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EDITED BY
Fuyou Guo,
Qufu Normal University, China

REVIEWED BY
Q Yuan,
Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences (CAS), China
Chunlin Li,
Institute of Applied Ecology (CAS), China
Jinping Zhang,
Hainan Normal University, China

*CORRESPONDENCE
Rongqing Han
✉ hanrongqing@sdnu.edu.cn

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Grain supply–demand in countries along the "Belt and Road" from 1993 to 2021: spatiotemporal evolution, match, security and driving mechanism

Weijuan Qu[1], Xiantao Tang[1], Xufang Zhang[2], Guohao Li[1], Jiahui Zhang[1], Xiaotong Song[1], Minghua Zhao[1] and Rongqing Han[1]*

[1]College of Geography and Environment, Shandong Normal University, Jinan, China, [2]Institute of Geographic Sciences and Resources, Chinese Academy of Sciences, Beijing, China

Introduction: The grain supply-demand balance is a long-standing concern for many countries and is essential to guaranteeing social stability, maintaining economic development and ensuring national grain security.

Methods: Based on the data of 65 countries along the "Belt and Road" (B&R) from 1993 to 2021, this paper analyzed the spatiotemporal evolution, the matching relationship, regional grain security situation and driving factors of grain supply-demand by measuring and classifying the grain self-sufficiency rate using methods such as geostatistical analysis and the GTWR model.

Results: The results indicated the following: (1) The B&R region was still at the primary stage of "food-based and feed-supplemented". Grain supply and demand in the B&R region showed a steady upward trend, with grain yield contributing more to grain supply than sown area. (2) Overall, the B&R region has been largely self-sufficient since 2007, with grain supply meeting demand, but the level of grain self-sufficiency varied considerably between countries. (3) More than 58% of the countries were in grain insecurity, concentrated in West Asia-Middle East and South-East Asia. The gravity center of both grain supply and demand was near East Asia. (4) In terms of matching supply-demand, most countries fell into the category of high supply-high demand and low supply-low demand, with basically the same level of grain supply and demand. (5) Grain yield had the largest positive impact on grain supply-demand, GDP had the largest negative impact, and temperature change and precipitation change had a relatively small effect. The effects of fertilizer use, grain yield, and GDP on grain supply-demand fluctuated greatly over time.

Discussion: These findings can provide a scientific basis for the country to formulate policies for a sustainable grain supply-demand system.

KEYWORDS

grain supply-demand, grain security, grain production and consumption, driving factors, the "Belt and Road"

1 Introduction

The United Nations 2030 Agenda for Sustainable Development Goals (SDGs), as a comprehensive global agenda (Sharma et al., 2024), emphasizes the eradication of hunger, the improvement of nutrition and the promotion of sustainable agriculture to achieve grain security (Opoku et al., 2024; Vishnoi and Goel, 2024). Grain security has four pillars including accessibility, availability, stability and utilization (Sumsion et al., 2023), mainly reflected in production, consumption, reserves and trade (Jiang et al., 2017). The grain supply-demand and their dynamic changes are mainly manifested in the changes in grain production and consumption (David et al., 2011; Jia and Zhen, 2021; Tian et al., 2016). A balanced and stable grain supply-demand is an important basis for grain security, effectively guaranteeing people's basic survival needs and promoting the sustainable development of grain system. Therefore, when there is a large grain supply-demand gap and self-sufficiency cannot be met, it is often described as grain insecurity (Hu et al., 2023). Currently, internal problems such as growing population, water and soil resource scarcity, soil pollution and uneven economic development (Cheng and Yin, 2024; Zhang et al., 2023), as well as external risks such as climate change, wars and conflicts, and major epidemics (Chowdhury et al., 2023; Farrell et al., 2020; Wang et al., 2024), pose a threat to future grain security (Jeníček, 2012; Zhou et al., 2022). These problems have led to unstable grain production, low production efficiency, and a gradual imbalance in the consumption structure (Lian et al., 2023; Nchanji and Lutomia, 2021), further resulting in an inability of grain supply to meet people's needs and a gradual grain supply-demand imbalance (FAO, 2021). Hence, exploring the spatiotemporal patterns of grain production and consumption, as well as the balance in grain supply-demand is crucial for ensuring regional grain security in the current context of sustainable development goals and the post-epidemic era.

To facilitate infrastructure development, strengthen regional economic cooperation, and promote sustainable regional development (Wang and Sarkar, 2022; Zhang et al., 2019), China proposed the "Belt and Road" Initiative (BRI) in 2013, which involves at least 65 countries with 62% of the world's population and 33% of the world's GDP (Wang et al., 2023; Zhang D. et al., 2022; Zhao L. et al., 2022). According to the Food and Agriculture Organization of the United Nations (FAO) database, the "Belt and Road" (B&R) region is globally important grain-producing and grain-consuming region, accounting for more than 40% of the world's grain production and consumption, which is critical to maintain the regional and global grain supply-demand balance (He et al., 2016; Wang et al., 2021). The B&R region has limited technical levels of grain production, inadequate infrastructure and low land use efficiency (Chen and Zhang, 2022). In some of these countries, grain supply is insufficient to meet the population's needs, highlighting an urgent need to strengthen international agricultural cooperation (Pyakuryal et al., 2010; Qinghua et al., 2023). However, grain production and consumption have been studied at different geographical scales, such as the provincial and municipal scales (Liu et al., 2023; Yu et al., 2024), the national scale (Ali et al., 2019; Gandhi and Zhou, 2014) and the global scale (Menconi et al., 2022). There are relatively few studies on the regional scale, especially on the differences in grain supply-demand in the B&R region. Therefore, this study was conducted at the regional and national levels to explore the relationship between grain supply-demand and grain security in the B&R region. It is helpful to grasp the situation of grain production and consumption in the B&R region, eliminate regional poverty, ensure grain security, and provide scientific reference for the grain trade cooperation of countries along the B&R region (Chen et al., 2018; Wang and Sarkar, 2022).

