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Optimizing the ecosystem service flow of grain provision across metacoupling systems will improve transmission efficiency

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ABSTRACT

Ecosystem service (ES) flow can address mismatches between the supply and demand of ESs. Nevertheless, how to improve ES flow considering spatial flow information and interactions among different flow systems is a research gap. Taking the Beijing-Tianjin-Hebei (BTH) urban agglomeration region of China as an example, this study combined both system and network perspectives to analyze the ES flow of grain provision before and after optimization. Metacoupling system analysis was adopted to assess intra-regional and extra-regional flow. Linear programming was used to calculate the optimal distance cost flow solution with constraints. A network model was finally applied to build and analyze flow and transmission networks. In 2020, BTH participated in nearly 10% of the national flow, among which 57% was extra-regional flow. After optimization, the proportion of extra-regional flow decreased to 36%, all of which was inflow from the nearest provinces, while intra-regional flow increased by 35%. The optimized flow reduced distance costs by 143% and decreased network complexity. Core transmission nodes with both high degree and betweenness centrality played prominent connection roles in the process of flow. Strengthening regional connections and simultaneously effectively managing core transmission nodes are of great significance for improving flow efficiency and ensuring food provision.

1. Introduction

Human dependence on ecosystem services (ESs) has been long-standing (Millennium ecosystem assessment, 2005). However, the continuous growth of the population and the rapid process of urbanization have reduced the ES supply and simultaneously increased the ES demand, finally leading to a spatial mismatch between ES supply and demand (Carpenter et al., 2009; Ouyang et al., 2016). In this imbalanced situation, ES flow can serve as a link between supply and demand (Metzger et al., 2021). Through transmission from the service providing area (SPA) to the service benefiting area (SBA), ES flow could reflect the interactions of matter, energy, and information between the SPA and the SBA (Bagstad et al., 2013; Kleemann et al., 2020; Wang, Zheng, et al., 2022). As an important provisioning ecosystem service, food provision provides fundamental material resources for subsistence (Richardson, 2010). Effective food flow could resolve the spatial mismatches between food supply and demand, realize cross-regional benefits, and improve the sustainability of food trade (Liu et al., 2022).

Currently, methods and models for ES flow assessment can mainly be divided into three types. In the first type, the actual usage of ESs is taken as the flow (Schirpke et al., 2019). In the second type, the spatial relationships between ES supply and demand are regarded as the flow (Rioux et al., 2019). The third type calculates flow based on the transmission processes of ESs (Zank et al., 2016). Compared with the first two types, the third type focuses more on describing the quantity and spatial process of flow from the SPA to the SBA. For some services, such as

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carbon sequestration and climate regulation, their non-physical characteristics make it difficult to describe spatial flow quantity (Li et al., 2019). In contrast, as a macroscopic and physical process, grain flow is usually based on grain trade and transportation, involving complex interactions between multiple systems and a wide spatial range (Karakoc et al., 2022; Wang et al., 2023). In this regard, the system analysis method can be adopted to analyze and explain the complex process of grain flow (Zhang et al., 2023). System analysis has usually been connected with metacoupling framework (Liu, 2017; Schröter et al., 2018). Metacoupling includes intracoupling and intercoupling, corresponding to the flow within the system and the flow among systems respectively (Liu, 2017; Tromboni et al., 2021). By considering connections among systems in the flow, the flow quantity can be simulated well based on the perspective of the metacoupling framework. This framework has great potential for analyzing the grain flow quantity across different spatial scales.

In contrast to the flow of natural biophysical processes and information, the food flow is a material flow that depends on artificial carriers and paths (Ala-Hulkko et al., 2019; Koellner et al., 2019; Mitchell et al., 2015; Wang et al., 2023). Network analysis could better visualize the abstract flow process into edge connections between nodes according to the actual situation, allowing more consideration of socioeconomic factors in the food flow (Felipe-Lucia, 2022). The flow network was constructed based on graph theory and network theory, including nodes and edges. The nodes represented elements that participated in the flow and the edges represented the relationships among nodes (Wang et al., 2020). The construction of network edges typically reflects real-world pathways such as roads, railways, and rivers. For food provision chains, network analysis focuses on the connections and relationships between various points in the distribution process, from production areas to consumption areas (Karakoc et al., 2022). However, a method that effectively integrates both the detailed connection relationships and flow paths identified via network analysis with the broader quantification of flow across different spatial regions as emphasized in system analysis is still lacking. Such an integration is essential for understanding the dynamics of food flow. For example, it could involve mapping the journey of staple foods from farms to cities, considering both the complexity of routes and the quantities transported (Liu et al., 2023). This comprehensive approach is crucial for attaining a detailed understanding of both the micro-level specifics of the movement of individual food items and the macro-level overview of the entire food provision system, which in turn can provide a reference for better management and optimization of food provision chains (Li & Wang, 2023).

Food provision, in fact, a complex process involving the transfer of food from the SPA to the SBA, including production, harvesting, processing, storage, transportation and sales. Therefore, its optimization can be considered from the perspectives of supply, demand, and flow (Garnett, 2013). The optimization of supply and demand mainly involves adjustment of the planting structure of the production areas and the dietary structure of residents (Springmann et al., 2023; Wang et al., 2022b). This requires a deep understanding of local agricultural practices, ecological constraints, and consumer preferences, which vary significantly across regions. Compared with this complex process of supply–demand optimization, optimized flow can improve the deficit in the SBA and can nicely balance the regional supply and demand. It can be viewed as a more effective optimization of the imbalance between supply and demand for some services. This aspect of optimization focuses on the efficiency and effectiveness of the food supply chain, ensuring that the movement of food from areas of surplus to areas of need is conducted in the most sustainable and cost-effective manner. However, research in this area is still relatively lacking. There are opportunities for using advanced technologies and innovative strategies to optimize flow. Multi-objective optimization can be used to optimize flow, balance different environmental, economic and social goals, and identify better distribution solutions (Robinson et al., 2016). By integrating various factors, this approach not only addresses the immediate need to balance the food supply and demand, but also helps achieve long-term sustainability goals.

Spatial food flow is usually involved in different scales and cross-regional interactions (Schröter et al., 2018). As the main grain-producing area and one of the largest three urban agglomerations in China, the Beijing-Tianjin-Hebei (BTH) urban agglomeration region plays an important role in national and regional food trade. In addition, it faces the dilemma of intra-regional food flow. Therefore, we combined system analysis with a network model to quantify and analyze grain flow before and after optimization. Our objectives were (1) to develop a new approach for quantification and analysis of the grain flow, and (2) to develop a convenient and feasible flow optimization method for material ES flows, such as food flow, that rely on artificial carriers and paths.

2. Materials and methods

2.1. Study area and materials

2.1.1. Study area

The BTH region (36.03°N—42.62°N, 113.52°E−119.85°E) is located in North China, and it encompass three major provincial administrative units—Beijing Municipality, Tianjin Municipality, and Hebei Province—as well as 11 prefectural level cities in Hebei (Fig. 1a and c). The terrain is high in the northwest and low in the southeast, with the Yanshan Mountains to the north, the Taihang Mountains to the west, and the North China Plain to the east and south (Fig. 1b). Among the major farm products grown in the BTH, grain accounts for more than 95%, mainly including wheat, rice, and maize. The North China Plain, on which the BTH is located, accounts for more than a quarter of China's annual grain production. In addition, as a national transportation hub, Beijing has a well-developed road network that connects all parts of China through BTH (Fig. 1a and e). As one of the three largest urban agglomerations in China, there are frequent population flows and socioeconomic interactions within the BTH, which also leads to an active flow of food. Hebei Province is able to export a large amount of grain while remaining self-sufficient, but the opposite is true for Beijing and Tianjin. Moreover, with the acceleration of urbanization, the continuous encroachment of developed land on cropland and the increase in the urban population have led to longer grain transportation distances and a greater demand in urban areas (Fig. S1). Therefore, clarifying the extra-regional flow and intra-regional flow to and from the BTH and identifying a better distribution of food through flow optimization is crucial for ensuring local and national food security.

