Environmental Sciences, Ningxia University, Yinchuan 750021, China*
[4] *Academy of Eco-civilization Development for Jing-Jin-Ji Megalopolis, Tianjin Normal University, Tianjin 300387, China*

Highlights

- A significant mismatch exists between grain supply and demand, and it shows a scale effect.
- Grain flows exhibited an increasing trend from 1980 to 2020, radiating from central and southern regions to peripheral areas.
- Grain flows effectively reduce the number of grain-deficit areas compared to scenarios without grain flows.

Abstract

A comprehensive assessment of grain supply, demand, and ecosystem service flows is essential for identifying grain movement pathways, ensuring regional grain security, and guiding sustainable management strategies. However, current studies primarily focus on short-term grain provision services while neglecting the spatiotemporal variations in grain flows across different scales. This gap limits the identification of dynamic matching relationships and the formulation of optimization strategies for balancing grain flows. This study examined the spatiotemporal evolution of grain supply and demand in the Beijing-Tianjin-Hebei (BTH) region from 1980 to 2020. Using the Enhanced Two-Step Floating Catchment Area method, the grain provision ecosystem service flows were quantified, the changes in supply–demand matching under different grain flow scenarios were analyzed and the optimal distance threshold for grain flows was investigated. The results revealed that grain production follows a spatial distribution pattern characterized by high levels in the southeast and low levels in the northwest. A significant mismatch exists between supply and demand, and it shows a scale effect. Deficit areas are mainly concentrated in the northwest, while surplus areas are mainly located in the central and southern regions. As the spatial scale increases, the ecosystem service supply–demand ratio (SDR) classification becomes more clustered, while it exhibits greater spatial SDR heterogeneity at smaller scales. This study examined two distinct scenarios of grain provision ecosystem service flow dynamics based on 100 and 200 km distance thresholds. The flow increased significantly, from 2.17 to 11.81 million tons in the first scenario and from 2.41 to 12.37 million tons in the second scenario over nearly 40 years, forming a spatial movement pattern from the central and southern regions to the surrounding areas. Large flows were mainly concentrated in the interior of urban centers, with significant outflows between cities such as Baoding, Shijiazhuang, Xingtai, and Hengshui. At the county scale, supply–demand matching patterns remained consistent between the grain flows in the two scenarios. Notably, incorporating grain flow dynamics significantly reduced the number of grain-deficit areas compared to scenarios without grain flow. In 2020, grain-deficit counties decreased by 28.79 and 37.88%, and cities by 12.50 and 25.0% under the two scenarios, respectively. Furthermore, the distance threshold for achieving optimal supply and demand matching at the county scale was longer than at the city scale in both grain flow scenarios. This study provides valuable insights into the dynamic relationships and heterogeneous patterns of grain matching, and expands the research perspective on grain and ecosystem service flows across

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Jiaxin Miao, E-mail: miao_jia_xin@163.com; #Correspondence Peipei Pan, E-mail: panpeipei626@163.com

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various spatiotemporal scales.

Keywords: Beijing-Tianjin-Hebei region, grain provision ecosystem service, grain flow, supply and demand match, distance threshold

1. Introduction

Ecosystem services are crucial in ecological and environmental management research, and they contribute to improvements in human well-being and sustainable development (Costanza *et al.* 1997; Wang J X *et al.* 2024). Grain provision ecosystem services are an important component of ecosystem services, which are fundamental for human survival and development, and the study of grain supply and demand is critical for ensuring the stability and security of food systems (Zhou and Liu 2024). Factors such as global climate change and the decline in arable land resources have posed tremendous challenges for grain production. The rapid population growth and urbanization have caused significant migration from rural to urban areas, which has increased grain demand and substantially affected regional ecosystem supply service flows (Liu Q H *et al.* 2022). Grain provision ecosystem service flow aids in formulating food production and distribution policies, optimizing resource allocation, and mitigating the risk of exacerbating grain shortages. In the context of ecosystem service research, investigating the patterns of grain supply–demand matching and the characteristics of grain flow is vital for ensuring regional grain security. This is a key aspect of achieving the United Nations Sustainable Development Goal 2: "End hunger, achieve grain security and improved nutrition, and promote sustainable agriculture".

Many scholars have extensively investigated ecosystem services (Fu and Zhang 2014; Peng *et al.* 2023). As global climate change, population growth, accelerated urbanization, over-exploitation of resources, and environmental pollution intensify, the pressure on ecosystems continues to rise. Research on the supply and demand of ecosystem services, as well as their supply–demand relationships, has become a critical approach for addressing environmental challenges and improving human well-being (Su R *et al.* 2024; Sun *et al.* 2024; Zhang *et al.* 2025). To achieve this, researchers often use socioeconomic statistics and land use data to estimate ecosystem service supply and human demand, and to identify their spatial distributions. However, spatial mismatches frequently exist between the locations of ecosystem service production and their usage (Brauman *et al.* 2007). These discrepancies result from an insufficient analysis of the spatial flow processes of ecosystem services from supply to use. A mismatch between supply and demand leads to the spatial flow of ecosystem services to address the ultimate human needs. Notably, ecosystem services can traverse boundaries, moving from service-providing areas (SPAs) to service-benefit areas (SBAs) in distant locations (Chen *et al.* 2020). In this context, studies on ecosystem service flows provide a potential solution to the spatial mismatch between supply and demand. Consequently, these studies have attracted significant research interest (Wang and Zhou 2019).

Ecosystem service flows emphasize the dynamic spatial processes involved in delivering ecosystem services. These flows are increasingly being employed to address the supply–demand dynamics and spatial mismatches of ecosystem services, thereby supporting their sustainable management (Serna-Chavez *et al.* 2014; Xia *et al.* 2024). While the concept of ecosystem service flows remains largely theoretical, it continually stimulates empirical studies (Peng *et al.* 2023). Consequently, research on ecosystem service flows has emerged as a vital hotspot in the field of ecosystem services (Wang and Zhou 2019). Recent studies have mainly investigated various types of ecosystem service flows, including freshwater service flows (Li *et al.* 2017; Enrica *et al.* 2021; Zhang C *et al.* 2021; Huang *et al.* 2024), carbon sequestration service flows (Schirpke *et al.* 2019; Zhu *et al.* 2024), windbreak and sand-fixation material flows (Wang J X *et al.* 2024), recreational and cultural ecosystem service flows assessed *via* stakeholder input (Lan *et al.* 2017; Xu *et al.* 2024), and grain provision ecosystem services analyzed from a trade perspective (Ala-Hulkko *et al.* 2019; Liu W *et al.* 2022; Su D *et al.* 2024; Zhou and Liu 2024). Research on these diverse categories of ecosystem service flows provides valuable insights into the supply–demand dynamics of various ecosystem services. Grain provision ecosystem service flow is crucial for linking agricultural ecosystems to human well-being (Felipe-Lucia *et al.* 2022; Peng *et al.* 2023). However, understanding the dynamics of this flow remains challenging.

Research on ecosystem service flows currently focuses on the simulation and assessment of spatial flows, highlighting the intensity and direction of flows associated with various processes (Zhou and Liu 2024). The transmission media for different ecosystem service flows vary, and the models or methods used to estimate their ecosystem service flows also differ. Several well-established methods for simulating ecosystem service flows have been developed, including the Soil and Water Assessment Tool (SWAT) (Nedkov and Burkhard 2012), the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Zhang *et al.* 2020), and the Hydrological Simulation Program Fortran (HSPF) (Liu *et al.* 2021). Nonetheless, these methods were primarily designed to quantify specific service flows, such as water ecosystem service flows (Yang *et al.* 2023). In the ARIES project, Bagstad *et al.* (2013) introduced the Service Path Attribution Network (SPAN), which suggests that ecosystem service flows are transmitted through specific carriers that are either tangible or intangible. The flow direction is determined by the properties of the transmission medium. Research on grain flows is currently limited and predominantly based on traditional models which fail to capture the complexity and dynamics of food flows across multiple spatiotemporal scales. Moreover, analyses of the intensity and direction

of grain service flows need strengthening, particularly from different impact scopes and distance perspectives, to enhance our understanding of flow dynamics. Considering that the transportation of grain relies on a fixed road network as its carrier, the breakpoint formula and field strength model (Wen *et al.* 2024) cannot effectively represent the hierarchical network of grain flow. The Enhanced Two-Step Floating Catchment Area (E2SFCA) method, which is grounded in accessibility analysis, provides decision-makers with a more intuitive quantification of grain flow (Tao *et al.* 2022). This approach can provide more direct and effective applications in grain flow management.

In addition, multi-scale research is essential for identifying the spatial differentiation patterns of ecosystem service flows, thereby informing differentiated regional regulatory strategies. The generation and consumption of ecosystem services are influenced by both natural and social developments across different temporal and spatial scales. Meanwhile, the spatial correlations and matching patterns of ecosystem service supply and demand vary across these scales (Yan *et al.* 2017). Current research on ecosystem service supply and demand includes multiple levels, such as the global (Peng *et al.* 2023), regional (Zhao *et al.* 2024), and landscape scales (Daniel *et al.* 2020). Large-scale assessments provide an overview of the overall matching status of ecosystem service supply and demand for guiding macro-level policy regulation. However, small-scale analyses provide detailed mismatch insights for allowing stakeholders to support the implementation of ecological restoration projects (Cui *et al.* 2019). Moreover, assessments conducted at different scales may reveal varying mismatch patterns and even lead to entirely different conclusions (Cui *et al.* 2019; Deng *et al.* 2023). Relying only on conclusions derived from a single scale can lead to inefficiencies in ecosystem service management and may cause conflicts if they are applied directly to other scales (Qiu *et al.* 2018). Furthermore, previous studies have mainly focused on the static supply and demand of ecosystem services, while often neglecting the role of spatial flows in identifying multi-temporal and spatial scale relationships for ecosystem service supply and demand. Therefore, exploring the supply and demand relationships of ecosystem services before and after incorporating ecosystem service flows across various spatial scales is crucial for identifying optimization strategies to address the supply and demand mismatches at different administrative levels. This approach provides both theoretical and practical support for the sustainable development of ecosystem services through precise, efficient, and multi-level management.

The Beijing-Tianjin-Hebei (BTH) region, one of China's largest urban agglomerations, faces significant disparities in grain supply and demand that are characterized by notable imbalances. Specifically, the flow of grain within the region can significantly influence regional grain supply capacity (Liu W *et al.* 2022). However, the current dynamic evolution of grain supply and demand matching patterns and grain flow within this region remain unclear. Reevaluating grain supply and demand patterns from the perspective of grain flows can enhance regional grain security regulation and provide a basis for external grain allocation (Lorilla *et al.* 2019). The key objectives of this study are to: (1) analyze the temporal and spatial evolution of grain supply and demand and their matching characteristics at various scales; (2) elucidate the direction, flow, and intensity of grain transfer from the supply to the demand, and reassess the regional supply–demand mismatches by considering grain flow; and (3) investigate the impact of varying distance thresholds on grain flow across different administrative levels to identify the dynamic evolution of matching characteristics of regional grain ecosystem services. This research can promote equilibrium in the grain supply and demand, thereby enhancing grain flow efficiency and ensuring grain security.