Numerous studies on the production and consumption of grains already exist. Nonetheless, the majority of current research frequently only explore grain production or consumption separately. Studies on grain production mainly centered on grain production efficiency (Lin et al., 2022; Lu et al., 2024), dynamic evolution characteristics of grain production (Zhang et al., 2023) and vulnerability of grain production systems (Yao et al., 2019). More studies have paid attention to the impacts of urbanization development (Gao et al., 2019) and climate change (Lolaso et al., 2024) on grain production. Research on grain consumption mostly focused on structure (Gandhi and Zhou, 2014) and pattern changes of grain consumption (Qin et al., 2023), as well as the prediction of future grain consumption trends (Zhang X. et al., 2022). These studies analyzed grain production and consumption from different perspectives. However, fewer studies integrate grain production and consumption to match grain supply-demand, and related studies are mainly concerned with exploring the dynamic evolution and spatiotemporal mechanisms of grain supply-demand in different regions (Hu et al., 2023; Schultze et al., 2024). Consequently, this paper incorporated grain supply and demand into a framework to analyze the spatiotemporal evolution of the type and matching relationship between grain supply and demand in the B&R region.

Grain supply-demand reflects the production capacity and consumption demand for grain in a country or region over a specific period (Fei et al., 2023). Grasping the characteristics of a region's grain supply-demand relationship is conducive to optimizing regional resource allocation and adjusting the structure of grain industry. The study of the grain supply-demand level in different regions requires an appropriate calculation criterion for a more in-depth evaluation, which is profit for a more comprehensive understanding of the situation of grain production and consumption in a region as well as conducting comparative analyses within the region. The calculation of grain self-sufficiency rate can effectively integrate grain production and consumption to explore grain supply-demand relationship (Liang et al., 2023; Liu et al., 2023), making it possible to study grain supply-demand under the same framework. This is instrumental in the coordinated management of grain supply-demand at the regional level and is suitable as a calculation standard for evaluating grain supply-demand level in different regions. In addition, the grain supply-demand relationship is affected by a variety of factors, such as sowing area (Feng et al., 2016), climate change (Mitchell et al., 2017; Schultze et al., 2024), and water resource carrying capacity (Khan et al., 2009; Zhao Y. et al., 2022). Only by comprehensively considering these factors can we have an overall perception of regional grain supply, demand and security. Hence, this paper discussed the spatiotemporal heterogeneity of factors affecting grain supply-demand in the B&R region from the perspectives of nature, economy and society. In summary, through a comprehensive study of the spatiotemporal evolution of regional grain supply-demand, the matching relationship, and the factors influencing them, the sustainability and stability of the regional grain system can be accurately assessed, which can provide a basis

TABLE 1 Regional division in the B&R region and country abbreviations.

Region/country number	Country
Southeast Asia (SEA)/11	Brunei Darussalam (BRN), Indonesia (IDN), Cambodia (KHM), Laos (LAO), Myanmar (MMR), Malaysia (MYS), Philippines (PHL), Singapore (SGP), Thailand (THA), Timor-Leste (TLS), Vietnam (VNM)
East Asia (EA)/2	China (CHN), Mongolia (MNG)
West Asia-Middle East (WAME)/19	United Arab Emirates (ARE), Bahrain (BHR), Egypt (EGY), Iran (IRN), Iraq (IRQ), Israel (ISR), Jordan (JOR), Kuwait (KWT), Lebanon (LBN), Oman (OMN), Palestine (PSE), Qatar (QAT), Saudi Arabia (SAU), Syria (SYR), Türkiye (TUR), Yemen (YEM), Armenia (ARM), Azerbaijan (AZE), Georgia (GEO)
South Asia (SA)/8	Afghanistan (AFG), Bangladesh (BGD), Bhutan (BTN), India (IND), Sri Lanka (LKA), Maldives (MDV), Nepal (NPL), Pakistan (PAK)
Central Asia (CA)/5	Kazakhstan (KAZ), Kyrgyzstan (KGZ), Tajikistan (TJK), Turkmenistan (TKM), Uzbekistan (UZB)
Central Eastern Europe (CEE)/20	Russian Federation (RUS), Albania (ALB), Bulgaria (BGR), Bosnia Herzegovina (BIH), Czech Republic (CZE), Estonia (EST), Croatia (HRV), Hungary (HUN), Lithuania (LTU), Latvia (LVA), Macedonia (MKD), Montenegro (MNE), Poland (POL), Romania (ROU), Serbia (SRB), Slovakia (SVK), Slovenian (SVN), Moldova (MDA), Ukraine (UKR), Belarus (BLR)

for decision-making to ensure a balanced grain supply-demand relationship for grain in the B&R region.

Based on this, this study adopted the production and consumption data of grain crops in the B&R region from 1993 to 2021 to depict the spatiotemporal evolution of grain production and consumption from both time and space dimensions, using time series analysis, geostatistical analysis and other methods. Moreover, the grain supply-demand relationship and the state of grain security were further explored from a grain security perspective by calculating the grain self-sufficiency rate. Finally, using the GTWR regression model, a multi-factor system was constructed to quantitatively analyze the spatial heterogeneity of the factors influencing grain supply-demand from natural, economic and social perspectives. This study intended to construct a sustainable grain supply-demand evaluation system, promote optimal allocation of agricultural resources in the B&R region, and provide theoretical support for promoting the balance of regional grain supply-demand and guaranteeing grain security.

2 Study area, data and methodology

2.1 Study area

The "Belt and Road" is a concept and initiative for cooperative development, an open platform for regional economic cooperation with no precise spatial scope. For convenience of study, the scope was divided into seven regions (Table 1; Figure 1a), a total of 65 countries, drawing on the results of the related research (Du et al., 2022; Li et al., 2021; Zhang et al., 2019). The study area spans Asia, Europe, and Africa. It covers several climatic zones, ranging from the tropical climate of Southeast Asia to the subtropical temperate climate of East Asia, to the arid continental climate of Central Asia to the humid continental climate of Central Eastern Europe (Wu et al., 2018; Zhang D. et al., 2021). Land cover types are complex and diverse, including cultivated land, grassland, forest and barren land (Figure 1b). The variability of land cover and climatic, hydrothermal conditions between different regions has led to significant regional differences in grain production. In terms of population distribution, the region is more populous, accounting for 62% of the world's population (Wang et al., 2023), but the distribution is highly uneven, with densely populated East, South and Southeast Asia having a high demand for grain and a complex consumption structure, whereas Central Asia and some Central Eastern Europe countries have lower population densities and a relatively low demand for grain.