2.1.2. Data sources

The data used in this study included socioeconomic data and statistical data for the BTH in 2020 (Table 1). Data on grain production, population, and grain consumption per capita were collected for 31 provincial administrative regions of China (excluding Hongkong, Macao, and Taiwan). Based on this, both the grain production and population data of all county-level regions in BTH were also collected. All of the spatial data were reprojected onto the same coordinate system, and the spatial resolution of all of the raster data was unified to 30 m to ensure consistency.

2.2. Assessment of grain supply, demand, and flow

The grain supply was obtained from the grain production reported in the statistical yearbook, including wheat, rice, maize, tubers, and beans, for each county in the BTH and other provinces in China. The grain demand was calculated according to the population and grain consumption. The grain consumption included direct consumption (staples) and indirect consumption (feed, seed, and other uses) (Xia et al., 2022; Zuo et al., 2023). Since the indirect consumption data obtained were national data, we assigned the data to each region according to the

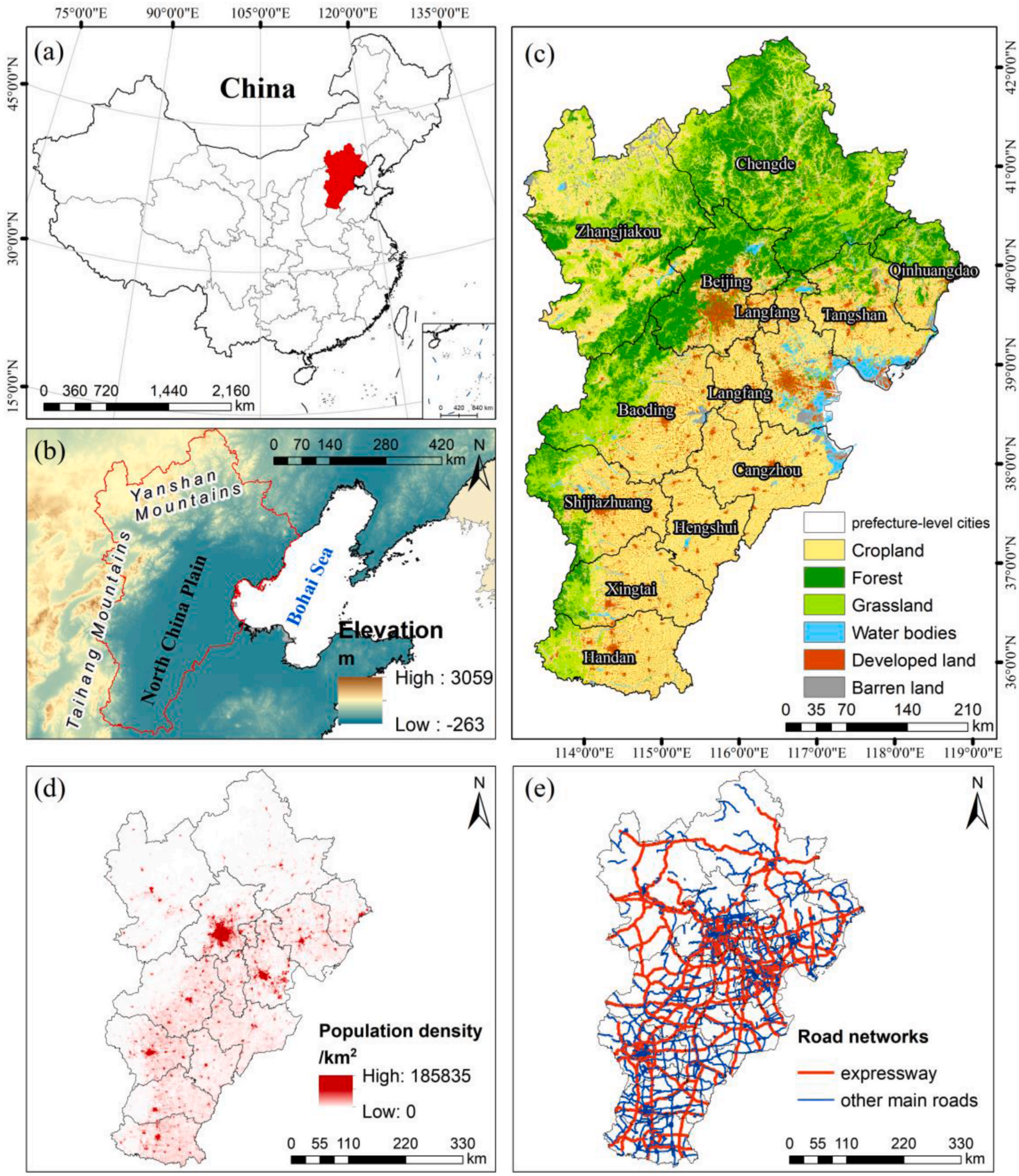

Fig. 1. Overview of the Beijing-Tianjin-Hebei region. (a) Location; (b) Elevation; (c) Land use pattern in 2020; (d) Population density in 2020; (e) Road networks in 2020.

population distribution.

$$D = \rho_u \times GD_u + \rho_r \times GD_r + F + SE + O \quad (1)$$

where D is the grain demand, ρ_u is the urban population, GD_u is the grain consumption per capita of urban residents, ρ_r is the rural population, GD_r is the grain consumption per capita of rural residents, F is the feed grain consumption, SE is the seed grain consumption, and O is the grain consumption for other uses.

The simulation of the grain flow was based on the spatial imbalance of the grain supply and demand. In this study, we utilized a metacoupling perspective: both the intracoupling among the counties in the BTH (intra-regional flow) and the intercoupling among the BTH and other provinces in China (extra-regional flow) were considered. It was assumed that the supply of each region was prioritized to meet the local demand (Kleemann et al., 2020). If there was a surplus, it flowed to other deficit regions; otherwise, it did not flow (Fig. 2a). If the national grain supply was greater than the grain demand, then some of the grain in the provinces with surplus did not participate in the national flow, and the allocation of the flow was based on the amount of grain surplus in the outflow provinces. The extra-regional flow was divided into outflow and inflow, and was calculated as follows (Song et al., 2020):

$$x_{kBTH} = x_{kB} + x_{kT} + x_{kH} \quad (2)$$

$$x_{BTHl} = x_{Bl} + x_{Tl} + x_{Hl} \quad (3)$$

Table 1
Data sources and detailed descriptions.

Data types	Data formats	Detailed descriptions and sources
Population density data	Raster, 1 km	The data were obtained from WorldPop (www.worldpop.org).
Road data	Shapefile	The most recent road data we obtained (2020) included highways, national roads, provincial roads, county roads, and township roads (www.openstreetmap.com).
Administrative boundary data		These data included provincial boundaries, prefecture-level city boundaries, and county boundaries (www.resdc.cn).
Grain production	Statistics	The grain production data included crops such as wheat, maize, rice, and soybeans and were obtained from the China Statistical Yearbook and the statistical yearbooks of each provincial administrative region (Table S2).
Population		The population data included both urban and rural populations, and were obtained from the statistical yearbooks of provincial administrative region (Table S1).
Grain consumption per capita		The grain consumption per capita data included the grain consumption per capita of both urban and rural residents, and was obtained from the statistical yearbooks of each provincial administrative region (Table S1).
Food balance sheet		This sheet included the types of grain, their uses, and amounts of each use and was obtained from the Food and Agriculture Organization of the United Nations.

$$x_{kl} = \frac{S_k\text{-}D_k}{\sum_{k=1}^{p}(S_k\text{-}D_k)} \times (D_l\text{-}S_l) \tag{4}$$

$$S_{BTH}\text{-}D_{BTH} = \sum_{k=1}^{p} x_{kBTH}\text{-}\sum_{l=1}^{q} x_{BTHl} + R \tag{5}$$

where x_{kBTH} is the inflow from surplus province k to the BTH, and x_{kB}, x_{kT}, and x_{kH} are the inflows from province k to the Beijing Municipality, Tianjin Municipality, and Hebei Province. x_{BTHl} is the outflow from the BTH to deficit province l, and x_{Bl}, x_{Tl}, and x_{Hl} are the outflows from the Beijing Municipality, Tianjin Municipality, and Hebei Province to province l, respectively. x_{kl} is the flow from surplus province k to deficit province l. S is the grain supply, D is the grain demand, p is the number of surplus provinces in China, q is the number of deficit provinces in China, and R is the grain that does not participate in the flow. R existed only when the national grain supply exceeded grain demand and at least one province in the BTH was a surplus province.