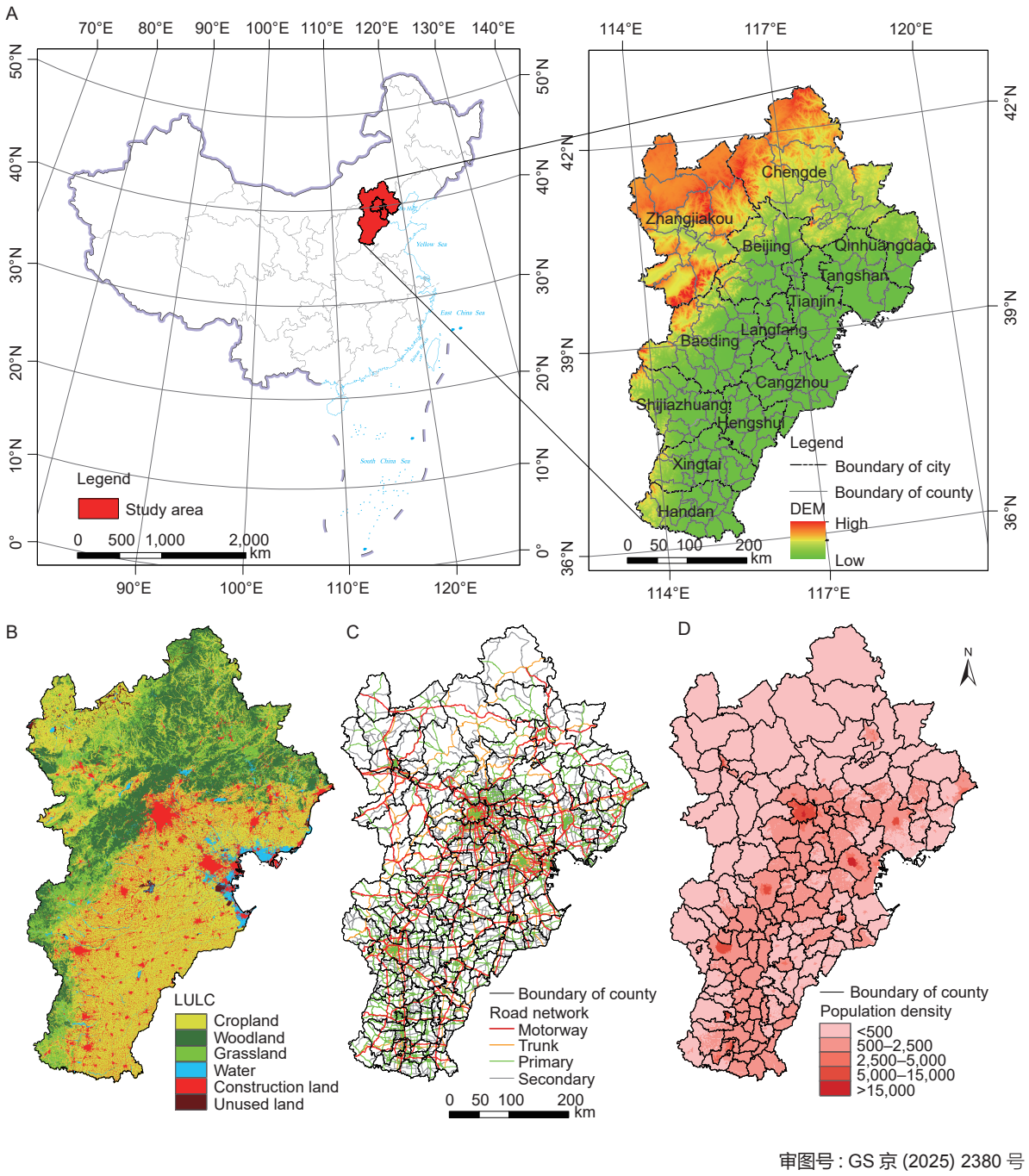
2. Materials and methods

2.1. Study area

The BTH region includes Beijing, Tianjin, and 11 prefecture-level cities in Hebei Province, China (Fig. 1-A). This region is bordered by the Yanshan Mountains to the north, the North China Plain to the south, the Taihang Mountains to the west, and Bohai Bay to the east. This region features diverse landforms, with higher elevations in the northwest and lower elevations in the southeast. The BTH region covers a total area of 218,000 km^2 and comprises 2.3% of the nation's total area (Fig. 1-B). According to the seventh national population census, the permanent population of the BTH region exceeds 110 million, with a high population density concentrated in Beijing and Tianjin (Fig. 1-D). In 2023, the total GDP of the BTH region reached 10.44 trillion CNY, reflecting rapid economic growth and a well-developed road network (Fig. 1-C), which supports frequent socioeconomic activities within the urban agglomeration. In 2023, grain production in Beijing, Tianjin, and Hebei Province reached 0.478, 2.557, and 38.099 million tons, respectively. Hebei Province, one of the main grain-producing regions in the country, plays a crucial role in ensuring grain security for the BTH region. With the acceleration of urbanization and population growth, the internal grain consumption structure of the BTH region has undergone significant changes, leading to a continuous increase in grain demand, particularly in the densely populated Beijing-Tianjin area. This has exerted considerable pressure on the regional grain supply and highlights a clear mismatch between grain supply and demand services. Therefore, elucidating the grain flow situation within the BTH region and accurately assessing ecosystem service supply–demand matching is crucial to ensure local grain security and promote coordinated regional development. These findings will provide a strong basis for future cross-regional research.

2.2. Data sources and processing

The data used in this study included administrative boundary data, road network data, land use data, demographics data, population distribution data, grain production data at the county level, and normalized difference vegetation index (NDVI) data. Specifically, the population spatial distribution data were derived by aligning the demographics data from the study years with the corresponding spatial distribution



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Fig. 1 Geographic location of the Beijing-Tianjin-Hebei (BTH) region in China (A), land use and land cover (LULC) map for 2020 (B), road network in 2020 (C) and population density in 2020 (D). DEM, digital elevation model.

grid data. The grain demand was calculated according to the methodology outlined by Meng and Li (2020), but some counties in the BTH region are missing significant data regarding meat, egg, and milk production. Consequently, per capita consumption was calculated using city-level statistical data to ensure consistency between municipal districts and counties. For years lacking county-level production data, the most recent available statistical data were used as proxies. Notably, the production data for pork in 1980 were largely incomplete. Therefore, the estimate was based on the average ratio of pork to beef and mutton production from other years. The road network data for 1980, 1990, and 2000 were obtained from the Global Roads Open Access Data Set, while the data for 2010 and 2020 were sourced from OpenStreetMap. All data were processed using ArcGIS and verified for topological accuracy (Appendix A).

2.3. Research framework

The framework of this study comprises three components (Fig. 2). First, the original patterns of grain supply and demand in the BTH region from 1980 to 2020 were analyzed at various scales. Second, the flow and direction of grain ecosystem services from 1980 to 2020 were simulated. Third, the final grain supply and demand matching in the BTH region was evaluated through the integration of original supply and demand relationships with the grain flow characteristics.

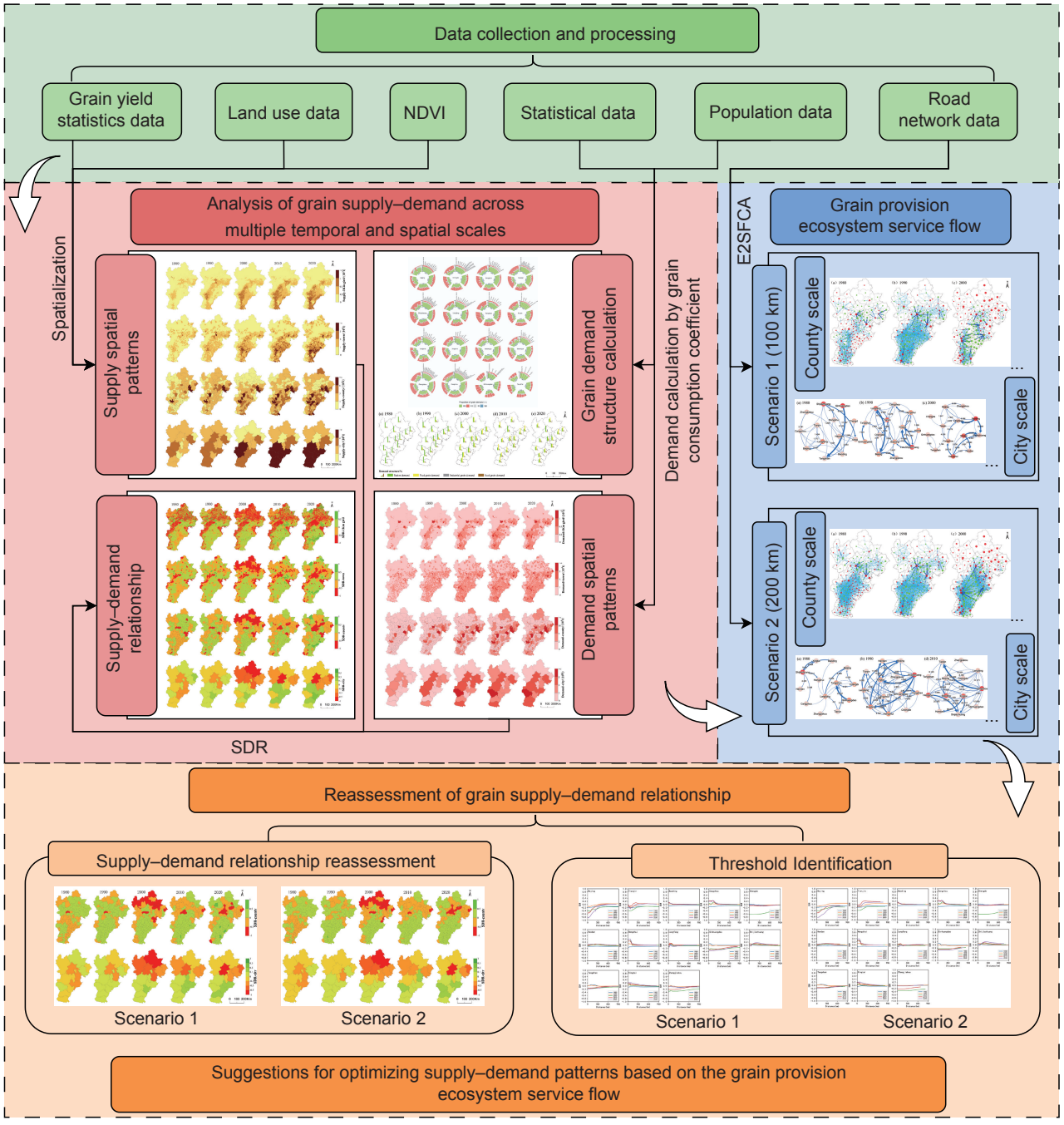


Fig. 2 Analytical framework of this study. NDVI, normalized difference vegetation index; SDR, supply–demand ratio.

2.4. Methods

Grain supply estimation Grain production mainly depends on cultivated land, which is a crucial component of the ecosystem. A strong linear relationship exists between NDVI and crop yield (Groten 1993), so NDVI is a reliable indicator of the grain production capacity of cultivated land. In this study, the ratio of grid NDVI values to the total NDVI values of the cultivated land was used as a coefficient to distribute grain yield across individual grid cells (Yin *et al.* 2023).

$$GP_{ir}=\frac{NDVI_{ir}}{NDVI_{sum,\,i}}\times GP_{sum,\,i} \quad (1)$$

where GP_{ir} denotes the grain production of grid cell r in county i (t); $NDVI_{ir}$ indicates the vegetation coverage index of grid cell r in county i; $NDVI_{sum,\,i}$ signifies the sum of the vegetation coverage indices of the cultivated land in county i; and $GP_{sum,\,i}$ denotes the total grain production (t) in county i.

Grain demand estimation The demand for grain can be represented by the product of per capita grain consumption and population density (Chen *et al.* 2024). Specifically, population density data were derived from statistical adjustments to the spatial distribution grid data. Unlike many current studies that directly use per capita grain consumption (Zhang P T *et al.* 2021; Yu *et al.* 2024), this study used county-level statistical yearbook data to account for ration demand (RD), feed grain demand (FD), industrial grain demand (ID), and seed grain demand (SD) in calculating total grain demand (Meng and Li

2020). The calculation of grain demand includes: RD derived from per capita grain consumption multiplied by population; FD determined based on the production quantities of pork, beef, mutton, poultry meat, eggs, aquatic products, and dairy products in each county/city; ID calculated using baijiu, beer, ethanol, and starch production; and SD accounting for 4% of total cereal output, with potatoes converted at a 5% grain equivalent rate. This method provides a more comprehensive and accurate estimate of grain demand. Per capita grain consumption was calculated as the ratio of total grain demand in each county to the total population.

$$GD_r=GD_{pc}\times\rho_{rpop} \quad (2)$$

where GD_r represents the grain demand amount (t) of grid cell r; GD_{pc} represents per capita grain consumption (t/person); and ρ_{rpop} denotes the population density.

Supply–demand ratio (SDR) of ecosystem services SDR measures the surplus or deficit of ecosystem services (An *et al.* 2024), and it indicates the balance between the actual supply of ecosystem services and human demand in a region (Bai *et al.* 2017).

$$SDR_x=\frac{ES_x-ED_x}{ES_x+ED_x} \quad (3)$$

where SDR_x represents the SDR of grain provision ecosystem services in region x (An *et al.* 2024), and ES_x and ED_x denote the grain supply and demand, respectively. An SDR_x value greater than 0 indicates a surplus of grain supply services, an SDR_x value less than 0 indicates a deficit, and an SDR_x value of 0 signifies a balance between grain supply and demand.