2.2 Data sources and processing

2.2.1 Data sources and concept definition

Grain generally refers to cereals, and the concept is defined in a broader and narrower sense. Based on the availability of long-time series data for the B&R region, this paper adopted the concept of cereals as defined by the FAO, which included eight grain crops: barley, maize, millet, rice, rye, oats, wheat, and sorghum (FAO, 2001).

Data on grain production and consumption, population, and sown area of different grain crops in the B&R region are derived from the FAO database (http://www.fao.org/faostat/). The data of the database has global coverage and high spatiotemporal resolution, which ensures wide comparability and accuracy of the data. The sources of data for the driver analyses such as GDP and PGDP for economic factors, and precipitation and temperature change data for natural factors and other impact factor data are shown in Table 2. In particular, grain production and consumption data were selected for the period 1993–2021. When exploring the factors affecting grain supply-demand, the years selected for the independent variables were 1993, 1995, 1997, 2003, 2009, 2010, 2014, and 2021.

2.2.2 Data processing

Since the Soviet Union was dissolved in 1991 and Czechoslovakia in 1993, and data are available for most countries along the B&R after 1993, 1993 was chosen as the start of this study. Some countries and regions such as Bahrain, Brunei and Singapore do not have relevant data in the FAO Food Production and Consumption Yearbook and are not discussed in the text. To guarantee the accuracy of the data, linear interpolation was

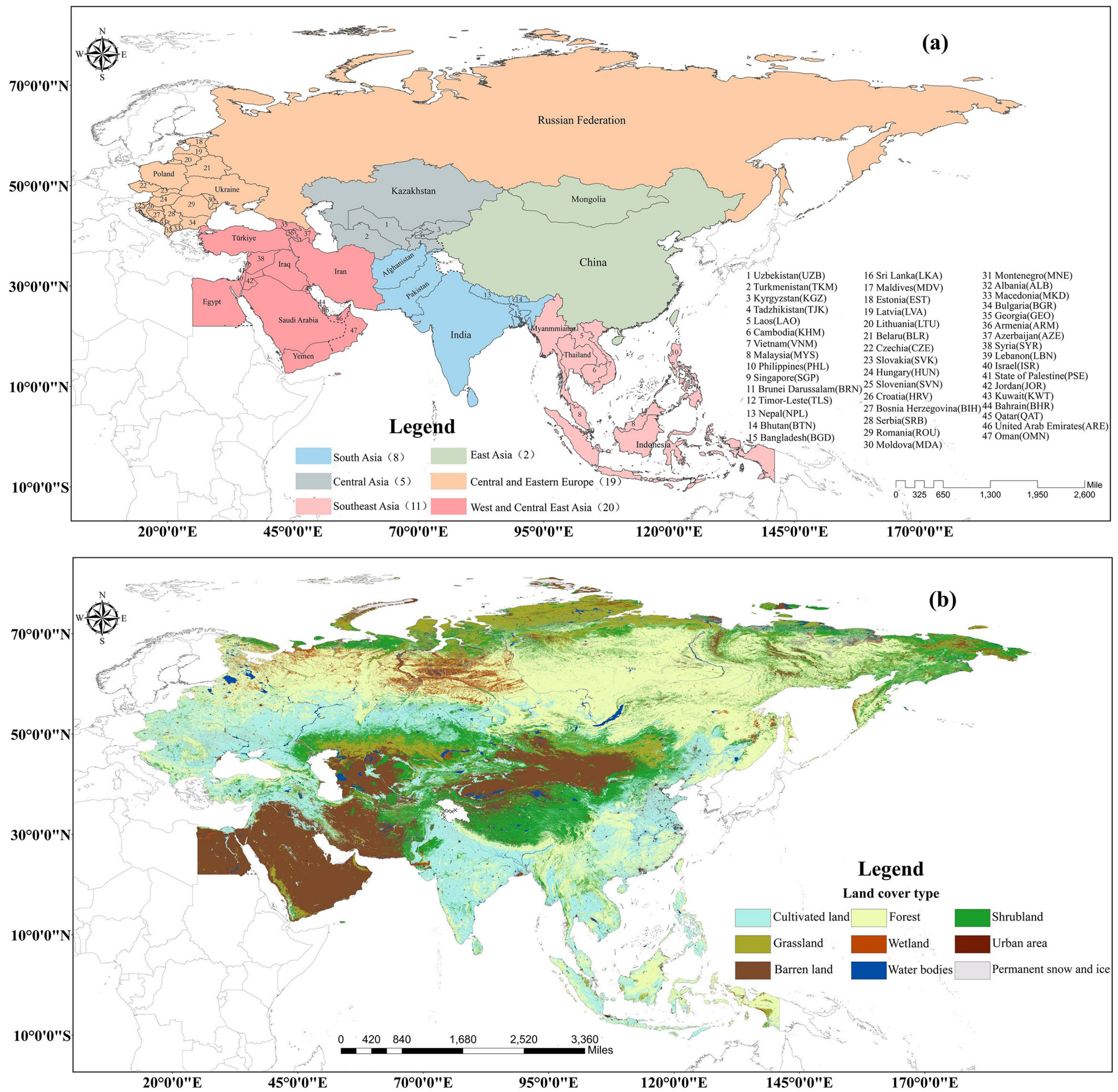

FIGURE 1
The study area **(a)** and land cover profile **(b)**.

used to deal with outliers in the production and consumption data. Missing data for individual years for Saudi Arabia, Thailand, Yemen, Bhutan, Syria, Iraq and Timor-Leste were filled in using interpolation of neighboring year values. Data for China exclude Hong Kong, Macao and Taiwan.

2.3 Research methodology

2.3.1 Grain self-sufficiency rate

Grain self-sufficiency rate is one of the critical indicators of grain security, and this paper focuses on the calculation of grain self-sufficiency to measure the grain supply-demand relationship (Liu et al., 2023). The formula for the grain self-sufficiency rate is as follows:

$$SSR = \frac{FS}{FD} \tag{1}$$

SSR stands for grain self-sufficiency rate. *FS* denotes grain supply and *FD* represents grain demand. When the grain self-sufficiency rate is >1, it indicates that the grain supply exceeds the demand, which is a grain surplus; while when the grain self-sufficiency rate is <1, the grain supply is insufficient to meet the demand, which is a grain deficit. To further refine the degree of surplus and deficit, we relied on the trend of grain self-sufficiency

TABLE 2 Impact factor data sources and classifications.