To calculate the intra-regional flow, first, for the three provincial-level administrative regions of Beijing, Tianjin, and Hebei, the intra-regional flow of the basic unit, the county, was calculated. Then, after meeting all the demand within the administrative region, any remaining surplus flowed to other provincial administrative regions. We divided the intra-regional flow into the oversupply situation and the undersupply situation. If the surplus in a province was greater than its deficit, the oversupply situation occurred:

$$x_{ij} = \frac{S_i\text{-}D_i}{\sum_{i=1}^{m}(S_i\text{-}D_i)} \times (D_j\text{-}S_j) \tag{6}$$

If the surplus of the province was less than its deficit, undersupply occurred:

$$x_{ij} = \frac{D_j\text{-}S_j}{\sum_{j=1}^{n}(D_j\text{-}S_j)} \times (S_i\text{-}D_i) \tag{7}$$

In Equations (6) and (7), x_{ij} is the flow from surplus county i to deficit county j in the province, m is the number of surplus counties in the province, and n is the number of deficit counties in the province.

Then, the flow among the provinces in the BTH was determined according to the results of the flow among the provinces, the surplus amount of surplus counties in the outflow provinces, and the deficit amount of deficit counties in the inflow provinces:

$$x_{ij} = \frac{S_i\text{-}D_i}{\sum_{i=1}^{m}(S_i\text{-}D_i)} \times x_{ab} \times \frac{D_j\text{-}S_j}{\sum_{j=1}^{n}(D_j\text{-}S_j)} \tag{8}$$

where x_{ij} is the flow from surplus county i in province a to deficit county j in province b, m is the number of surplus counties in province a, and n is the number of deficit counties in province b.

2.3. *Grain ecosystem service flow optimization*

Linear programming was conducted to optimize the grain flow (Robinson et al., 2016). In the distance cost optimization, distance cost minimization was taken as the objective function, and the supply and demand relationship was used as the constraint to allocate the budgets to all deficit units. The calculation of the flow cost was divided into the extra-regional part and the intra-regional part (Fig. 2b). For the extra-regional part, only the inflow cost was considered, while for the intra-regional part, both the inflow cost and outflow cost were considered. This analysis was conducted through programming in MATLAB 2018a.

$$\begin{cases} \textit{Minimize}\left(f = \sum_{k=1}^{p} C_{\mathrm{kBTH}} \bullet x_{\mathrm{kBTH}} + \sum_{i=1}^{m}\sum_{j=1}^{n} C_{\mathrm{ij}} \cdot x_{\mathrm{ij}}\right) \\ S_{BTH}\text{-}D_{BTH} = \sum_{k=1}^{p} x_{kBTH}\text{-}\sum_{l=1}^{q} x_{BTHl} + R \\ x_{kBTH} \le S_k\text{-}D_k \\ \sum_{i=1}^{m} x_{ij} \le D_j\text{-}S_j \\ \sum_{j=1}^{n} x_{ij} = S_i\text{-}D_i \\ x_{kBTH} > 0 \\ x_{BTHl} \ge 0 \\ x_{ij} > 0 \\ R \ge 0 \end{cases} \tag{9}$$

where C is the cost of grain transportation, k is the surplus province, l is the deficit province, p and q are the numbers of surplus provinces and deficit provinces, i is the surplus county in the BTH, j is the deficit county in the BTH, and m and n are the number of surplus counties and deficit counties in the BTH, respectively.

2.4. *Network analysis of grain flow and flow transmission*

In this study, we constructed the original grain flow and optimized grain flow networks, as well as the grain flow transmission network based on the optimized flow. Then, these networks were analyzed according to their relevant network attributes (Fig. 2c). All flow results were visualized by ArcGIS 10.6, and the figures were drawn with Origin 2021.

2.4.1. *Constructing the grain flow network and transmission network*

The nodes, the edges, and the flow relationships are the most

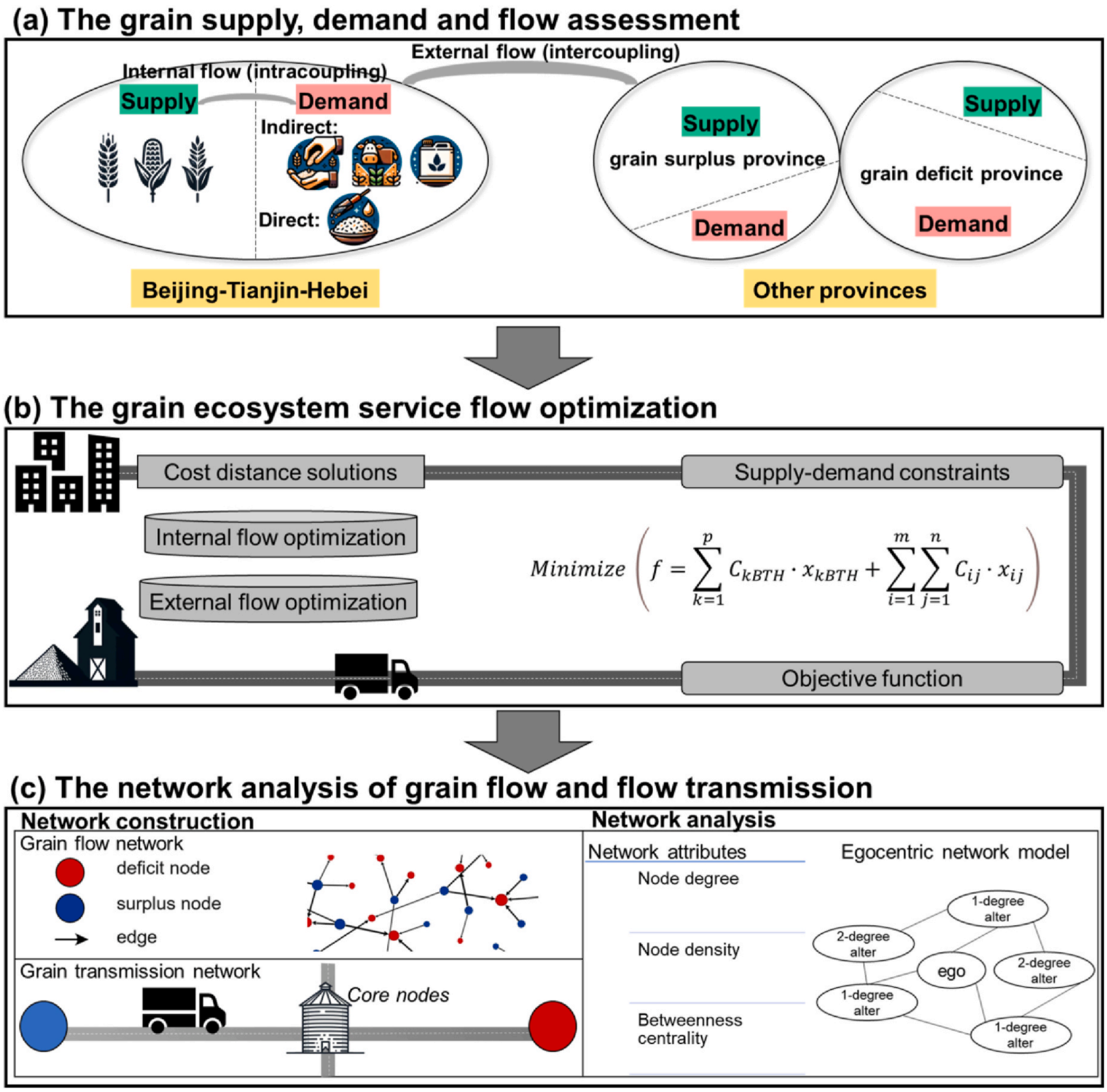

Fig. 2. Methodological framework of this study.

important parts of network construction. Thus, this process mainly consisted of three steps.