Grain provision ecosystem service flow If a mismatch exists between grain supply and demand, then grain flows between regions to meet the demand. The Two-Step Floating Catchment Area (2SFCA) method combines transportation distance with supply–demand relationships into a single metric. The 2SFCA method was originally developed for analyzing access to medical facilities (Radke and Mu 2000). However, this method did not account for the reduced accessibility with increasing distance. Tao and Cheng (2016) incorporated a distance decay function into 2SFCA to optimize the model, leading to the development of E2SFCA. This paper presents the E2SFCA method, which uses a linear decay function (Zhou and Liu 2024). The model suggests that the grain supply at supply nodes decreases with increasing transportation distance, reaching zero at a specified threshold (Ala-Hulkko *et al.* 2019; Su D *et al.* 2024). Considering the existing research and preference for cost-saving (Liu W *et al.* 2022; Su D *et al.* 2024), two-grain flow scenarios are proposed. The first scenario assumes that surplus grain in each county can flow freely within a 100 km distance threshold. The second scenario indicates that once the grain demand of the city is met, surplus grain can flow outside the city within a 200 km distance threshold. Conversely, if no surplus exists, the city only receives grain inflows and does not allow grain outflows. This analysis is based on four assumptions: (1) Grain supply from outside the study area is not considered; (2) grain flows occur only once each county meets its own demand; (3) areas with excess supply are classified as supply nodes, while areas with a supply deficit are designated as demand nodes; and (4) the grain flow follows the road network when moving from supply nodes to demand nodes.

To assess the supply and demand intensity at the nodes, the node intensity (N_i) was introduced (Zhou and Liu 2024).

$$N_m=|S_m-D_m| \quad (4)$$

where N_m represents the strength of node m, and S_m and D_m denote the supply and demand at that node, respectively.

Grain circulation is influenced by various factors such as geographical distance, economic development, and policies (Han *et al.* 2020), which complicate the accurate estimation of actual grain flow. To simplify the process, this study adopted an accessibility-based approach and used the E2SFCA algorithm to simulate cross-regional grain flow. This method involved two steps, starting with the supply and demand nodes, respectively. In the first step, the potential demand within the service area of supply node j was determined based on the production-to-consumption ratios:

$$R_j=\frac{S_j}{\sum D_k W_t}\ |k\in\{d_{jk}\in D_r\} \quad (5)$$

$$W_t=\begin{cases}1-d_{jk}/d_0 & d_{jk}\le d_0\\ 0 & d_{jk}>d_0\end{cases} \quad (6)$$

where R_j represents the ratio of the supply share allocated from supply node j to each demand node k relative to the total demand within the service range; S_j and D_k represent the intensities of the supply and demand nodes, respectively; d_{jk} denotes the distance between supply node j and demand node k; W_t indicates the distance weight between the supply and demand nodes; d_0 signifies the set transportation distance threshold; and D_r indicates the service area formed by supply node j within the set distance threshold d_0. Within the service range of supply node j, the accessibility of grain demand decreases linearly from supply node j to d_0, and the allocated amount of grain ultimately decreases to zero.

In the second step, for each supply intensity N_i of the supply node within the service area formed by demand node k at a specified distance threshold d_0, weights were assigned based on the distance. The weighted supply proportions were summed to obtain the supply-to-demand ratio RF_k for each demand node k:

$$RF_k=\sum R_j W_t|j\in\{d_{jk}\in D_r\} \quad (7)$$

By combining the results from the E2SFCA algorithm with grain demand, the grain share was calculated for inflow node k:

$$F_k=D_k\times RF_k \quad (8)$$

where F_k represents the grain flow into demand node k, and D_k denotes the demand intensity of node k.

According to the relationship between the total inflow intensity of demand node k and the distance weight, the grain circulation volume between all supply nodes within the service range and demand node k was calculated as follows:

$$FI_{jk}=F_k\times\frac{S_j W_t^{jk}}{\sum S_j W_t^{jk}} \quad (9)$$

where FI_{jk} represents the flow intensity from supply node j to demand node k, S_j denotes the supply amount at supply node j, and W_t^{jk} denotes the distance weight between nodes j and k.

The outflow/inflow of the corresponding node (F) was calculated through the summation of the flow intensity (FI) within the service range centered on the supply/demand nodes:

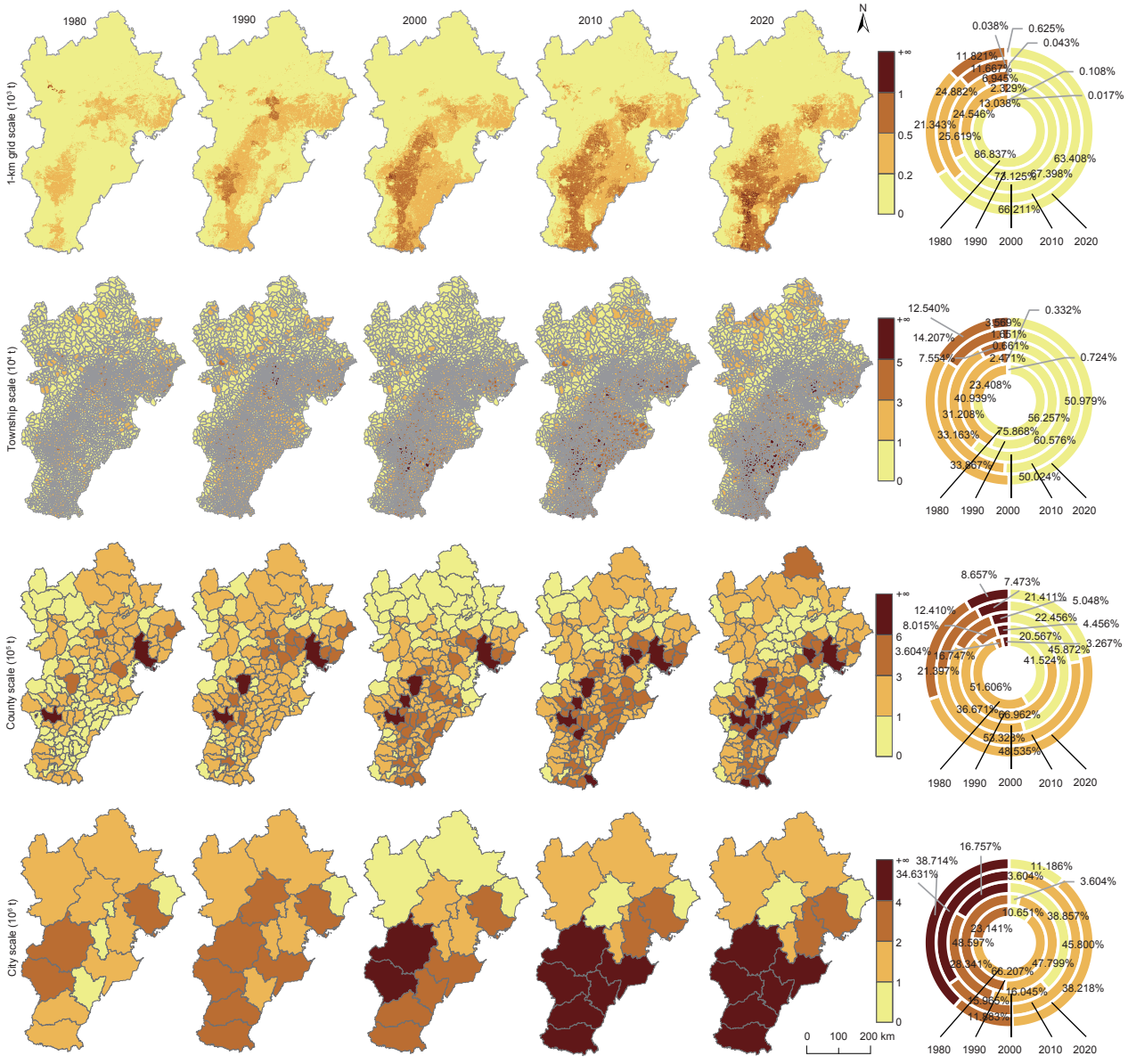
$$F=\sum FI \quad (10)$$

3. Results

3.1. Characteristics of the temporal and spatial evolution of grain provision supply and demand at different scales

Analysis of the temporal and spatial changes in grain supply Fig. 3 shows that grain production in the BTH region followed a general upward trend from 1980 to 2020, with annual output increasing from 18.7 to 40.4 million tons. Hebei Province consistently produced more grain output than Beijing and Tianjin, with its annual output increasing from 15.5 to 37.8 million tons. In contrast, grain production in Tianjin exhibited slight fluctuations, increasing from 1.38 to 2.28 million tons over the study period. Moreover, grain production in Beijing initially increased, peaking at 2.65 million tons in 1990, before declining to 0.305 million tons by 2020. This reduction can be attributed to the rapid urbanization and changes in planting structures, which significantly reduced the area of grain cultivation, leading to a continuous annual decline in grain output. The spatial distribution of grain production in the BTH region remained relatively uniform across different periods, although significant internal disparities were observed (Fig. 3), consistent with the variations in cultivated land distribution.

The grain supply patterns varied across different scales. As the scale increased, the distribution profile became aggregated and expanded outward, which masked internal differences within the region. At the 1 km grid and township scales, the spatial distributions were similar, with high-supply areas concentrated in the central and southern parts of Hebei, while low-supply areas were mainly found in the northwestern mountainous and hilly regions. At the county scale, the proportion of high grain-producing areas increased. Specifically, the proportion of areas producing more than 0.3 million tons rose from 6.87% in 1980 to



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Fig. 3 Spatial distribution of grain supply in the Beijing-Tianjin-Hebei (BTH) region from 1980 to 2020.

30.05% in 2020. Regions with stronger grain supply capabilities included the municipal districts of Tangshan, Shijiazhuang, and Baoding, as well as Ningjin County and Dingzhou City. The Shijiazhuang municipal district comprises several high-yield, high-quality soybean areas, while the Gaocheng District is recognized as a nationally advanced grain production area and serves as the country's largest production base for strong gluten wheat. Fengnan District and Caofeidian District in Tangshan are recognized for their rice production, while Fengrun District is known for its wheat output. Ningjin County, Dingzhou City and the municipal district of Baoding are identified as high-yield wheat areas. These regions benefit from relatively favorable natural conditions, well-established agricultural foundations, and strong grain production capabilities. In contrast, Beijing, Zhangjiakou, and Chengde exhibited weaker grain supply capacities due to limited cropland. At the prefecture-level city scale, the grain supply varied significantly among the different regions.

In addition, the spatial distributions of high-yield and low-yield grain production areas in the BTH region varied significantly across different scales. At the 1 km grid scale, the spatial heterogeneity between high-yield and low-yield areas was pronounced, with the northern region predominantly showing low yields. As the scale increases, high-yield areas begin to emerge in the northern region. Over the past 40 years, the proportion of high-yield grain production areas at various scales has exhibited an increasing trend, indicating that increasing grain production was the predominant trend in this region.