Influence factors	Methods of measurement	Data source website
X1: GDP	Total annual GDP	https://data.worldbank.org.cn/
X2: PGDP	Total GDP/total population	https://data.worldbank.org.cn/
X3: Fertilizer use	Total annual emissions of fertilizer	http://www.fao.org/faostat/
X4: Sown area	Total sown area	http://www.fao.org/faostat/
X5: Urbanization	Urban population/total population	http://www.fao.org/faostat/
X6: Grain yield	Total grain production/area sown	http://www.fao.org/faostat/
X7: Temperature change	Difference in mean annual temperature between neighboring years	https://crudata.uea.ac.uk/cru/data/hrg/cruts_4.07/crucy.2304181636.v4.07/countries/tmp/
X8: Precipitation change	Difference in annual precipitation between neighboring years	https://crudata.uea.ac.uk/cru/data/hrg/cruts_4.07/crucy.2304181636.v4.07/countries/pre/
X9: Water resource	Water reserves/total population	https://data.apps.fao.org/aquastat/

rate in the study area in each year, and found that when the self-sufficiency rate was around 0.5 and 1.5, the change of deficit and surplus grain showed a significant difference. Therefore, we selected 0.5 and 1.5 as the cut-off points to further categorize grain deficit and surplus in order to more accurately depict different degrees of grain supply and demand. The final classification results were obtained as follows: high surplus (>1.5), low surplus (1–1.5), low deficit (0.5–1), and high deficit (0–0.5).

2.3.2 Classification of grain supply-demand

To compare the dynamic changes of grain supply-demand in the B&R region, eight nodes of the study period were selected according to the changes in the difference between supply and demand, and the *Z*-score normalization method was used to obtain the normalized results of grain supply and demand. The standardized values of grain supply-demand include positive and negative, with positive values indicating changes above the mean and negative values indicating changes below the mean. Finally, it is divided into four types: high supply-high demand, high supply-low demand, low supply-high demand, and low supply-low demand.

2.3.3 Determination of grain security situation

There are three types of grain insecurity: Grain insecurity occurs when there is a state of grain deficit, including both increasing and decreasing trends of grain deficit. It occurs when grain supply-demand changes from surplus to deficit.

There are three types of grain security. Grain security is considered when there is a state of grain surplus, which includes both increasing and decreasing trends of surplus. Another type that is classified as grain security occurs when the grain supply-demand balance shifts from deficit to surplus.

2.3.4 Gravity center model

The gravity center model is a geographical analysis technique used to determine the gravity center location of a region or object (Wang et al., 2022a; Meng et al., 2021). It helps to analyze the course, state and trend, as well as reflecting the spatial mobility of the regional elements (Truelove, 1993). This paper determined the spatial gravity center coordinates and shift distance utilizing the gravity center model to reveal the spatial changes in grain production and consumption. The formulas are as follows:

$$\bar{X}_i = \frac{\sum_{i=1}^{n} P_i X_i}{\sum_{i=1}^{n} P_i}, \bar{Y}_i = \frac{\sum_{i=1}^{n} P_i Y_i}{\sum_{i=1}^{n} P_i} \quad (2)$$

$$d_i = k \times \sqrt{(\bar{X}_j - \bar{X}_i)^2 + (\bar{Y}_j - \bar{Y}_i)^2} \quad (3)$$

Where $(\bar{X}_i, \bar{Y}_i)$ are the coordinates of the gravity center, P_i is the grain production or consumption data for country i, X_i is the horizontal coordinate of the centroid of country i, and Y_i is the vertical coordinate of the centroid of country i. d_i is the shift distance of the gravity center of country i.

2.3.5 Standard deviation ellipse

The standard deviation ellipse is a method commonly used in spatial statistics and geographic information systems (GIS) to represent the distribution range and concentration of spatial data points (Lefever, 1926; Zhao Z. et al., 2023). Where the larger the spatial scale of the standard deviation ellipse, the more dispersed the spatial distribution of the data. In this paper, the standard deviation ellipse was used to portray the overall dynamic evolutionary trend and spatial concentration of grain production and consumption (Yang et al., 2022). The formulas for the azimuthal angle α, x-axis standard deviation σ_x and y-axis standard deviation σ_y of the standard deviation ellipse are shown, respectively:

$$tan\alpha = \frac{\left(\sum_{i=1}^{n} w_i^2 \tilde{x}^2 - \sum_{i=1}^{n} w_i^2 \tilde{y}^2\right) + \sqrt{\left(\sum_{i=1}^{n} w_i^2 \tilde{x}^2 - \sum_{i=1}^{n} w_i^2 \tilde{y}^2\right)^2 + 4\sum_{i=1}^{n} w_i^2 \tilde{x}_i^2 \tilde{y}_i^2}}{2\sum_{i=1}^{n} w_i^2 \tilde{x}_i \tilde{y}_i} \quad (4)$$

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n} (w_i \tilde{x}_i \cos\alpha - w_i \tilde{y}_i \sin\alpha)^2}{\sum_{i=1}^{n} w_i^2}} \quad (5)$$

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^{n} (w_i \tilde{x}_i \sin\alpha - w_i \tilde{y}_i \cos\alpha)^2}{\sum_{i=1}^{n} w_i^2}} \quad (6)$$

Where $(x_i, \; y_i)$ denotes the spatial location of the study object. w_i denotes the corresponding weight. $(\tilde{x}_i, \; \tilde{y}_i)$ denotes the coordinate deviation from the location of each study object to the gravity center (X_i, Y_i).