Step 1: Identifying surplus and deficit nodes

The administrative center of each flow unit was regarded as the node of the network. The budget calculated via subtraction of the grain supply from the demand of each flow unit was used to describe the surplus and deficit characteristics of the node.

Step 2: Defining the network edges

For the grain flow network, the directed grain flow pathway from a grain providing node to a grain benefiting node was defined as the edge, and its quantity was obtained based on the flow calculated above. For the grain transmission network, the road pathway simplified according to the road network was defined as the edge, including expressways, national roads, and provincial roads. The edges between the deficit nodes served as virtual transmissions and were depicted as dotted lines, and the other edges were regarded as real transmission and were depicted by solid lines. Based on these definitions, the flow edges among the nodes were determined, and two flow networks and a transmission network were constructed.

Step 3: Spatial construction of the network

Finally, Gephi and ArcGIS were used to spatially map the nodes and edges to form the network. For the mapping nodes, the size and color of the node were used to indicate the surplus and deficit status of the county in which each node was located. The directed polylines starting from the providing nodes and reaching the benefiting nodes were used to map the grain flow edges, and the thickness of the line corresponded to the quantity of grain flow. The undirected polylines that covered all nodes were used to map the grain transmission edges.

2.4.2. *Analyzing the grain flow network and transmission network*

Analyzing the network structure is the key to clarifying flow relationships and promoting grain transportation efficiency. In this study, network density, node degree, and node betweenness centrality were applied to describe the characteristic attributes of the network (Lin et al., 2014). These attributes were used to analyze and compare the differences between the original and optimized grain flow networks.

$$\rho = E/n(n\text{-}1) \tag{10}$$

where ρ is the network density, E is the number of edges, n is the number of nodes, and $n(n-1)$ is the theoretical maximum number of edges.

$$D(i) = OD(i) + ID(i) \tag{11}$$

where $D(i)$ is the degree of node i, and $OD(i)$ and $ID(i)$ are the out-degree and in-degree of node i, respectively.

$$B(i) = \sum_{a,b} \frac{\sigma(a,i,b)}{\sigma(a,b)} \tag{12}$$

where $B(i)$ is the betweenness centrality of node i, $\sigma(a,i,b)$ is the number of shortest paths between node a and b passing through node i, and $\sigma(a,b)$ is the total number of shortest paths between a and b.

The principle of the egocentric network was applied to analyze the core nodes that were identified via network attribute analysis (Chung, 2021). The egocentric network was usually used in the analysis of the social network. The center in the egocentric network is called the ego, and the elements connected to it are called alters (Wu et al., 2015). In this study, the connections among the core nodes and their 1-dgree directly connected alters and 2-degree indirectly connected alters were showed in the analysis of the core nodes.

3. Results

3.1. Spatial patterns of the grain supply, demand, and budgets in the BTH

In 2020, the grain supply in the BTH was 4.00×10^7 tons, and it was primarily concentrated in the southeastern plains. Notably, more than 90% of the grain supply was contributed from 11 cities in Hebei Province, and most of it was from the six cities of Baoding, Handan, Shijiazhuang, Xingtai, Cangzhou, and Hengshui. In contrast to the distribution of the supply, the spatial variation in the grain demand among cities was less pronounced. The demand in the BTH was 4.79×10^7 tons, and it was concentrated in most of the cities in the eastern regions. Beijing, Tianjin, Baoding, Shijiazhuang, and Handan collectively accounted for 60% of the overall demand.

The deficit in grain production reached 7.85×10^6 tons, and thus, the BTH region as a whole was not self-sufficient. Among them, the Beijing Municipality and Tianjin Municipality were in deficit. Although Hebei Province had a grain surplus of 3.8×10^6 tons, Langfang, Tangshan, Qinhuangdao, Shijiazhuang, Zhangjiakou, and Chengde in Hebei Province experienced grain deficits. On the county level, 102 out of 200

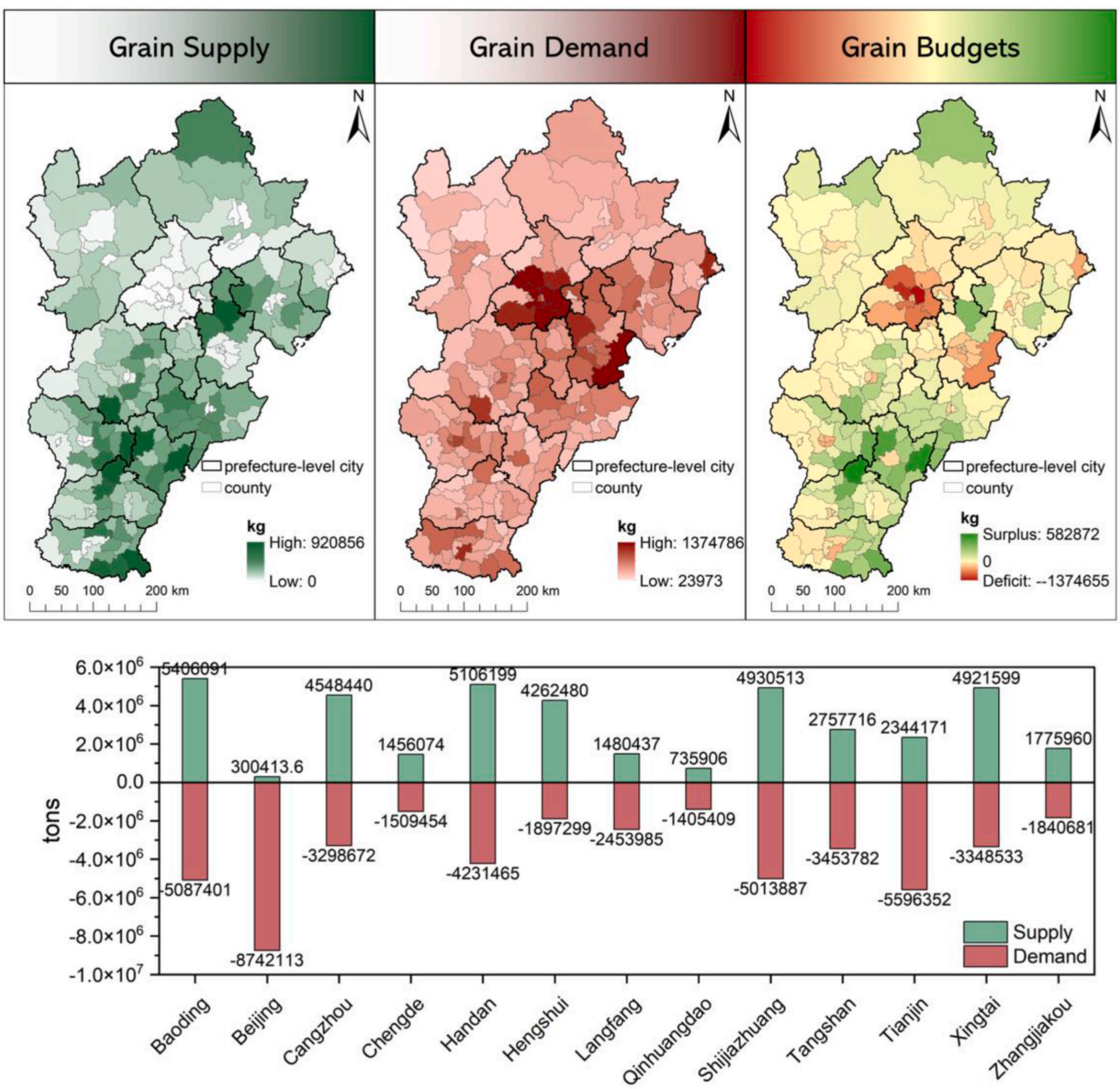

Fig. 3. Grain supply, demand, and budgets of the Beijing-Tianjin-Hebei region in 2020.

counties reported deficits, with the majority situated in the west and north, including Beijing, Tianjin, certain municipal districts of prefectural level cities, and mountainous counties (Fig. 3).