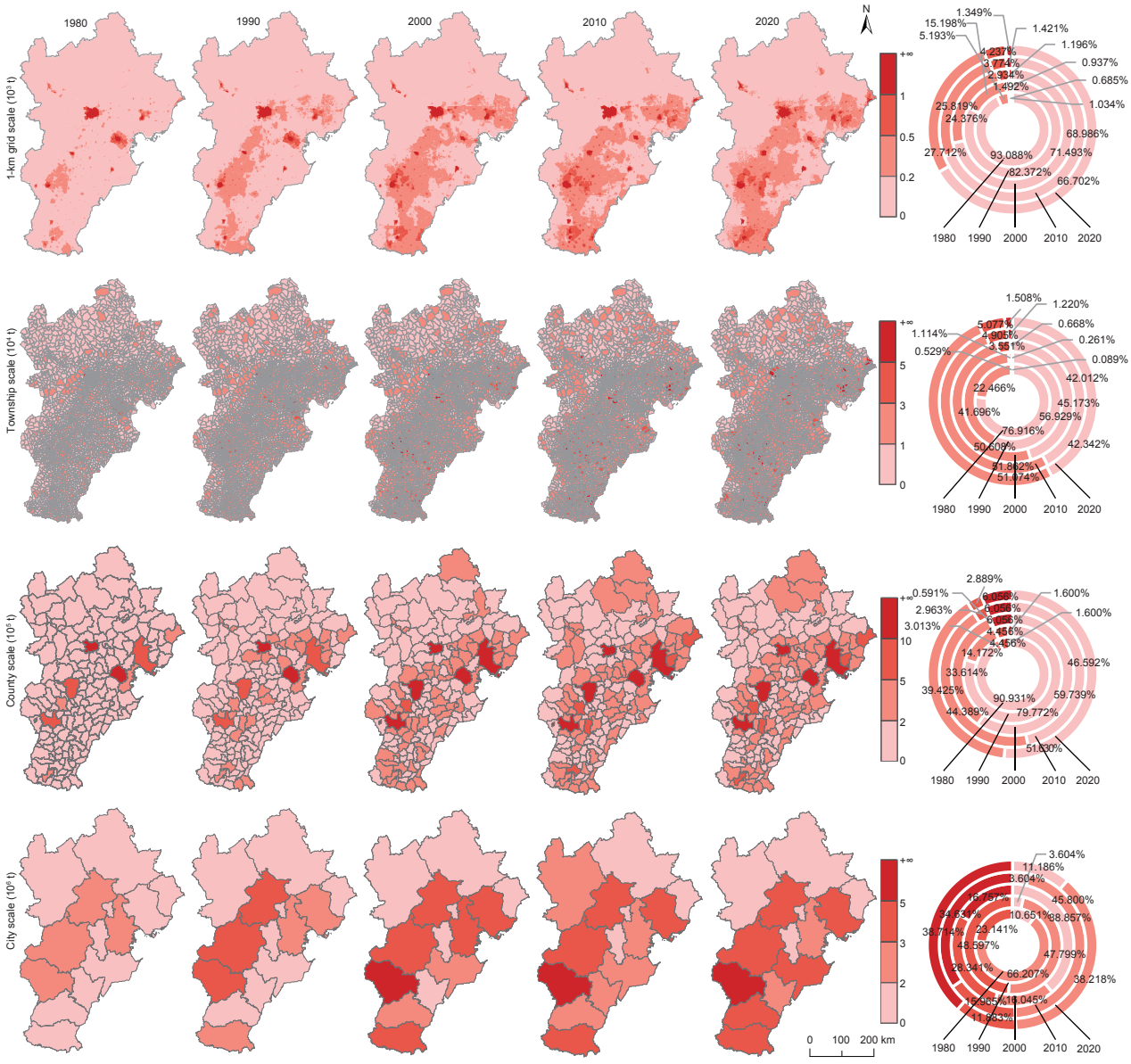
Analysis of the temporal and spatial changes in grain demand From 1980 to 2020, grain demand in the BTH region displayed stable growth, increasing from 21.1 to 40 million tons. At the municipal level, Shijiazhuang exhibited the highest average grain demand, at 4.185 million tons, followed by Baoding, Handan, and Tangshan. Conversely, Chengde and Qinhuangdao exhibited the lowest grain demand, at 1.367 and 1.169 million tons, respectively. Grain demand distribution follows a consistent spatial pattern across scales, with higher demand in the southeast and lower demand in the northwest. As the scale increases, the concentration of grain demand becomes more pronounced (Fig. 4). At the 1 km grid scale, areas of high grain demand are typically distributed in a point-like pattern, consistent with the regions of high population density. At the township scale, high-demand areas become more dispersed. At the county scale, the municipal districts of Beijing, Tianjin, Shijiazhuang, Tangshan, and Baoding consistently exhibit high grain demand. Since 2000, the grain demand in various municipal districts and counties in central and southern Hebei Province has increased significantly due to the higher population densities in these urban areas, leading to greater grain demand compared with other municipal districts and counties. Furthermore, Xinji City, Dingzhou City, Luannan County and Yongnian County, where animal husbandry is more prominent, exhibit higher demand for feed grains, which increases the demand for grain services. In contrast, the northern regions remain relatively underdeveloped, resulting in lower grain demand.

From 1980 to 2020, the proportion of areas with high grain demand values in the BTH region showed an overall upward trend across the different scales, particularly at the 1 km grid scale and the township scale, where the proportions of high-value areas increased year by year. At the 1 km grid scale, the proportion of areas with demand exceeding 500 tons per km^2 increased from 1.72% in 1980 to 5.59% in 2020. At the township scale, the proportion of areas with demand exceeding 30,000 tons increased from 0.62% in 1980 to 6.58% in 2020. At the county and city scales, the proportions of high-value areas of grain demand showed fluctuating growth trends overall, necessitating further analysis of the changes in grain demand structure.

Furthermore, an analysis of grain demand structure can provide insights into the volume and trends of demand for different types of grains, and it can present valuable references for adjustments in planting structures and more accurate assessments of the grain supply and demand relationship. Grain demand is mainly categorized into ration demand and indirect grain demand. Indirect grain demand refers to grains used for feed, industrial purposes, and seeds (Meng and Li 2021). From 1980 to 2020, the structure of grain consumption in the BTH region underwent significant changes, with a general decline in RD. The proportions of RD in Beijing, Tianjin, and Hebei decreased from 73.9, 79.1, and 70.4% to 65.5, 54.5, and 35.7%, respectively. At the city scale (Appendix B), the proportion of RD was relatively high in 1980, reaching an average of 71.2%. As living standards improved, dietary structures evolved from merely meeting basic needs to achieving nutritional balance, leading to significant changes in grain consumption patterns (Dong *et al.* 2015). Consequently, the proportion of RD steadily decreased, while the proportion of FD increased. In 2000, the proportions of RD and FD became roughly equal. By 2010, the proportion of RD had decreased to 30.57%, while the proportion of FD had increased from 9.74% in 1980 to 49.67%. By 2020, the proportions of RD and FD were approximately equal, both around 40%. This shift may be attributed to the impact of COVID-19 on livestock and industrial production. The proportion of grain used for ID decreased at first and then increased, indicating an overall fluctuating upward trend. Moreover, the proportion of grain used for SD was relatively stable with minimal change. Over the past 40 years, the proportion of RD in Beijing has consistently remained above 50%, while Tangshan and Shijiazhuang have exhibited higher FD proportions of 41.39 and 39.54%, respectively. Cangzhou and Baoding exhibited the largest ID proportions of 16.22 and 16.18%, respectively. From a county-level perspective (Appendix C), the changes in the grain demand structure were similar to those observed at the municipal level. Over the past four decades, the proportion of RD has steadily declined, while the FD has significantly increased. The proportions of ID and SD have remained low, with only slight increases. Notably, Guantao, Luannan, Zhengding, and Wuji counties, as well as Xinle and Xinji cities, exhibited high proportions of FD, all exceeding 50%.

3.2. Identification of supply and demand matching characteristics of grain provision services at different scales

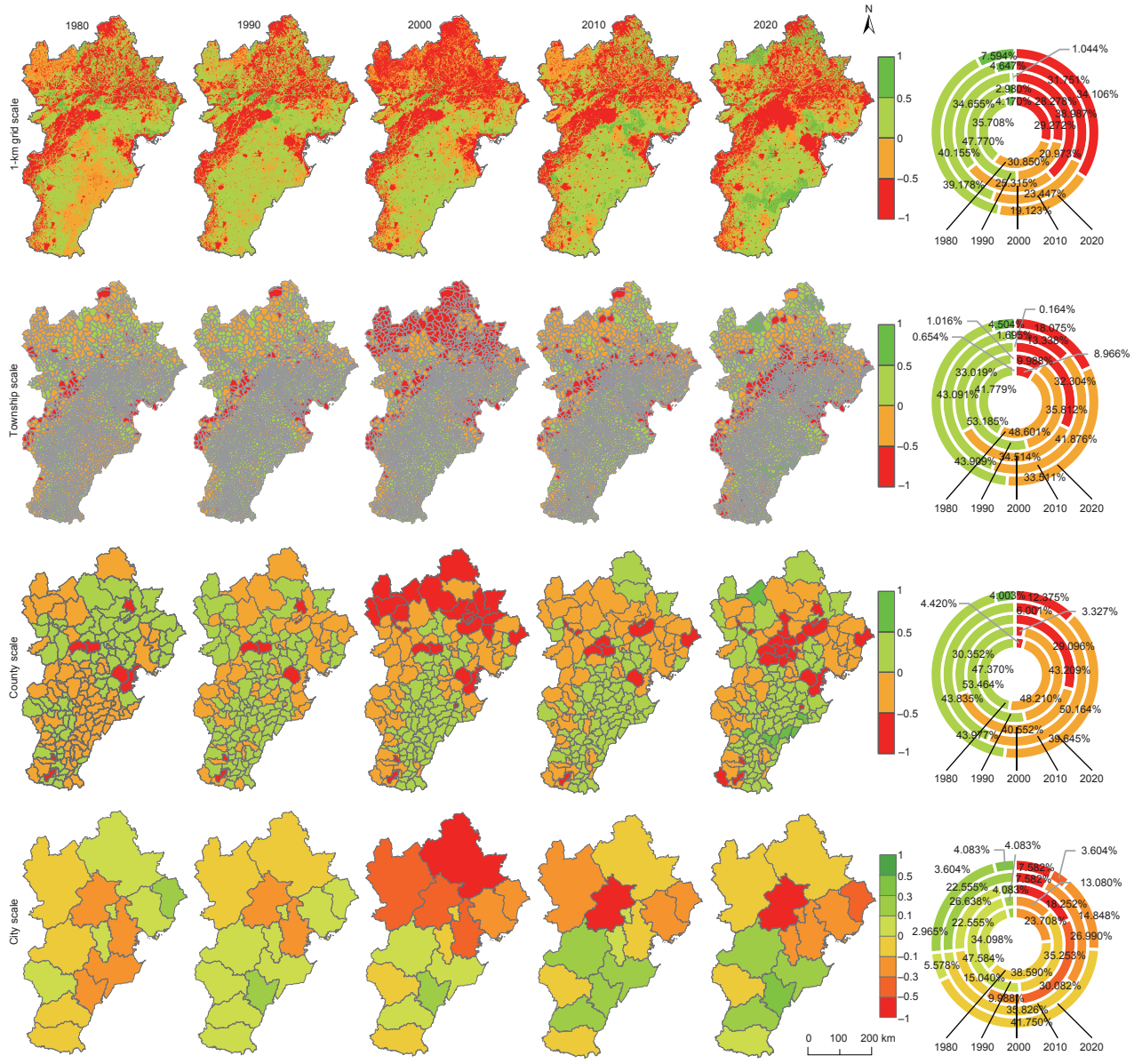
The results in Fig. 5 indicate that scale effects have



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Fig. 4 Spatial distribution of grain demand in the Beijing-Tianjin-Hebei (BTH) region from 1980 to 2020.

significantly influenced the supply and demand dynamics of grain provision services in the BTH region. At both the grid and township scales, spatial heterogeneity was evident. At the grid scale, the area facing a shortage of grain provision services increased and then decreased, yet it maintained a relatively consistent spatial distribution. The deficit areas were mainly located in the northwestern region, characterized by limited cultivated land. However, with more available cultivated land, the southeastern region mainly exhibited a surplus of grain provision services. At the township scale, the distributions of surplus and deficit areas for grain provision services were more concentrated compared with the grid scale. At the township scale, some deficit areas have transitioned into surplus areas. With advancements in agricultural technology and policy adjustments, grain production in some northwest regions has shifted from deficit to surplus. At the county scale, grain supply service deficits in the BTH region were mainly located in densely populated urban centers. From 1980 to 2020, the proportion of deficit areas increased at first and then decreased, reaching 52.63, 46.54, 69.65, 56.17, and 52.02%, respectively. The number of counties with grain deficits were 87, 54, 79, 67, and 66, respectively. At the city scale, Beijing, Tianjin, and Zhangjiakou have consistently been identified as deficit areas, with Beijing facing the most severe deficits. The grain supply gap in Beijing increased from 0.902 million tons to 3.28 million tons during the study period. In contrast, Qinhuangdao, Tangshan, Langfang, Shijiazhuang, and Chengde transitioned from surplus areas to deficit areas, with Langfang experiencing the most significant shift, as its SDR changed from 0.108 to –0.338. Meanwhile, Hengshui, Cangzhou, Xingtai, Baoding, and Handan shifted from



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Fig. 5 Spatial distribution of the grain supply–demand ratio (SDR) across different scales in the Beijing-Tianjin-Hebei (BTH) region from 1980 to 2020.

deficit areas to surplus areas, with Hengshui showing the largest change, as its SDR shifted from –0.130 to 0.365. The changes in SDR from 1990 to 2010 were particularly pronounced. The northwestern region of Hebei exhibited the highest proportion of deficit areas, reaching a peak in 2000. This was due to persistent droughts and adjustments in planting structures, which resulted in reduced sown areas, reduced grain production, and an inability of grain services to meet demand. A multi-scale analysis revealed that as the scale increased, the classification of SDR became more concentrated. Conversely, at smaller scales, the spatial heterogeneity of SDR became more pronounced. Therefore, when formulating policies, the differences in SDR across different spatial scales must be considered to ensure the most effective allocation of resources.

3.3. Spatiotemporal evolution of grain provision ecosystem service flow

The county is the smallest administrative unit responsible for implementing policies and formulating specific measures set by the state (Han *et al.* 2020). Therefore, this study investigated grain flow at the county and city scales. Two-grain flow scenarios were considered based on previous research (Liu W *et al.* 2022; Su D *et al.* 2024). The first scenario involves the free flow of surplus grain between counties within a specified distance threshold of 100 km. The second scenario permits surplus grain to flow outside the city after the local demand is met, within a 200 km distance threshold. If the city grain supply is insufficient to meet local demand, only intra-city flow occurs, with grain supplied from other cities but not flowing beyond the city limits.