2.3.6 Building a system of driver indicators

In order to measure the factors affecting grain supply-demand, this paper took the ratio of grain supply and demand as the dependent variable. Referring to related studies and the availability of indicators (Awad, 2023; Carr et al., 2024; Feng et al., 2016; Gao et al., 2019; He et al., 2022; Schneider et al., 2011; Zhao Y. et al., 2022), 11 indicators (Grain yield, Sown area, GDP, PGDP, Fertilizer use, Population, Agricultural added value, Urbanization, Water resource, Temperature change and precipitation change) were initially identified as independent variables. Some indicators (such as Population, GDP, and PGDP) have a direct impact on grain demand, but indirectly affect grain supply by changing market demand and price mechanisms. On the contrary, grain yield, sown area, fertilizer use, water resource and other indicators directly affect grain supply, while indirectly affecting grain demand through changes in production.

The reasons for selecting different indicators are as follows. Grain yield and sown area are the most basic factors affecting grain supply (Feng et al., 2016), which directly determine grain production capacity and indirectly affect demand through market mechanisms. Therefore, the selection of these two indicators is conducive to a more comprehensive analysis of the relationship between grain supply and demand. Economic development is one of the crucial factors affecting grain supply-demand (Awad, 2023), and GDP and PGDP were used to test the differences in the impact of different economic levels on grain supply-demand. The fertilizer use can promote grain production. Still, overuse may cause soil pollution, leading to problems such as soil quality degradation (He et al., 2022). Therefore, the fertilizer use can affect grain supply-demand by affecting grain supply. Population is a direct factor affecting grain demand, and as population increases, grain demand also increases (Schneider et al., 2011). Agricultural added value often implies an increase in agricultural productivity, which in turn increases grain production and affects the level of grain supply to further meet grain demand. The development of urbanization is accompanied by a reduction in the rural population and a reduction in the area of arable land, which in turn affects grain supply and demand (Gao et al., 2019). Changes in temperature and precipitation affect the hydrothermal conditions for grain production, and under the right hydrothermal conditions, the efficiency of grain production increases (Carr et al., 2024), making the grain supply stable. Therefore, these two indicators of climatic factors were selected to study the extent of their impact on grain supply-demand. Water resource determine the efficiency of irrigated agriculture, which in turn affects grain supply and demand by influencing grain production (Zhao Y. et al., 2022). Next, the indicator covariance test was conducted, and two indicators (Population and Agricultural added value) that did not pass the covariance test were eliminated. Finally, nine indexes were obtained as independent variables to measure grain supply and demand (Table 2).

2.3.7 Spatiotemporal geographically weighted regression models

Traditional geographically weighted regression (GWR) models have limitations in their application to specific situations, mainly due to the limited sample size of cross-sectional data (He and Yang, 2023; Wang et al., 2022b). To solve this problem, Huang et al. (2010) introduced the time dimension in the GWR model and constructed the GTWR model to more comprehensively consider the combined effects of spatiotemporal factors.

The GTWR model is based on the weighted regression of the neighboring sample points of each observation, and the spatial weight matrix is applied to the linear regression model to solve the spatial non-stationarity problem more effectively (Zhao M. et al., 2023). The model is commonly used for exploring geographical processes and analyzing the spatial distribution of geographical phenomena (Wang Y. et al., 2022). In this paper, the GTWR model was used to explore the factors influencing grain supply-demand. The dependent variable selected by the GTWR model is the ratio of grain supply and grain demand, and the independent variable is the nine indicators in Table 2. Its calculation formula is as follows:

$$y_i = \beta_0(\mu_i, v_i, t_i) + \sum_{k=1}^{p} \beta_k(\mu_i, v_i, t_i)x_{ik} + \varepsilon_i \tag{7}$$

Where y_i is the observed value, (μ_i, v_i) is the latitude and longitude coordinates of the ith sample point. (μ_i, v_i, t_i) is the spatiotemporal coordinates of the ith sample point. $\beta_k(\mu_i, v_i, t_i)$ is the regression constant of the ith point. $\beta_0(\mu_i, v_i, t_i)$ is the kth regression parameter of the ith point. x_{ik} is the value of the independent variable x_k at the ith point. ε_i is the residual term of the corresponding sample point.

3 Results

3.1 Temporal evolution of grain supply and demand

3.1.1 Temporal evolution of grain supply

Overall, total grain production and yield in the B&R region have shown a significant upward trend mainly due to advances in grain cultivation technology (Figure 2a). The inter-annual growth rate of 2.08% for grain yield and 2.13% for total grain yield was generally consistent. The sown area of grain showed a slow upward trend in fluctuation, with an inter-annual growth rate of 0.071% (Figure 2b), suggesting that the increase in grain production had come mainly from the rise in yield brought about by scientific and technological progress and other factors.

The total grain production and sown area accounted for more than 50% of the global share from 1993 to 2021 (Figure 2c), suggesting that grain cultivation in the B&R region played an important role in balancing grain supply-demand relations globally. However, the two had different trends, with the proportion of sown area to the world showing a fluctuating downward trend, with an average annual rate of decline of 0.31%, and the proportion of total grain production to the world showing a fluctuating upward trend, with an average annual growth rate of 0.06%. It showed that grain production in the B&R region has an increasing impact on the global grain supply market.

3.1.2 Temporal evolution of grain demand

The grain demand structure in the B&R region presented a characteristic of "food-based and feed-supplemented" (Figure 2d). Of these, the share of food and other uses was about 85%, with