3.2. Extra-regional and intra-regional grain flow characteristics in the BTH

In 2020, a total of 2.39×10^7 tons of grain participated in the flow in the BTH, accounting for nearly 10% of the national grain flow (Fig. S2). Among them, the extra-regional flow was 1.37×10^7 tons and the intra-regional flow was 1.02×10^7 tons, accounting for 57% and 43%, respectively. Regarding the extra-regional flow, the outflow was 17% (2.28×10^6 tons), while the inflow was 83% (1.14×10^7 tons). Although the BTH was in deficit as a whole, since Hebei Province had a grain surplus, this part of the grain surplus flowed out. The outflow went to 14 provinces with grain deficits, mostly in southern China. The outflow mainly went to Guangdong and Zhejiang, the two provinces with the most severe deficits accounting for 54%. The inflow was from other 14 surplus provinces, mainly located in Northeast and North China, and all of this grain flowed into Beijing and Tianjin (Figs. 4a and 5a). The largest grain import province was Heilongjiang, accounting for 33% of the total inflow. The overall direction of the intra-regional flow was from southeast to northeast. Among the intra-regional flow, 93.2% flowed within Hebei (9.46×10^6 tons), 4.4% flowed within Tianjin (4.51×10^5 tons), 1.7% flowed from Hebei to Beijing (1.73×10^5 tons), and 0.7% flowed from Hebei to Tianjin (6.67×10^4 tons) (Figs. 4b and 5b).

3.3. Distance cost optimized extra-regional and intra-regional grain flow

After optimization, 1.38×10^7 tons of grain participated in the intra-regional flow, accounting for 64%, and 7.85×10^6 tons of grain participated in the extra-regional flow, accounting for 36%. For the intra-regional flow, 54% flowed within Hebei (7.43×10^6 tons), 18.2% flowed from Hebei to Beijing (2.50×10^6 tons), 24.6% flowed from Hebei to Tianjin (3.38×10^6 tons), 2.3% flowed within Tianjin (3.21×10^5 tons), and 0.9% flowed from Tianjin to Hebei (1.30×10^5 tons). Most of these intra-regional flows were concentrated in the southeast. For the extra-regional flow, the outflow was cut, and the grain from the surplus provinces closest to the BTH flowed to cities that still had deficits after optimizing the intra-regional flow. Among the extra-regional flow, 1.1% flowed from Inner Mongolia Autonomous Region to Zhangjiakou (8.33×10^4 tons), 9.8% flowed from Liaoning Province to Chengde and Qinhuangdao (1.00×10^5 tons and 6.71×10^5 tons, respectively), and 89.1% flowed from Shandong Province to Tangshan, Langfang, and Beijing (6.95×10^5 tons, 3.60×10^5 tons, and 5.94×10^6 tons, respectively) (Fig. 6).

Compared with the results of the original flow and optimized flow, the distance cost-optimized flow significantly reduced the transportation cost while fully ensuring the provision of all grain deficits. Although the extra-regional outflow decreased to zero after optimization, the total amounts of extra-regional inflow and intra-regional flow remained almost unchanged. The overall transportation cost was decreased by 143% through optimization. Among them, the cost of extra-regional flow was decreased by 213% and the cost of intra-regional flow was decreased by 29% (Fig. 7).

3.4. Analysis of the grain flow network and grain transmission network

The grain network attributes of the original and optimized flow are shown in Table 2. Compared with the original network, the optimized network exhibited a significant decrease in its edges, density, and degree. There was a power law relationship between the node degree and betweenness centrality, which was stronger in the original network and weaker in the optimized network (Fig. 8). The nodes with high flow were identified as the core flow nodes of the grain flow network. For the original network, core flow nodes with high inflow were all municipal districts and most of them were located in Shijiazhuang, while the core flow nodes with high outflow were mainly located in Xingtai, Hengshui, and Shijiazhuang (Table S2). For the optimized network, the core flow nodes with high inflow differed from those in the original network, being mainly located in Beijing, Tianjin, and Shijiazhuang, while the core flow nodes with high outflow remained almost the same as those in

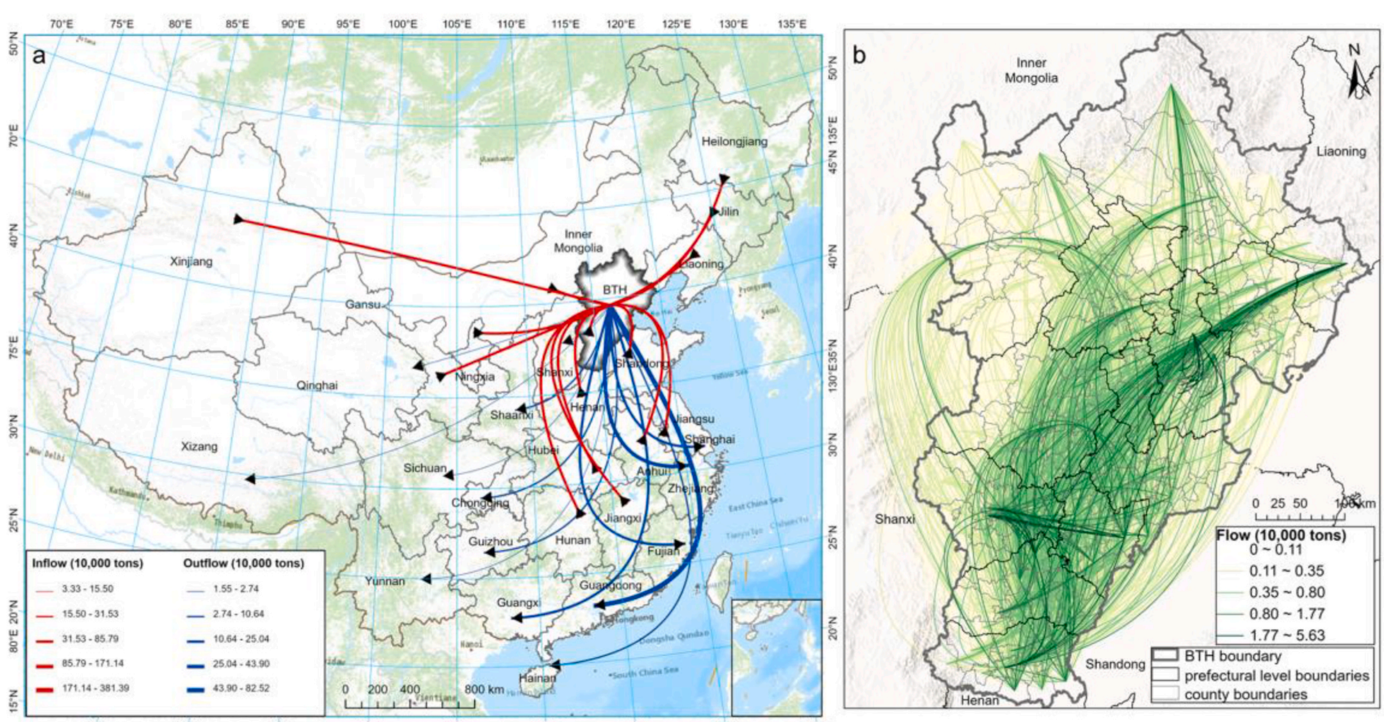

Fig. 4. Spatial distribution of the grain flow related to the Beijing-Tianjin-Hebei (BTH) region. (a) Extra-regional grain flow between the BTH and other provinces across China. (b) Intra-regional grain flow among the counties in the BTH.