This study examined the characteristics of spatial flow in grain supply services to identify the supply and demand relationships through simulation. The sizes and directions of grain flow between different administrative units at the county and city levels were analyzed under the two scenarios. Compared with the static SDR, SDR significantly varied across the various regions.

Scenario 1: Free movement of grain within a 100 km distance threshold Grain flow is closely associated with the distance between SPAs and SBAs, i.e., closer proximity results in greater grain transfer volumes. Within a 100 km threshold, grain flows freely between the counties (Fig. 6). At the county scale, the BTH region had 416 grain flow routes in 1980, with a total flow of 2.17 million tons. The highest grain flow occurred between the Shunyi District and Beijing municipal district, with a total flow of 178,372 tons. In 1990, the region had 391 grain flow routes, with a total flow of 5.02 million tons. The maximum grain flow in 1990 was between the same districts as in 1980, with 344,860 tons. In 2000, the BTH region had 339 grain flow routes, with a total flow of 4.96 million tons. The maximum flow shifted from Ningjin County in Xingtai City to Shijiazhuang municipal district, with a flow of 264,060 tons. By 2010, the region had 447 grain flow routes, with a total flow of 9.52 million tons. The maximum flow occurred between Baodi District in Tianjin and Tianjin municipal district, amounting to 345,920 tons, or 3.6% of the total. In 2020, the region had 409 grain flow routes, with a total flow of 11.81 million tons. The maximum flow direction remained the same as in 2000, with a total flow of 510,500 tons, which accounted for 4.32%.

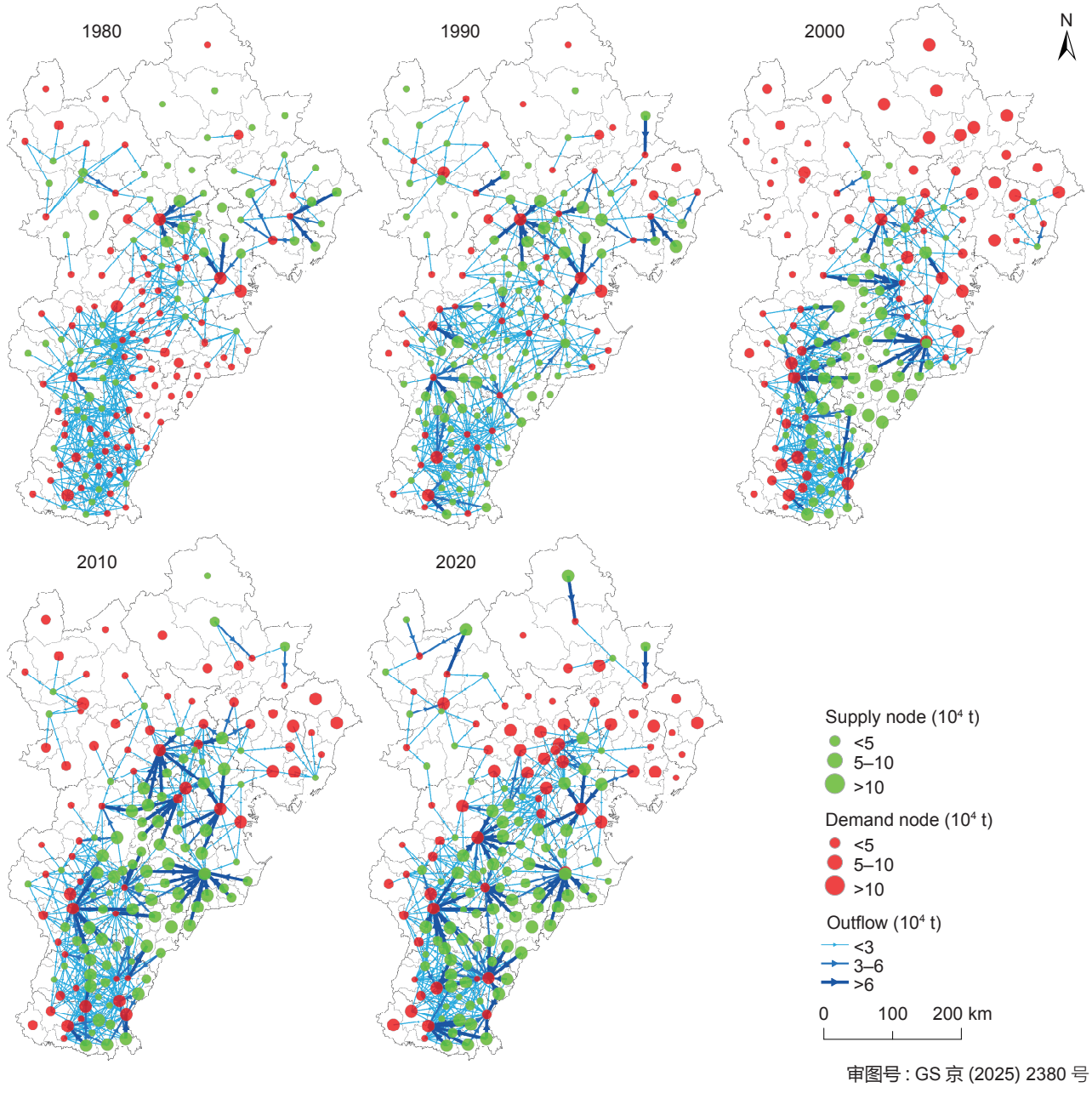


Fig. 6 Directions and intensities of grain flow between counties in the Beijing-Tianjin-Hebei (BTH) region from 1980 to 2020 (where grain flows freely between counties within a 100 km distance threshold).

At the city level (Fig. 7), the main inter-city flow in 1980 was from Qinhuangdao to Tangshan, with a flow volume of 174,370 tons. In 1990, the largest flow shifted from Langfang to Beijing (127,400 tons), followed by Shijiazhuang to Xingtai (118,660 tons). In 2000, the maximum flow was 399,910 tons, from Baoding to Langfang. In 2010 and 2020, the main flows were from Xingtai, Hengshui, and Baoding to nearby cities. The maximum flows were from Xingtai to Handan (535,870 tons) and Xingtai to Shijiazhuang (856,870 tons).

Scenario 2: Grain flow within a 200 km distance threshold, prioritizing local city needs When the allowed delivery distance was increased from 100 to 200 km, the scale of grain flow between counties expanded (Fig. 8). With the grain outflow from cities limited to only the surplus supply, the needs of counties within these cities were effectively met. For 1980, 1990, 2000, 2010 and 2020, the grain provision ecosystem service flow routes in the BTH region numbered 1,009, 1,267, 1,056, 1,243, and 1,166, respectively, with total flow volumes of 2.41, 5.14, 5.82, 9.88, and 12.37 million tons, respectively. From 1980 to 2000, the municipal districts and counties with the largest grain flow volumes remained consistent for both Scenario 2 and Scenario 1, with volumes of 174,450, 340,090, and 151,500 tons. In 2010 and 2020, the maximum flow volumes occurred within Tianjin, particularly from Wuqing District and Baodi District to the municipal area, with flow amounts of 393,390 and 354,280 tons, respectively. At the city scale (Fig. 9), the inter-municipal flow in the BTH region in 1980 was mainly from Qinhuangdao to Tangshan, with a volume of 174,370 tons. By 1990, Shijiazhuang emerged as the city with the highest grain outflow, with the largest flow recorded from Shijiazhuang to Xingtai at 202,030 tons. In 2000, the main grain-exporting cities were Hengshui, Xingtai, and Baoding, with a maximum flow of 496,850 tons occurring from Hengshui to Shijiazhuang. In 2010 and 2020, the maximum flows were from Cangzhou to Tianjin (1.10 million tons) and Hengshui to Shijiazhuang (1.12 million tons), respectively.

Overall, the number of grain flow routes in each grain flow scenario first decreased and then increased, and they were concentrated in the central-southern region and the eastern coastal areas due to more convenient transportation and higher SPA densities. The flow volume followed a trend of first increasing, then decreasing, and then increasing again due to the high grain supply volume in the SPAs. In 2000, a reduction in planting area and drought led to a reduction in grain production. Moreover, the northwest region had more deficit areas and fewer surplus areas. Due to distance constraints, the internal BTH region could not provide additional grain to these deficit areas. Major cities such as Baoding, Shijiazhuang, Xingtai, and Hengshui exhibited high outflow volumes.

3.4. Changes in grain supply and demand matching based on grain flows

Compared with traditional ecosystem supply and demand assessments that often overlook ecosystem service flows,

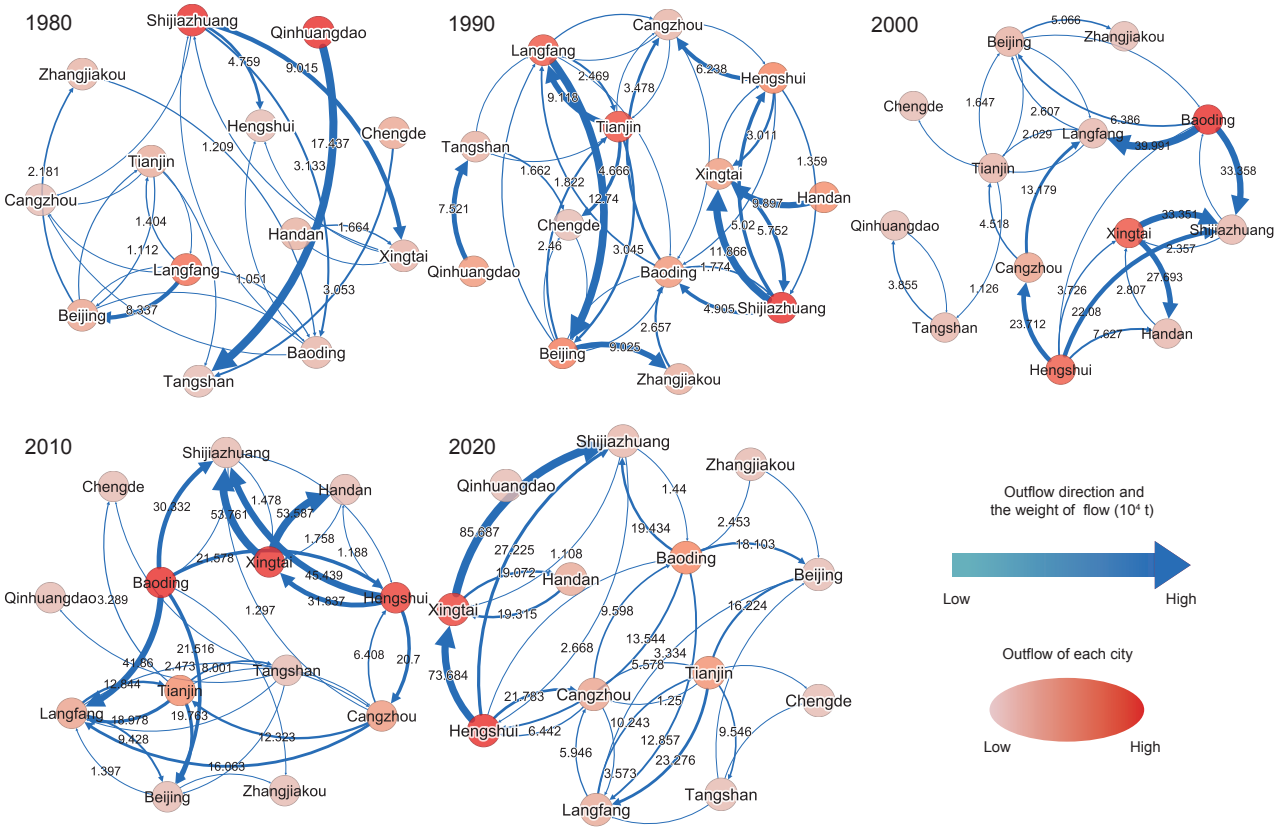


Fig. 7 Directions and intensities of grain flow between cities in the Beijing-Tianjin-Hebei (BTH) region from 1980 to 2020 (where grain can flow freely between cities within a 100 km distance threshold).