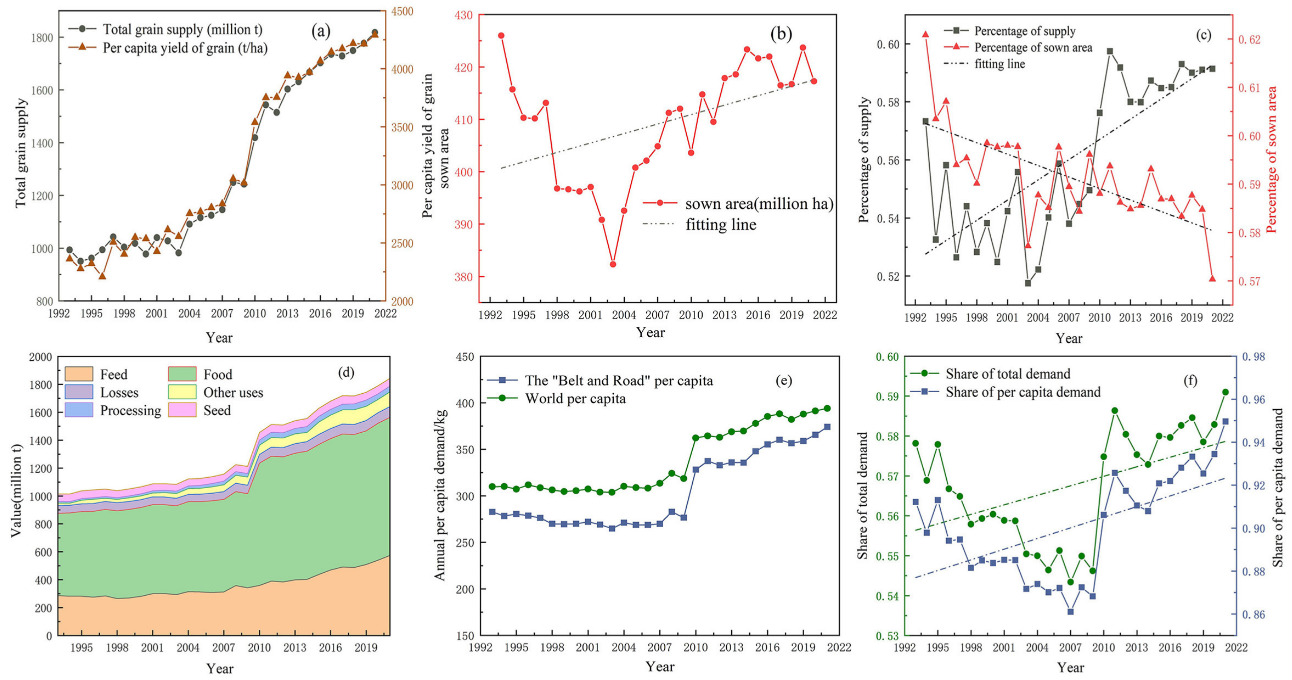

FIGURE 2
Trends in total grain production, grain yield **(a)**, sown area **(b)**, and total grain production and sown area as a proportion of global ratio in the B&R region **(c)**. Share of different grain demand **(d)**, change in per capita grain demand in the world and countries along the B&R **(e)** and share of grain demand in the global ratio **(f)**.

<15% for industrial food, feed, seed and losses. Since 1993–2021, the different modes of consumption have all shown an upward trend in fluctuations, only to varying degrees, with seed being the mode of consumption with the smallest increase at 0.03%. The consumption mode with the most significant increase was other uses, at 4.96%, also illustrating the increasing diversity of grain consumption patterns in the region.

Per capita grain consumption has been consistently lower than global per capita grain consumption since 1993–2021 (Figure 2e), because most of the B&R region are either developing or underdeveloped countries with low grain consumption level. Both per capita grain consumption in the B&R region and globally have shown a slight upward trend, and the overall magnitude of change has been broadly similar in both cases. However, the growth rate varies, with the average annual growth rate of the B&R region being 0.94%. Comparatively, global per capita consumption grew at a slightly slower rate of 0.82% per annum, reflecting a gradual narrowing gap of the per capita consumption levels between the countries along the B&R and the global. In stages, per capita grain consumption in the B&R region showed a steady downward trend from 1993 to 2009, with an average annual rate of decline of 0.15%. The fastest growth rate was recorded in 2009–2010, from 328.2 kg/person to 337.3 kg/person, an increase of 2.7%, and the period 2011–2021 showed a slight upward trend of 0.77%.

Per capita consumption as a share of global increased slightly in fluctuations between 0.86 and 0.96, with an average annual increase of 0.13% (Figure 2f). Of these, per capita consumption accounted for the smallest global share, 86.1%, in 2007 and the largest share, 94.9%, in 2021. The proportion of grain consumption in the B&R region to the world is between 0.5 and 0.6, showing a slow upward trend with fluctuations, with an average annual increase of 0.07%. The proportion of grain consumption in the B&R region to global accounted for more than 54%, with the smallest share of 54.3% in 2007 and the largest share of 59.1% in 2021. This indicated that per capita grain consumption in the B&R region was still relatively low, not reaching the global average. On the other hand, the overall grain consumption in this region accounts for a relatively high proportion of the world's total, and changes in grain demand will have a significant impact on global grain demand.

3.2 Spatial evolution of grain supply and demand

According to the stage of the temporal dynamics of the grain supply and demand gap, the point of time at which the change in the grain supply and demand gap reaches its maximum or minimum value over a period of time is selected as the turning point. Such time nodes selected are representative and can reflect the internal detailed changes in the grain supply and demand gap, which is conducive to combining and exploring the subsequent temporal and spatial evolution and analysis of influencing factors. Finally, eight nodes, 1993, 1995, 1997, 2003, 2009, 2010, 2014, and 2021 were selected for analysis (Figure 3).

3.2.1 Evolution of spatial gravity centers of grain supply and demand

Figure 4 illustrated the spatial concentration of grain supply-demand and changes in the spatial gravity center. Table 3

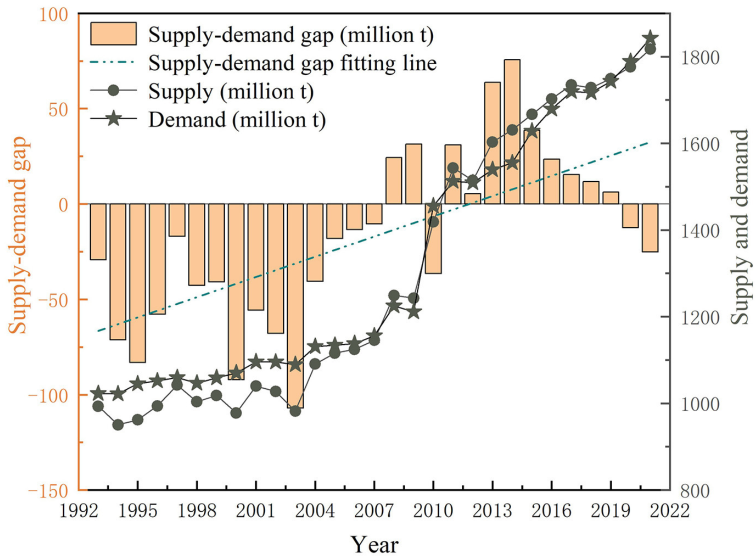

FIGURE 3
Overall trends in grain supply-demand gaps in the B&R region.

demonstrated the spatial scale size, movement distance and gravity center of coordinates of grain supply-demand. Overall, the contraction of spatial gravity center of grain demand was more pronounced and the spatial distribution was more concentrated than that of grain supply.