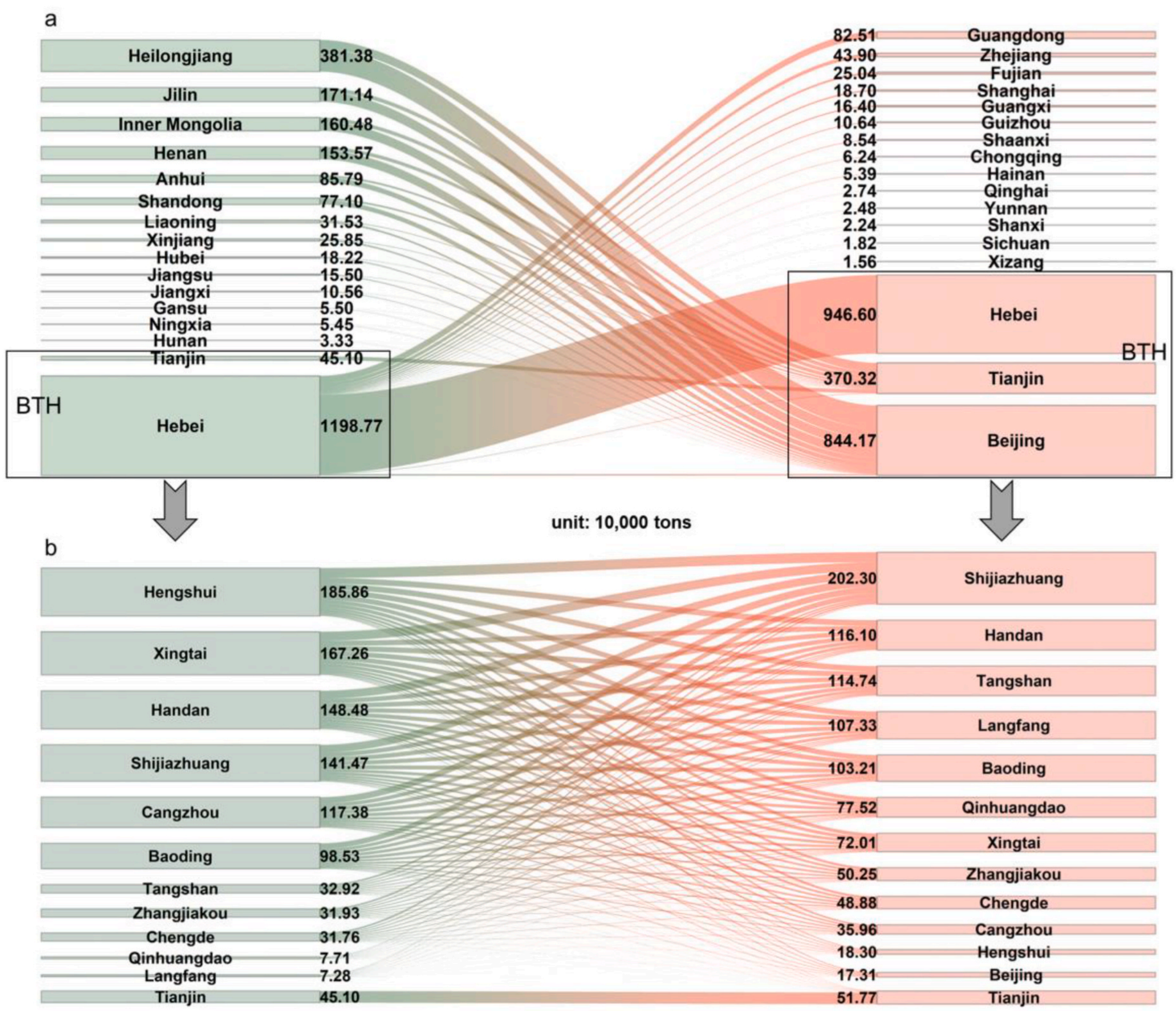

Fig. 5. Quantity of grain flow related to the Beijing-Tianjin-Hebei (BTH) region. Green denotes the service providing areas and red denotes the service benefiting areas. (a) Extra-regional grain flow quantity between the BTH and other provinces across China. (b) Intra-regional grain flow quantity among the cities in the BTH. Note: Due to rounding, some data may differ between the total and sub-total.

the original core flow nodes (Table S3).

The grain flow transmission network based on the simplified road network covered all of the nodes. These transmissions followed the grain gradient from high budgets to low budgets and could transfer grain to each node in the BTH. There were 431 edges across 200 nodes. Among them, 257 edges were real transmissions and 174 edges were virtual transmissions. The virtual transmissions were mainly located in Beijing and Tianjin (Fig. 9). The relationship between the degree and betweenness centrality was a power law relationship (Fig. S3). The core transmission nodes in the transmission network, characterized by both a high degree and high betweenness centrality were identified based on this relationship, and they played prominent connection roles in the transmission network (Table S4). Through the directly connected 1-degree alters and the indirectly connected 2-degree alters of these five core transmission nodes, nearly 45% of the nodes and nearly 30% of the transmissions were covered in the BTH (Fig. 9).

4. Discussion

4.1. Applicability of the metacoupling system and network model to grain flow optimization

In this study, the system perspective was adopted to describe the flow. Many previous studies have assumed that the study area is a closed system and have simplified or not considered the extra-regional flow (Liu et al., 2022; Lyu & Wu, 2023; Zhou & Liu, 2023). This treatment reduced the complexity of the flow, but it neglected the interactions between the intra-regional system and extra-regional systems. The perspective of the metacoupling framework is essential for accurately portraying the complex interplay between the various elements within and outside of the system (Liu et al., 2015). In particular, in Beijing and Tianjin, the extra-regional flow played a crucial role as the intra-regional flow was unable to support these regions.

We applied linear programming while considering the constraints of grain supply, demand, and distribution in the real world to optimize the grain flow (Lee & Sidford, 2014; Wang et al., 2019). The results of the linear programming optimization were analyzed using the network model and compared with the original flow. The results showed that our simulation of flow closely approximated the real flow (Konar et al., 2018; Lin et al., 2014, 2019). The optimization disrupted the original flow network and decreased its complexity (Karakoc et al., 2022). A simpler network structure reduced the dependencies among the nodes, thereby increasing the resistance of the food system to interference (Wang et al., 2022).

This optimization solution improved food accessibility for residents in BTH and reduced reliance on extra-regional food sources (Yoshii and Oyama, 2011). In recent years, the Chinese government has focused on ensuring national food security (Huang & Yang, 2017), with a key goal being to improve the food self-sufficiency rate (Ghose, 2014). After optimization, the grain self-sufficiency rate increased from 60% to 67%,