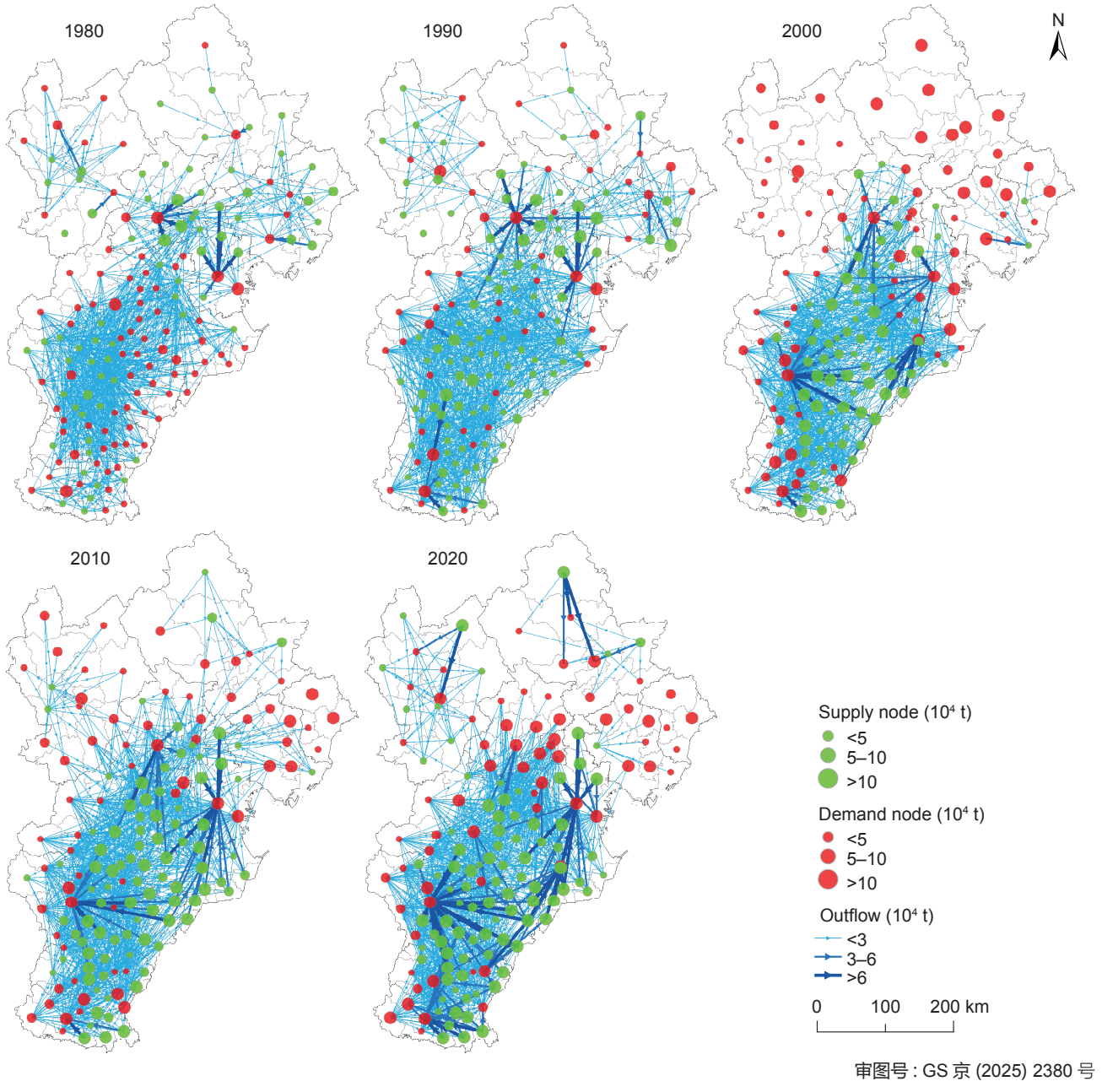


Fig. 8 Directions and intensities of grain flow between the counties in the Beijing-Tianjin-Hebei (BTH) region from 1980 to 2020 (where grain within the city can flow up to a 200 km distance threshold once its internal demand is met).

this study quantified spatial grain flows and integrated the initial supply and demand conditions to reassess the regional grain supply and demand balance. This approach provides a direct basis for optimizing the grain supply–demand matching pattern. If deficit areas receive grain inflows from surplus areas that precisely meet the supply–demand gap, those areas are considered balanced. However, if the grain flow does not completely resolve the supply shortage or oversupply, these areas are classified as potential SBAs or SPAs. According to the methodology outlined in previous studies (Feng *et al.* 2021), the basic calculation rules are as follows: supply–demand–outflow>0 indicates an SPA, supply–demand–outflow=0 indicates a supply–demand balance area, and supply–demand–outflow<0 indicates an SBA.

The specific spatial distributions of changes in the supply–demand matching status under the two scenarios are illustrated in Table 1 and Figs. 10 and 11. Compared to the scenario without grain flow, both grain flow scenarios reduced the number of deficit areas at the county scale. In 1980, 2000, and 2010, more counties achieved supply–demand balance in Scenario 2 compared with Scenario 1. However, the reduction in the number of SBAs was less than or equal to that in Scenario 1. This was due to the inability of some cities to meet their grain needs, with the surplus grain counties in those regions unable to supply grain to the SBAs of the neighboring cities. At the city scale, the results of both grain flow scenarios were similar in 1980, with both leading to increases in deficit areas. In 1990, Scenario 1 displayed no change in deficit areas, while Scenario 2 led to an increase in the number of deficit areas. From 2000 to 2020, the results

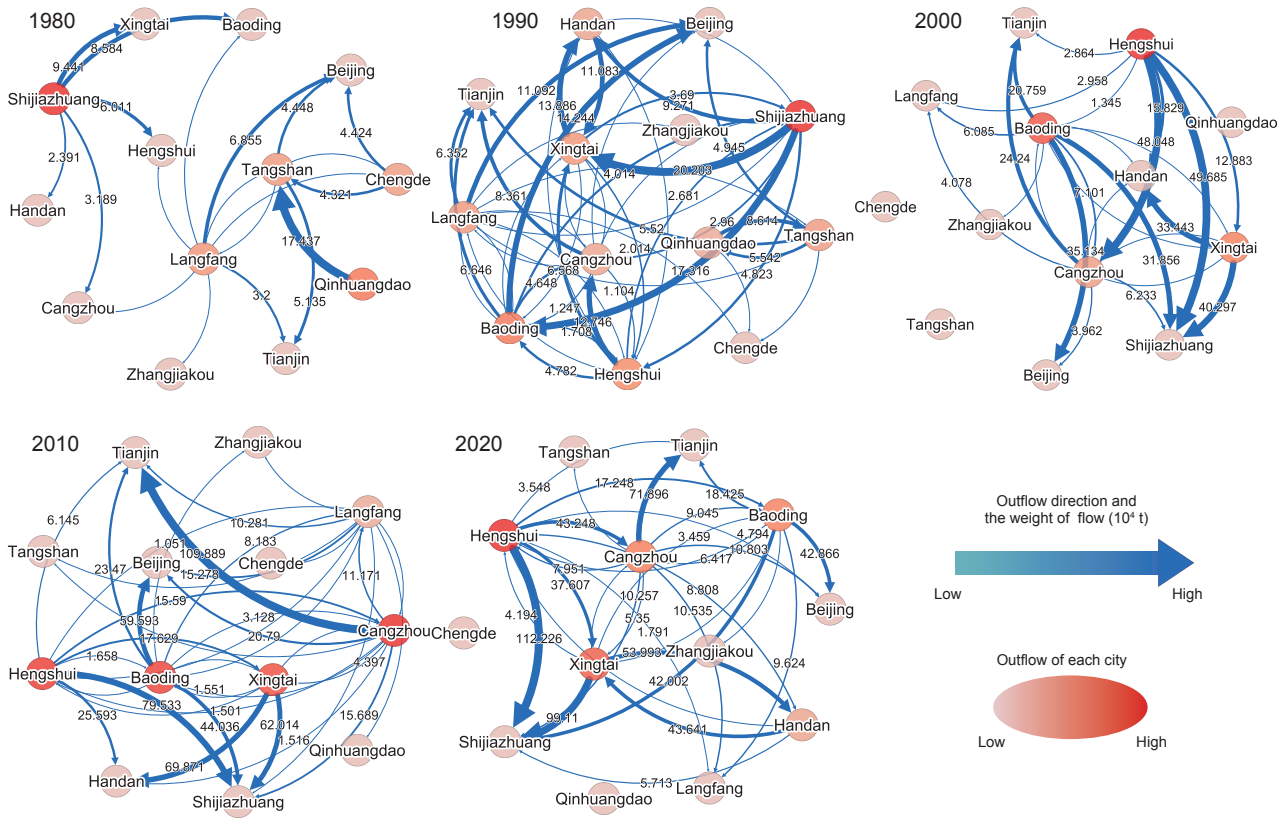


Fig. 9 Directions and intensities of grain flow between the cities in the Beijing-Tianjin-Hebei (BTH) region from 1980 to 2020 (where grain within the city can flow up to a 200 km distance threshold once its internal demand is met).

Table 1 Changes in SPAs, SBAs, and the supply–demand balance areas under different scenarios in the Beijing-Tianjin-Hebei (BTH) region from 1980 to 2020[1)]

Scale and scenario		Number of SPAs					Number of supply–demand balance areas					Number of SBAs				
		1980	1990	2000	2010	2020	1980	1990	2000	2010	2020	1980	1990	2000	2010	2020
County	Original	70	103	78	90	91	0	0	0	0	0	87	54	79	67	66
	Scenario 1	20	34	28	28	20	63	98	70	88	90	74	25	59	41	47
	Scenario 2	7	30	20	25	25	70	103	78	90	91	80	24	59	42	41
City	Original	5	9	4	5	5	0	0	0	0	0	8	4	9	8	8
	Scenario 1	3	9	7	7	6	1	0	0	0	0	9	4	6	6	7
	Scenario 2	2	7	4	6	7	1	0	1	0	0	10	6	8	7	6

[1)] SPA, service-providing area; SBA, service-benefit area.

of both scenarios were similar, with grain flow contributing to reductions in the number of deficit areas. The grain supply service met the demand of the supply areas and preferentially supplied grain to neighboring areas through spatial flow. From 1980 to 2020, the grain surplus areas in the BTH region expanded and became concentrated in the central and southeastern regions.

The specific changes in supply–demand matching for cities are as follows. Scenario 1: In 1980, Langfang transitioned from a surplus area to a deficit area, while Qinhuangdao shifted from a surplus area to a balanced supply and demand area. No changes occurred in 1990. In 2000, Langfang, Shijiazhuang, and Handan shifted from deficit to surplus areas. In 2010, Shijiazhuang and Handan transitioned from deficit to surplus areas. In 2020, Shijiazhuang changed from a deficit area to a surplus area. Scenario 2: In 1980, Langfang and Shijiazhuang shifted from surplus areas to deficit areas, while Qinhuangdao changed from a surplus area to a balanced supply and demand area. In 1990, both Langfang and Qinhuangdao transitioned from surplus areas to deficit areas. In 2000, Handan changed from a deficit area to a surplus area, while Hengshui shifted from a surplus area to a balanced supply and demand area. In 2010, Tianjin, Shijiazhuang, and Handan transitioned from deficit areas to surplus areas, while Baoding and Langfang shifted from surplus areas to deficit areas. In 2020, Tianjin and Shijiazhuang changed from deficit areas to surplus areas. In summary, these changes indicate that grain circulation can address regional supply and demand mismatches, compensate for spatial deficits, or cause regions to transition

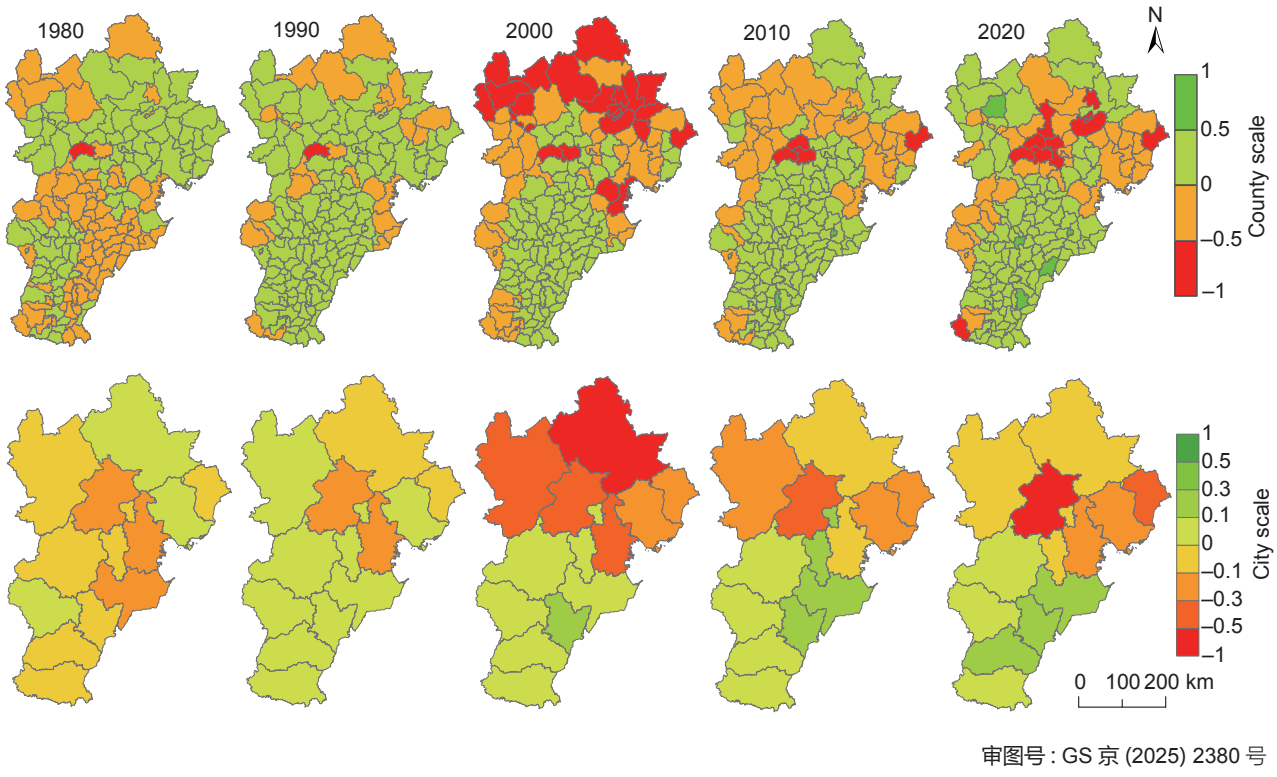


Fig. 10 Spatial distribution of the grain supply–demand ratio (SDR) under Scenario 1 in the Beijing-Tianjin-Hebei (BTH) region from 1980 to 2020.