The long axis of standard deviation ellipse of grain supply had a greater degree of expansion and contraction, indicating that the main pulling force for grain supply is in the east-west direction (Figure 4a). The spatial gravity center of grain supply was mainly concentrated in East Asia, with the direction of movement showing southeast followed by northwest. The overall spatial scale of standard deviation ellipse showed a slight contraction, with a more concentrated spatial distribution and an average annual contraction of 1.69%.

The long axis of standard deviation ellipse of grain demand had also a greater degree of expansion and contraction, indicating that the main pulling force for grain demand was in the east-west direction (Figure 4b). The spatial gravity center of grain demand was mainly concentrated in East Asia, with the direction of movement showing southeast followed by northeast. The spatial scale variation of standard deviation ellipse showed a more substantial contraction and a more concentrated spatial distribution, with an average annual contraction of 3.04%.

3.2.2 Classification of grain supply-demand

Most of the grain supply-demand types in the B&R region have been low supply-low demand and high supply-high demand, with a relatively small proportion of low supply-high demand and high supply-low demand countries (Figures 5a–h). In this case, countries near the line (supply = demand) had supply and demand at roughly the same level, whether high or low.

The number of countries with low supply-low demand was the largest, showing an overall decreasing trend of large decreases followed by small increases (Figure 5i), decreasing from 37 countries in 1993 to 23 countries in 2003 and then to 28 countries in 2021. The number of countries with high supply-high demand was also high, showing an overall leveling trend with a significant increase followed by a significant decrease, from 17 in 1993 to 26 in 2003, and back to 17 countries by 2021. On the contrary, the number of countries with high supply-low demand was the smallest, with only a few countries falling into the category in some years, such as Thailand and Kazakhstan, and, in particular, no country fell into the category in 1993. The number of countries with low supply-high demand was also relatively small, showing an overall increasing trend of large increases followed by small decreases, from 6 in 1993 to 18 in 2014 and 11 in 2021. It can be seen that, on the one hand, the supply-demand of most countries along the B&R were basically the same, that is, high supply areas were also high demand areas. On the other hand, the overall grain demand of the region was high.

Regarding regional differences in grain supply-demand, countries in the high supply-high demand category were mainly located in Central Eastern Europe, such as Hungary, Romania, Belarus and Serbia. Countries in the low supply-low demand category are concentrated in West Asia-Middle East, such as Kuwait, Oman and Yemen. Countries belonging to the low supply-high demand category were fewer in number and included countries such as Israel, Saudi Arabia and Slovenia. Countries in the high supply-low demand category were in countries such as Kazakhstan, Turkmenistan, Thailand and Malaysia.

3.3 Grain supply-demand match in spatiotemporal evolution and grain security

3.3.1 Grain supply-demand match in spatiotemporal evolution

Both supply-demand for grain in the B&R region were on an upward trend (Figure 3), with grain demand outstripping supply