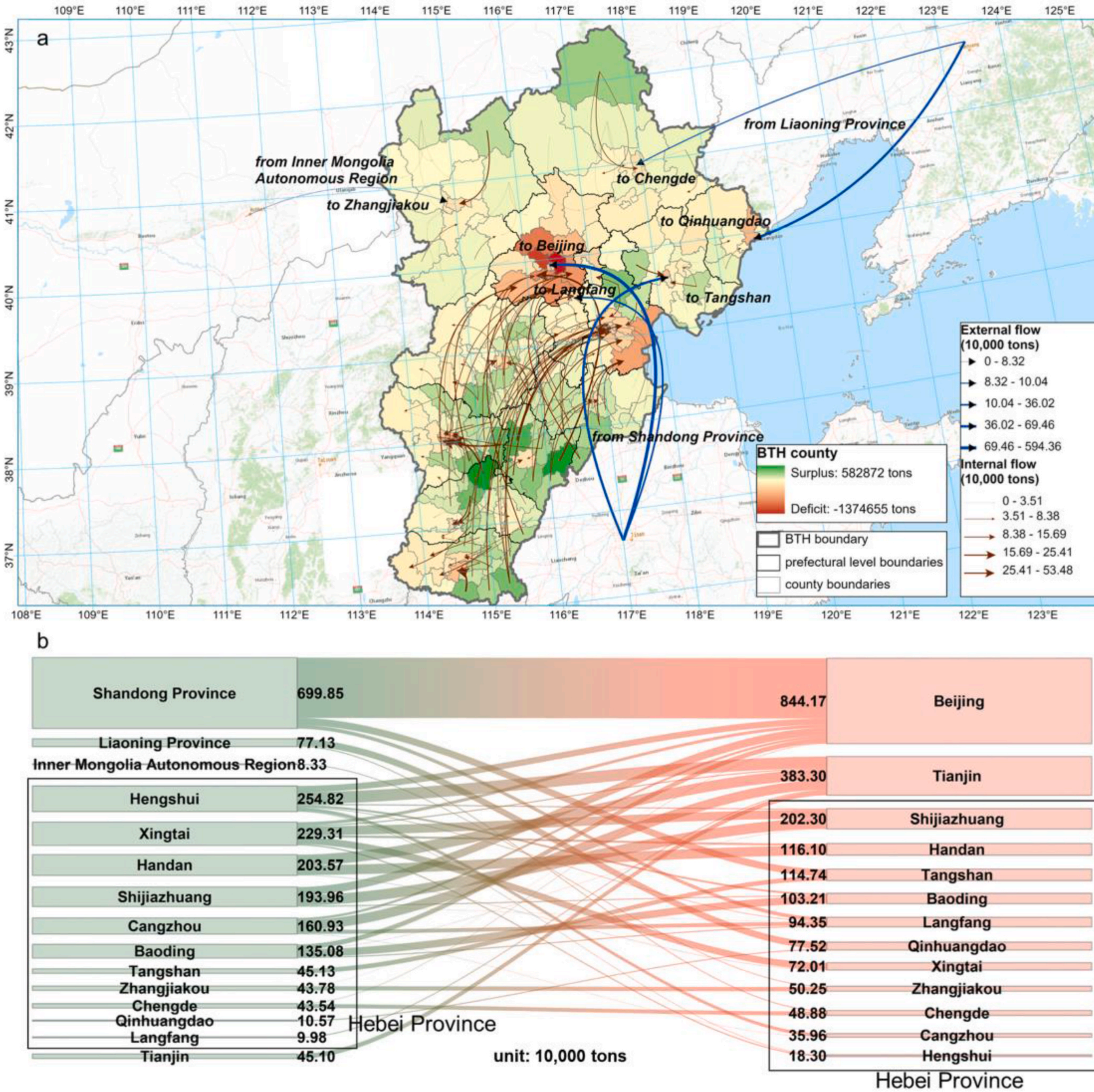

Fig. 6. Distance cost optimized grain flow related to the Beijing-Tianjin-Hebei (BTH) region. Green denotes the service providing areas and red denotes the service benefiting areas. (a) Spatial distribution of the extra-regional and intra-regional grain flow related to the BTH. (b) Extra-regional and intra-regional grain flow quantity related to the BTH.
Note: Due to rounding, some data may differ between the total and sub-total.

reducing dependence on Northeast China. Meanwhile, the reduction in distance cost means that residents in the BTH can obtain cheaper grain. Although this cost saving is ultimately borne by other provinces, maintaining a stable and reliable food provision for the BTH, especially for the capital, Beijing, remains a high priority of the Chinese government and is deemed more important than meeting demand in other regions (Li, Zhang, et al., 2022).

4.2. Distance cost optimization of grain ecosystem service flow promotes regional coupled connections

The distance cost optimization of the grain flow related to the BTH conducted in this study overcomes the inter-provincial constraints and ensures multi-faceted coordinated development of the cities and counties within the BTH (Li, Hou, et al., 2022; Shakya et al., 2021). Through optimization, two main linkages are formed among the cities and counties in the BTH. The first linkage is located in the western part of the BTH, throughout Beijing, Langfang, Baoding, Shijiazhuang, Xingtai, and Handan. This linkage is dominated by inflows to Beijing, accounting for 68% of the total flow among the linkage. The flow between Baoding and Shijiazhuang accounts for 17%. The second linkage is located on the east coast of the BTH, throughout Qinhuangdao, Tangshan, Tianjin, Cangzhou, Hengshui, and Xingtai. The inflow into Tianjin accounts for 64% among this linkage. In addition, 25% of the

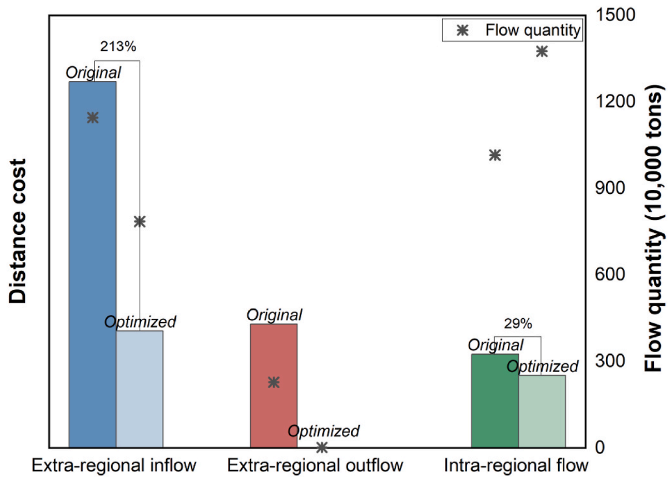

Fig. 7. Comparison of the original flow and the optimized flow in terms of the distance cost and flow quantity.

Table 2
The network attributes of the original and optimized grain flows.

Attributes	Original	Optimized
Nodes	200	182
Edges	9996	172
Density	0.251	0.004
Degree	49.1	0.86

grain in this linkage is transported from Hengshui and Xingtai to Qinhuangdao. These two linkages are located in the western and eastern parts of the BTH and are centered on Beijing and Tianjin, respectively. This connects Beijing and Tianjin with the cities in Hebei via the grain flow.

According to the spatial plan for the coordinated development of the BTH, the further development of the BTH will be concentrated along the Beijing–Baoding–Shijiazhuang development axis, Beijing–Tianjin development axis, and Beijing–Tangshan–Qinhuangdao development axis (OCDBTH, 2015). Our results correspond well to this plan. The first linkage nearly coincides with the Beijing–Baoding–Shijiazhuang development axis and radiating agricultural areas in the south. The second linkage connects the three axes from the industrial areas in the northeast and east to the agricultural areas in the south. The strengthening of these connections as a result of the optimized grain flow plan will not only drive the development of industries related to food transportation cities and counties along the linkage, but will also develop a closer cooperation between policy formulation and implementation (Bingham et al., 2022). This coordination is not limited to food trade but may also extend to a wider range of agricultural, economic, and environmental policies (Chen et al., 2014; Lobell & Villoria, 2023; Maiyar et al., 2015; Kinnunen et al., 2020).

4.3. Significance of the core transmission nodes for grain flow

In the optimized grain flow transmission network for the BTH, the pivotal role of the transmission nodes is paramount for ensuring an efficient and stable grain distribution (Xu and Sun, 2021). Represented by the five identified core transmission nodes, these nodes can mainly be divided into three types (Bellocchi et al., 2021). First, high outflow

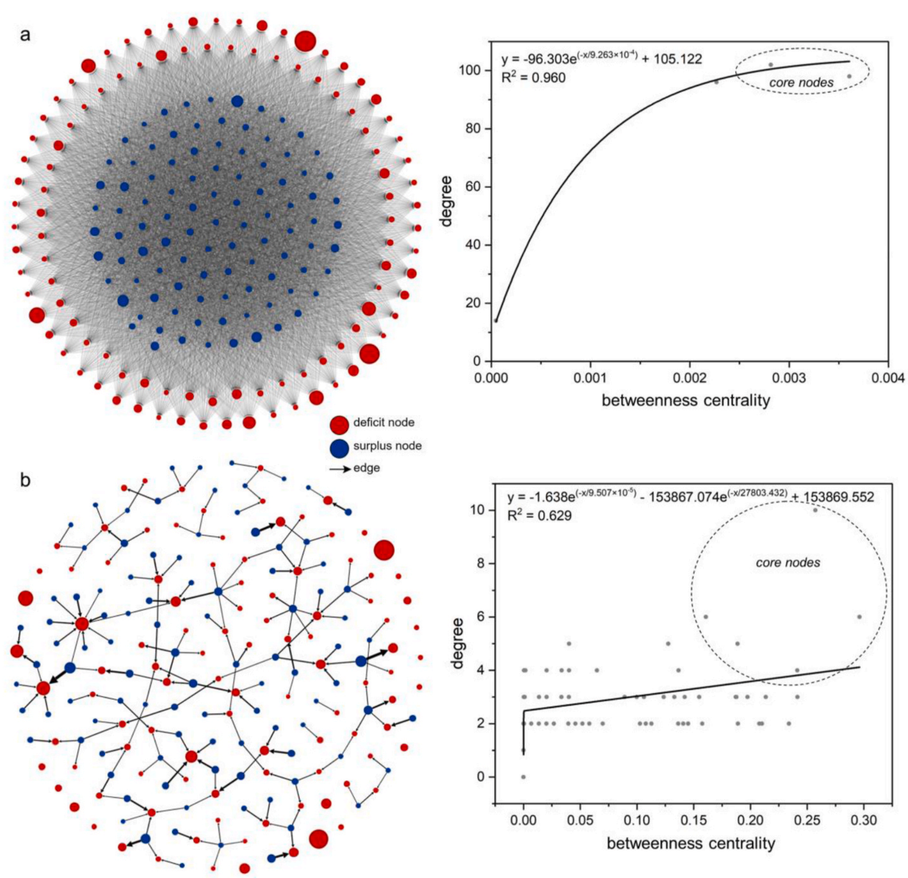

Fig. 8. Original and optimized grain flow networks and the corresponding relationships between the node degree and betweenness centrality: (a) The original grain flow; and (b) The optimized grain flow.