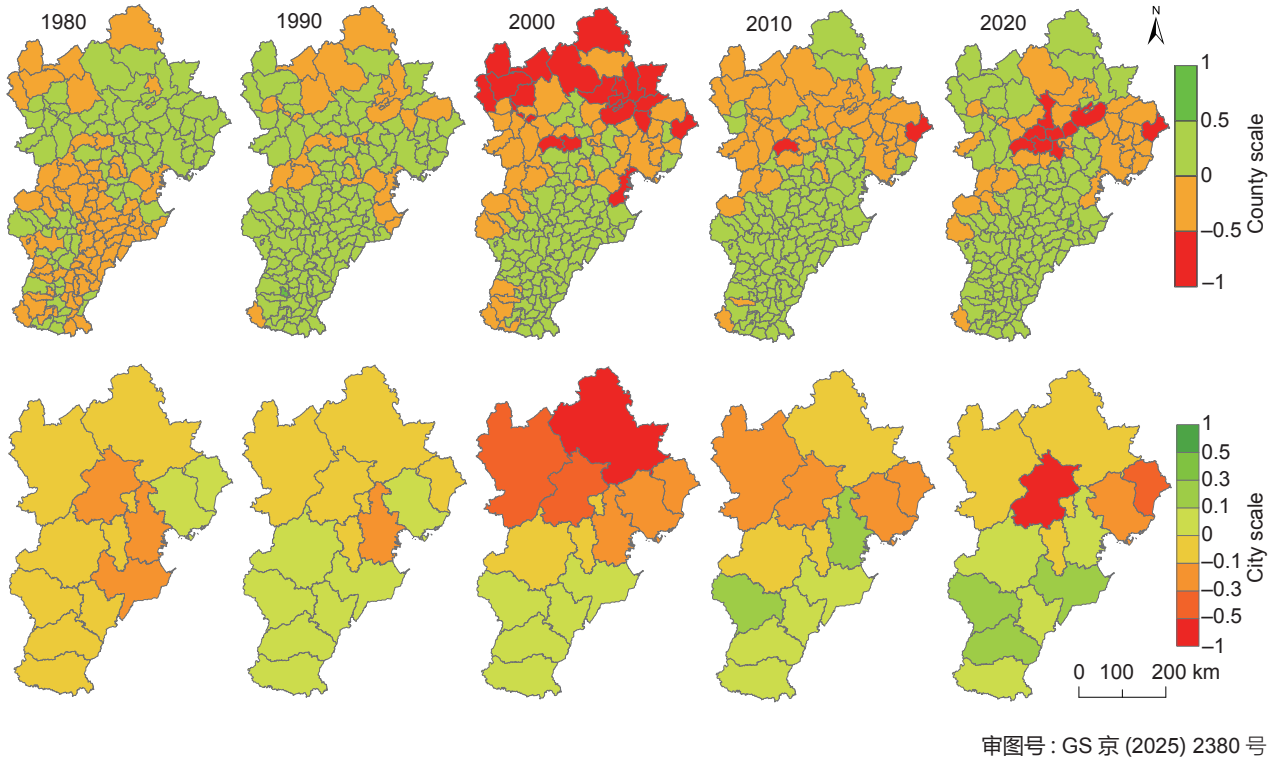


Fig. 11 Spatial distribution of the grain supply–demand ratio (SDR) under Scenario 2 in the Beijing-Tianjin-Hebei (BTH) region from 1980 to 2020.

from surplus to deficit states. This forms the basis for optimizing the alignment of grain supply and demand and the spatial arrangement of regional grain production.

4. Discussion

4.1. Assessment of grain supply and demand

Ensuring a stable supply is crucial for maintaining grain security

and social stability. This study used multi-scale spatial analysis to identify the heterogeneous patterns of grain supply and demand at different spatial levels. This approach prevents the decision-making imbalances that can result from using a single scale and provides management strategies for optimizing the grain supply–demand balance with targeted spatial and scale-specific goals. Specifically, optimizing the grain supply and demand in the BTH region is crucial for effective regional and national grain management. The spatial and temporal variations in grain supply are influenced by factors such as climate, cultivated land area, and crop yield. Similarly, the spatial and temporal changes in grain demand are influenced by factors such as population size, consumption patterns, and urbanization. The results of this study reveal that grain production in the BTH region is mainly concentrated in Baoding, Shijiazhuang, Xingtai, and Handan cities in the central and southern parts of Hebei Province. In contrast, high-demand areas for grain are mostly found in cities or regions with dense populations, consistent with previous research findings (Wang *et al.* 2021; Zhang P T *et al.* 2021; Meng *et al.* 2023). The assessment of grain demand in this study differs from those in previous studies (Zhang P T *et al.* 2021), which used a basic measure of the demand needed to meet China's per capita grain security. The BTH region exhibits a high proportion of grain consumption for feed due to a gradual increase in the rigid demand for grain. Furthermore, the limitations of cropland and water resources significantly affect grain production, potentially leading to a more constrained supply–demand relationship. This study comprehensively considered grain consumption across various counties, including feed grains, industrial grains, and seed grains. Grain demand was calculated using conversion coefficients, and the evolving characteristics of the demand structure were analyzed. This approach is crucial for elucidating grain consumption trends, optimizing grain production structures, formulating production policies, ensuring grain security, and adapting to changes in population structure. The grain demand calculated in this study for 2020 was slightly lower than that reported by Fang *et al.* (2024), as the grain demand algorithm referenced by Meng and Li (2020) did not account for grain loss. Overall, the results of this study are consistent with previous research findings, confirming the reliability of the results.

Ecosystem services exhibit spatial heterogeneity across different scales (Yin *et al.* 2023). Large-scale analyses often overlook regional differences in internal grain supply and demand, while small-scale analyses can accurately identify spatial heterogeneity. Changes in scale directly influence the spatial aggregation characteristics of supply and demand matching. As the scale increases, the spatial distribution of the SDR in the BTH region becomes more clustered. For grain supply, the clustering of high-yield areas in the northwest, which was observed at the grid and township scales, was not apparent at the county scale. This finding is consistent with previous studies in the BTH region (Shen *et al.* 2021).

4.2. Changes in supply and demand matching from the perspective of grain provision ecosystem service flow

This study examined ecosystem service flows from a dynamic perspective, particularly the evolutionary patterns of grain supply and demand matching across multiple spatiotemporal scales. Previous research explored the trade-offs between ecosystem service supply and demand, and highlighted spatial mismatches between supply and demand areas (Wei *et al.* 2017), but often focused only on local supply and demand (Larondelle and Lauf 2016). However, neglecting the spatial flow processes may result in outcomes that do not accurately reflect the actual conditions (Vrebos *et al.* 2015). Ala-Hulkko *et al.* (2019) used the E2SFCA method to assess the grain accessibility scores of various European countries. Their results revealed that grain spatial flow impacts its supply ecosystem service production and consumption dynamics. That study used road network-based accessibility analysis to quantify grain flow, helping decision-makers to understand resource demand distribution, yet it did not assess the grain flow directions between European countries. To expand on that approach, this study incorporated the direction of grain flow to effectively assess the supply–demand matching relationship. The results revealed that as grain moves across regions, the spatial mismatch between grain supply and demand varies significantly. Furthermore, this study used two scenarios to simulate grain flow, prioritizing the supply–demand balance at both the county and city scales.

Analyzing grain flows can provide a policy basis for inter-regional food allocation. In the 100 km threshold scenario, grain flows freely among counties within a 100 km radius, causing the boundaries between cities to become less distinct. Although the overall grain supply and demand of cities are not directly considered, counties with a higher grain surplus can supply grain to severely deficit areas in neighboring cities, thereby alleviating their deficits. In the 200 km threshold scenario, grain flow is prioritized at the city scale. If a supply–demand imbalance occurs at the city scale, the grain cannot flow out. Consequently, high-yield grain-producing areas within the deficit city can only sustain intra-city flow, while severely deficit neighboring areas outside the city remain without additional grain supplies. In cases of grain shortages, regions may adjust the cross-regional flow of grain to protect local grain industries or ensure grain security. Establishing cooperative mechanisms between adjacent regions can facilitate the grain circulation infrastructure, and reduce movement costs and risks. The findings of this study provide valuable guidance for government agencies in formulating policies tailored to regional differences. These policies may include grain production and sales partnerships, grain price regulation, purchase subsidies, preferential transport rates, and assessments of cross-regional grain flow volumes.

Moreover, examining the transmission paths and flow scale of grain provision ecosystem services is crucial for identifying the supply and beneficiary areas of that service. It also provides a foundation for quantifying the value of these services, which is essential for developing an effective farmland ecological compensation mechanism. By quantifying the specific amounts and payment flows from contributing to receiving areas, ecosystem service flows can enable targeted and accurate ecological protection compensation. This will ensure that farmers or regions

contributing more to ecosystem services receive higher compensation, thereby promoting coordinated regional development and achieving regional balance.

4.3. Supply and demand matching characteristics of grain provision ecosystem services at different distance thresholds

Designing scenarios with specific grain transport distance thresholds can provide direct guidance for optimizing grain supply and demand. This study extends previous research by categorizing the scales into different grain flow scenarios and incorporating multiple distance thresholds to elucidate the supply–demand matching characteristics of grain provision ecosystem services. In particular, the transport distance is a key parameter for analyzing the spatial flow of grain, and recent studies have used fixed distance thresholds to account for transportation costs. For example, Ala-Hulkko *et al.* (2019) applied 250, 500 and 1,000 km thresholds in their European study; a Pearl River Delta study used thresholds of 50, 100 and 200 km (Liu W *et al.* 2022); and a Hangzhou Bay study used a 100 km threshold (Su D *et al.* 2024). In addition to analyzing the fixed grain flow distance thresholds (100 and 200 km), this study calculated distance decay values at 10 km intervals and evaluated the changes in SDR across cities with transport distances. Moreover, this study explored the distance threshold at which the maximum number of grain supply–demand balance zones would be achieved at both the county and city scales within the BTH region. As the distance threshold increases, the characteristics of grain supply and demand matching in the BTH region at both the city and county scales vary significantly. The distance thresholds required to achieve the maximum number of grain supply and demand balance areas were found to differ between the city and county scales. Figs. 12 and 13 illustrate the variations in SDR across different cities under the two grain flow scenarios with distance thresholds. Under Scenario 1, at the city scale from 1980 to 2000, short-distance transportation of grain achieved optimal supply and demand matching at distances of 60, 100, and 100 km. In 2010, the optimal distance increased to 400 km. By 2020, the optimal distance reached 520 km. The numbers of SPAs at these points were 6, 9, 7, 9, and 9, respectively. At the county scale from 1980 to 2020, the optimal distance thresholds for achieving supply and demand matching were 60, 710, 310, 760, and 780 km, with the total numbers of SPAs and supply–demand balance areas being 85, 137, 102, 124, and 128, respectively. Under Scenario 2, at the city scale, the SDR variations in Beijing, Tianjin, and Zhangjiakou significantly differed from those in Scenario 1. This can be attributed to the restrictions on outward grain flow in Scenario 2, leading to a relatively higher SDR compared with Scenario 1. From 1980 to 2010, short-distance transportation achieved optimal supply and demand matching at distances of 60, 50, 100, and 130 km. In 2020, the optimal distance increased to 590 km. The numbers of SPAs at these points were 5, 9, 7, 8, and 10, respectively. At the county scale, from 1980 to 2020, the distance thresholds for achieving the highest number of supply–demand balances were 60, 220, 230, 270, and 630 km. The sum of SPAs and the numbers of areas reaching supply–demand balance were 84, 135, 101, 118, and 130, respectively. Compared with the original supply–demand matching status of each year, without considering grain flow, the number of supply areas meeting demand increased significantly (70, 103, 78, 90, and 91, respectively). These findings highlight the differences in the distance thresholds required to achieve the highest number of supply–demand matches across the different years.

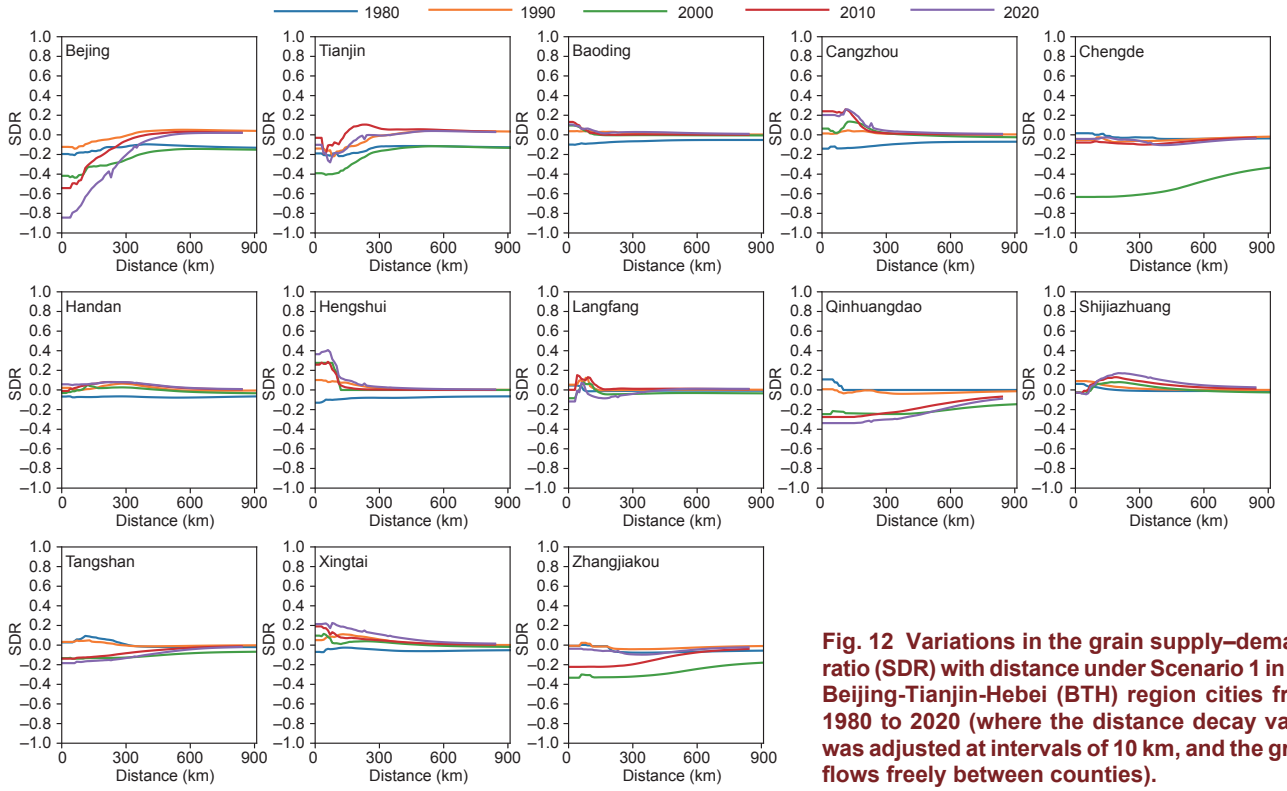


Fig. 12 Variations in the grain supply–demand ratio (SDR) with distance under Scenario 1 in the Beijing-Tianjin-Hebei (BTH) region cities from 1980 to 2020 (where the distance decay value was adjusted at intervals of 10 km, and the grain flows freely between counties).

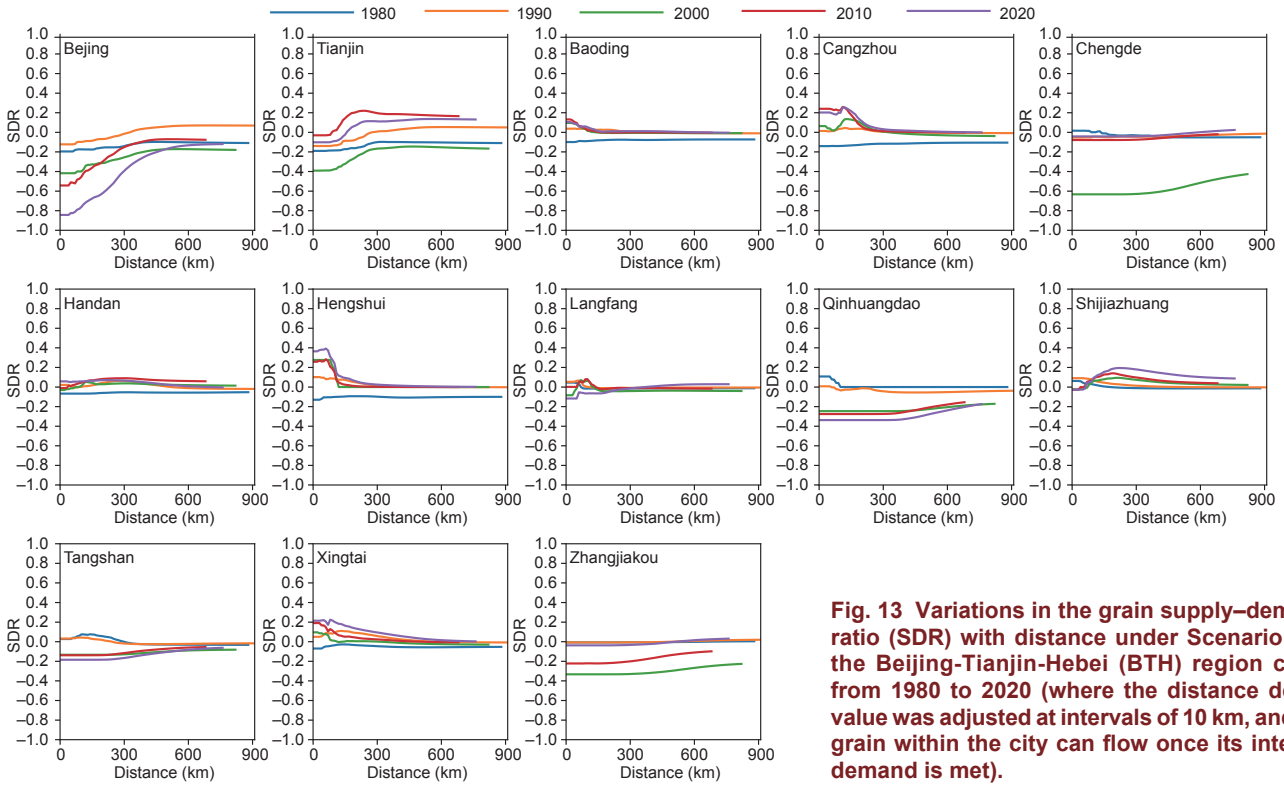


Fig. 13 Variations in the grain supply–demand ratio (SDR) with distance under Scenario 2 in the Beijing-Tianjin-Hebei (BTH) region cities from 1980 to 2020 (where the distance decay value was adjusted at intervals of 10 km, and the grain within the city can flow once its internal demand is met).

These findings provide a basis for precise grain production regulation and indicate the need for long-term research in this area.

The findings of this study can provide sustainable management strategies for optimizing grain transportation routes, modernizing grain circulation facilities, reducing transportation losses and waste, and ensuring stable grain supplies across different scales (in alignment with regional policies). In general, the optimal distance threshold for supply–demand matching was longer at the county scale than at the city scale. This is due to the relatively concentrated distribution of high grain supply areas in the central and southern parts of the BTH region, where short-distance flows can meet the grain supply demands of neighboring cities. Meanwhile, it is noteworthy that despite the southern part of BTH region being a major grain-producing area, counties like Fuping in Baoding and She in Handan still face severe grain supply–demand tensions. Their grain deficits are difficult to alleviate due to the mountainous terrain, limited cropland, and water scarcity. In addition, She County's developed livestock industry exacerbates the issue due to its high feed grain demand. Future strategies should focus on protecting farmland, developing specialty agriculture, strengthening regional cooperation, and establishing a robust grain reserve system to enhance grain supply stability. At the city scale, it is essential for high-yield grain cities such as Handan, Baoding, Shijiazhuang, and Hengshui to enhance agricultural productivity, optimize grain circulation and market mechanisms, and improve coordination with neighboring regions for grain distribution. These measures will not only ensure the local supply–demand balance but also help alleviate grain deficits in the surrounding cities. As the structure of grain consumption has shifted, the proportion of grain used for feed has been increasing annually. Therefore, rationally adjusting agricultural planting structures and improving feed grain production efficiency are crucial for ensuring a secure supply of feed grain. In contrast, the demand areas are mainly located in the northern part of the BTH region, particularly in deficit counties within Zhangjiakou and Chengde, which requires longer-distance transportation to achieve optimal supply and demand matching at the county scale. To address this issue, enhancing the logistics and warehousing infrastructure in the northern part of the BTH region is crucial. For the key grain transportation hubs of Beijing and Tianjin, it is imperative to refine their transportation service systems, reduce losses during grain transportation, and enhance their grain transport services.

4.4. Limitations and prospects

This study analyzed the changes in supply–demand matching patterns and innovatively incorporated various grain flows to enhance the study of grain ecosystem services across multiple spatiotemporal scales, thereby optimizing strategies for more effective grain flow regulation. However, this approach has certain limitations. First, this study thoroughly examined the spatiotemporal pattern of grain flow within the BTH region, but it did not account for actual cross-regional grain flow, including imports from other provinces or abroad. Regional research can offer valuable insights into a region's ability to maintain the balance of its grain supply and demand structure (Wen *et al.* 2024; Zhou and Liu 2024). Consequently, future studies should consider service flow from both near and distant coupling perspectives and further quantify cross-regional grain provision ecosystem services based on those findings. This study considered road transport as the only mode of transportation in analyzing grain

flow. To enhance the accuracy of grain flow assessments, future research should incorporate all transportation modes, including road, rail, and waterways. This study approached the potential flow of grain supply services through a supply–demand matching framework combined with accessibility calculations. Given the scarcity of real-world grain flow data and the influence of complex factors on grain movement — including natural, cultural, and policy elements — future research should integrate these factors to comprehensively analyze the drivers of grain movement. Furthermore, social-ecological network analysis can provide a comprehensive perspective on both ecological and social systems, while avoiding the limitations of single-aspect considerations (Peng *et al.* 2024). Therefore, future analyses should explore the evolution of ecosystem service flows within social-ecological frameworks to enhance risk management.

5. Conclusion

This study quantitatively evaluated the supply and demand levels of grain provision services in the BTH region at different scales from 1980 to 2020, using the E2SFCA method to assess grain flow. Furthermore, changes in grain supply and demand matching characteristics were examined under different distance threshold scenarios. The results revealed that the spatial patterns of supply, demand, and SDR of the grain provision ecosystem service exhibit scale-dependent effects. The demand side was more sensitive to scale changes, with larger scales leading to more clustered classifications for SDR. Furthermore, the grain flow exhibited an upward trend over time, with its spatial pattern shifting from the central and southern regions to the surrounding areas. At the county scale, the supply and demand matching patterns remained similar in both scenarios, with grain surplus areas expanding outward. Notably, the optimal distance thresholds for supply–demand matching were longer at the county scale than at the city scale in both scenarios. Consequently, the BTH region should develop multi-scale, differentiated grain management policies, enhance the inter-regional logistics infrastructure, optimize grain transportation routes in accordance with regional scales and policies, and facilitate cross–regional coordination of grain flow to effectively alleviate the risk of supply–demand imbalances.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used Kimi to assist in improving the clarity and readability of the language. All content generated was carefully reviewed and revised by the authors as necessary, and the authors take full responsibility for the final content of the article.

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