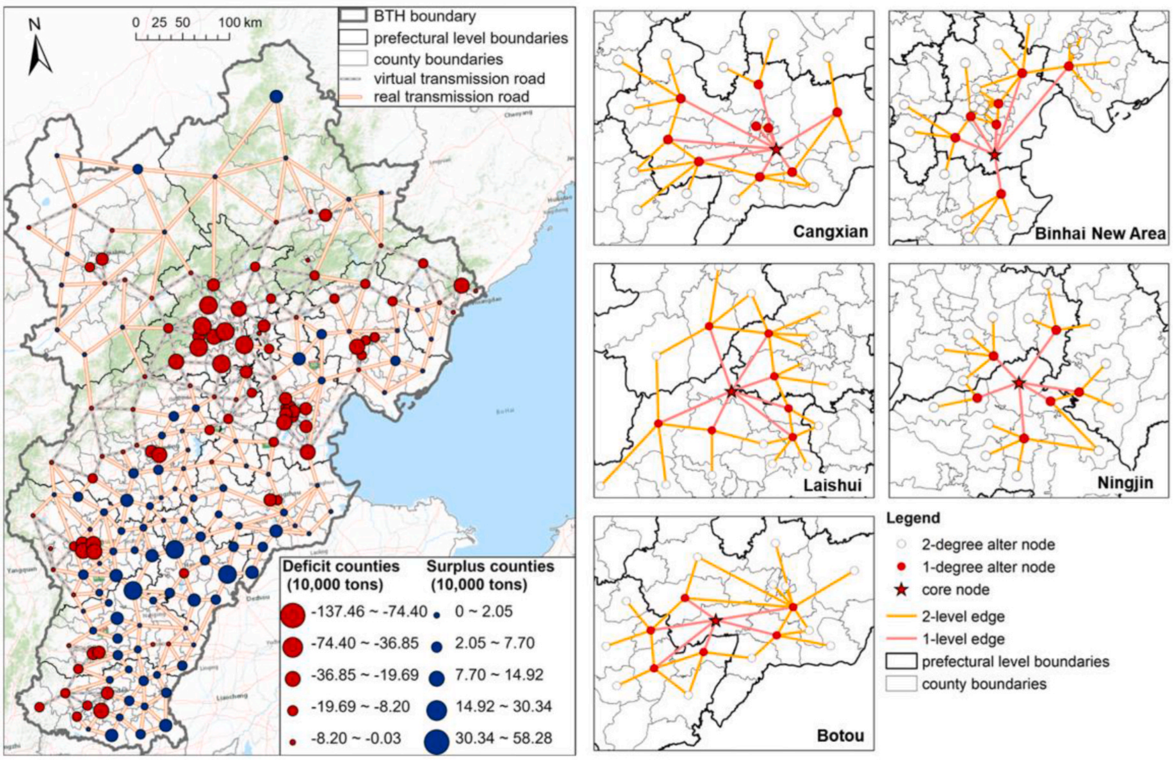

Fig. 9. Simplified grain transmission network for the Beijing-Tianjin-Hebei region and spatial connections of the core transmission nodes in the grain transmission network after optimization.

nodes, represented by Ningjin, are the county with the highest grain output and the largest grain surplus in BTH (Hebei Provincial Bureau of Statistics, 2020). Second, important traffic nodes such as the Binhai New Area and Laishui. These nodes, while not having high grain outflows, become important transit points for grain transmission due to their convenient traffic or key locations. The Binhai New Area, located in the eastern coastal area of Tianjin, is the largest port and important transportation center in northern China. It serves as a center for grain import and export and becomes a hub connecting the southeastern part of the BTH to the northeastern region, effectively radiating throughout the BTH (You et al., 2014). Laishui is located in the central-western part of the BTH and is a key node for transporting grain from the southern part of the BTH to the mountainous areas in the northwest (Zhao et al., 2017). The third type, such as Cangxian and Botou, is both a major outflow node and a key traffic node. These nodes not only facilitate a certain amount of grain outflows, but can also act as transit points in the transmission network (Hu et al., 2022).

The effective management of these transmission nodes is the key to bolstering the resilience and sustainability of the regional grain provision chain. For the first type of transmission nodes, priority should be given to upgrading infrastructure in the areas surrounding these nodes. This includes improving roads, and enhancing transportation links that connect these nodes to other areas in the BTH to efficiently handle high quantity of grain flow during peak demand periods (Duan et al., 2021; Jiang et al., 2022; Raj et al., 2022). For the second type of transmission nodes, increasing storage capacity of these transmission nodes can help buffer against grain shortages caused by provision chain disruptions (Bai & Sun, 2021). This is especially important for managing nodes in the network that are connected by virtual transmissions. The second type of transmission nodes are often linked to some of high-deficit nodes through virtual transmissions, especially near Beijing and Tianjin. Although there is no direct flow between these transmission-connected nodes, they must rely on transportation from other sources.

4.4. *Limitations and future prospects*

There are three main limitations in this study. First, the original flow calculated served as a simulation of the actual grain trade, and the flow optimization was performed based on this simulation. The scarcity of real-world grain flow made validating our results challenging. Nevertheless, the optimization remains feasible when flow data becomes available (Robinson et al., 2016). Second, the optimization of the grain flow using linear programming only considered the supply and demand constraints. In fact, grain flow optimization is a complex process that is related to market dynamics, policy decisions, and other unpredictable factors. However, due to the difficulties in obtaining various types of data, it is difficult to conduct more precise optimization. Third, the road network used for grain transmission may have simplified the actual complexities of the traffic network. In future research, more detailed information about the grain flow assessment, optimization, and analysis processes should be considered. A more elaborate grain flow model that is suitable for actual and dynamic food trades should be further explored. To achieve flow optimization, the total process of supply, flow, and demand should be optimized, and economic and policy implications and environmental influences should be integrated into the optimization model. In addition, diverse transportation pathways, including roads, railways, and waterways, should be considered to create a more accurate model of the grain transmission when analyzing the food flow.

5. Conclusions

In order to improve the ES flow is an effective manner, it is necessary to resolve the mismatches between the ES supply and demand. Thus, in this study, we constructed a comprehensive grain flow process, including supply–demand flow assessment, flow optimization, and flow analysis for the BTH. In 2020, in terms of grain flow, among the three provinces in the BTH, only Hebei Province was self-sufficient. The inflow into the BTH mainly came from North China and Northeast

China, while the outflow was mainly directed to southern and eastern China. The optimized flow cuts the outflow from the BTH and increases the proportion of intra-regional flow. Compared with the original flow, the optimized flow greatly reduces the distance cost and the complexity of the flow network. These intra-regional flows can form two main linkages in order to promote the regional connections in terms of many aspects among the cities and counties in the BTH. The nodes with both a high degree and high betweenness centrality were identified as core transmission nodes of the transmission network. These nodes are either major outflow nodes, important traffic nodes, or both. Effective management of these core transmission nodes is the key to maintaining a stable food provision. By combining system and network analysis approaches, this method identifies practical strategies for improving the efficiency and sustainability of food distribution, particularly in the context of highly urbanized and intensive food supply–demand flow regions such as the BTH.

CRediT authorship contribution statement

Guangji Fang: Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Xiao Sun:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Hua Zheng:** Writing – review & editing. **Peng Zhu:** Writing – review & editing. **Wenbin Wu:** Supervision. **Peng Yang:** Funding acquisition. **Huajun Tang:** Resources.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2024.103420.

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