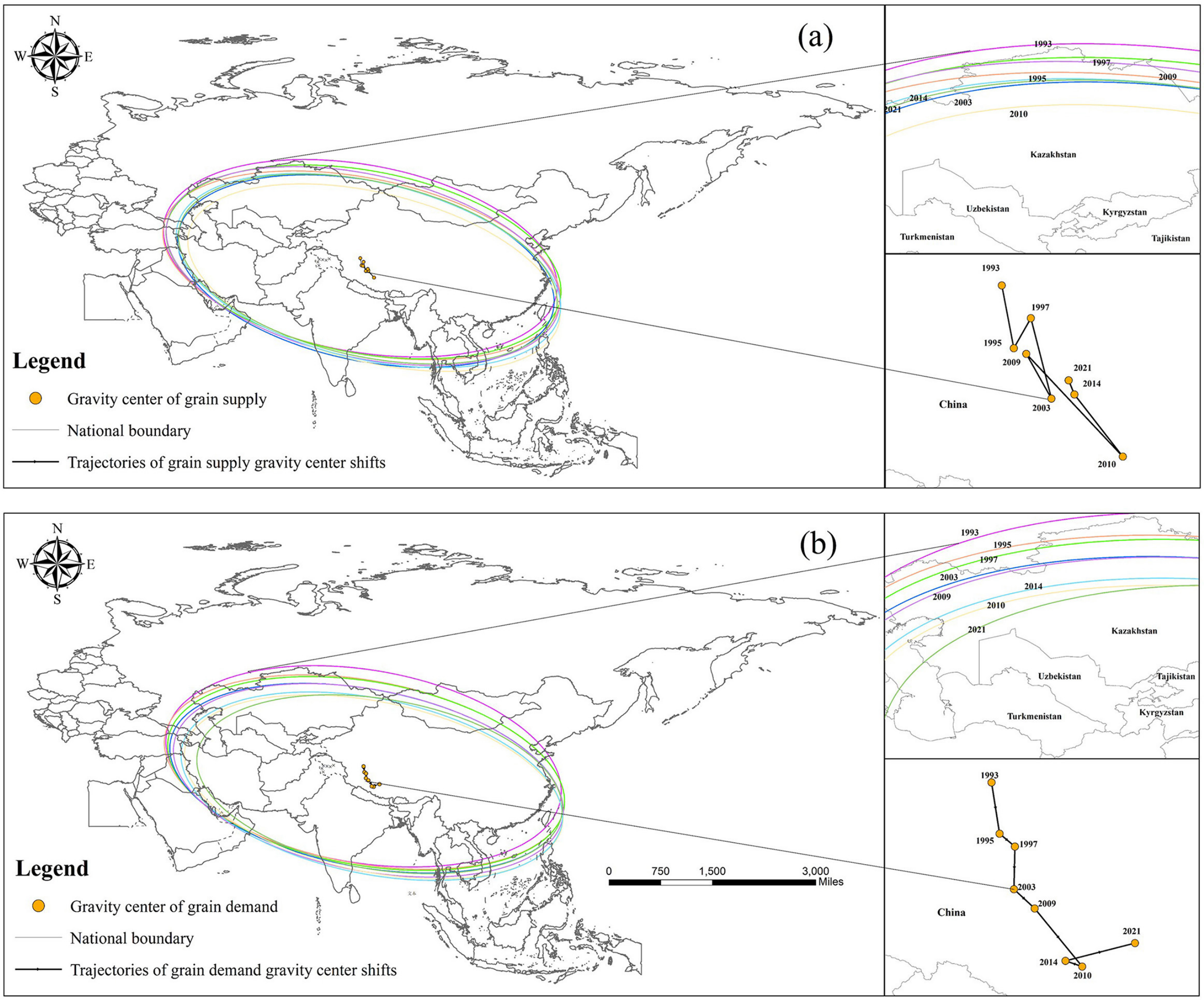

FIGURE 4
The trajectory of the gravity center in space (**a**: grain supply, **b**: grain demand).

and the supply-demand gap being <0 before 2007, and then grain supply outstripping demand after 2008, except in 2010, 2020 and 2021. Overall, although there were more years in which demand exceeded supply in the B&R region, the gap between supply and demand showed an upward trend, and the gap gradually became positive, with grain supply gradually being able to meet demand.

By calculating the ratio of grain supply to demand, the resulting values are graded and finally the changes in the number of countries with different levels of grain deficit and surplus are obtained (Figures 6a–h). Overall, the number of grain-surplus countries showed a relatively large increase of 23.5%, from only 17 in 1993 to 21 in 2021, with the largest number of grain-surplus countries, 26, in 2009. On the contrary, there is a smaller decline in the number of grain-deficit countries, by 9.3%, from 43 in 1993 to 39 in 2021, with the largest share of grain-deficit type countries, 75%, in 2003, where the gap between supply-demand is at its maximum, which is in line with the changes in Figure 3. From the perspective of spatial distribution, from 1993 to 1995, there were more grain-deficit countries in the northern part of the region than in the southern. After 1995, this gradually shifted, with more grain-surplus countries in the northern part compared to the southern part.

There was also a significant difference in the levels of grain deficit and surplus, with both low-surplus and high-deficit countries showing a decreasing trend, while in contrast, both high-surplus and low-deficit countries show an increasing trend. First, the number of high-deficit countries declined from 26 to 20. Of these, the maximum was reached in 1997, with 30 countries falling into this category, representing 50% of the B&R region. High-deficit countries, affected by arid climates, were concentrated in West Asia-Middle East, with Oman being the most grain deficit country in the region, with a low grain self-sufficiency rate (Figure 6i). Second, the number of low-deficit countries rises from 17 to 19, with little overall change. It reached its maximum in 2021, with 19 countries, representing 31.67% of the B&R region. This type of country was mainly concentrated in the West Asia-Middle East and

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TABLE 3 Changes in the spatial gravity center of and scale of grain supply/demand.

Year	Grain supply			Grain demand		
	Gravity center coordinate	Spatial scale size	Movement distance	Gravity center coordinate	Spatial scale size	Movement distance
1993	(82°53′59″,34°57′27″)	2,579.451		(82°41′44″,34°37′19″)	2,669.128	
1995	(83°10′2″, 33°27′58″)	2,441.759	3.348	(82°52′3″, 33°25′25″)	2,567.433	1.676
1997	(83°34′19″, 34°10′44″)	2,526.811	1.518	(83°14′33″, 33°7′27″)	2,552.273	1.213
2003	(84°4′44″, 32°16′14″)	2,377.496	0.819	(83°12′9″, 32°8′40″)	2,446.409	0.467
2009	(83°28′54″, 33°19′54″)	2,539.521	1.971	(83°41′23″, 31°41′41″)	2,481.236	0.996
2010	(85°45′28″, 30°53′34″)	2,226.452	1.218	(84°48′3″, 30°19′5″)	2,265.084	0.663
2014	(84°36′12″, 32°22′4″)	2,403.983	0.362	(84°25′36″, 30°27′13″)	2,350.993	1.756
2021	(84°28′13″, 32°42′14″)	2,334.855	1.872	(86°2′5″, 30°52′1″)	2,178.534	0.414

Southeast Asia near the equator, such as Indonesia and Singapore. Third, the number of high-surplus countries rose significantly from only 1 in 1993 to 12 in 2014, reaching a maximum of 20% of the B&R region. This increase in the countries with high-surplus was concentrated in Central Eastern Europe, such as Ukraine, Bulgaria, Romania and Serbia, with Bulgaria having the largest grain surplus and a high rate of grain self-sufficiency. Finally, low-surplus countries declined from 16 to 11. Of these, the largest number was reached in 2009, with 20 countries, representing 33.33% of the B&R region. Low-surplus countries were mainly concentrated in Southeast Asia and South Asia, with some other countries also falling into the category in some years, such as Russian Federation in 1997 and later, and some countries in Central Eastern Europe, such as Ukraine, Poland, Moldova and Romania.

3.3.2 Grain security in the context of grain supply-demand match

To judge regional grain security based on changes in grain supply-demand, we selected 2008 and divided the research period into two stages, with 1993–2008 as the first phase (Figure 7a) and 2008–2021 as the second phase (Figure 7b), to incorporate the previous characteristics of changes in grain supply-demand. Among them, 2008 was chosen because the difference between grain supply and demand started to be >0 after 2008 (Figure 3), which represented grain supply gradually meets grain demand.

According to the changes in the different types of countries in the two phases (Figures 7a, b), the overall grain security situation in the B&R region was not optimistic. In both stages, the number of countries experiencing an increase in grain shortages was the highest, mainly concentrated in West Asia-Middle East and near the equator in Southeast Asia. There were 24 countries in the first phase, decreasing to 22 in the second phase. The number of countries that shifted from a grain surplus to a deficit showed a relatively large increase, from one to five, with increases in countries such as China, Viet Nam and Nepal. In contrast, the number of countries changing from a grain deficit to a surplus showed a relatively large decline, from 8 to 3 countries, including Laos, Russian Federation and Pakistan. The number of countries with increased grain surplus increased from 12 to 15, with increases mainly in West Asia-Middle East, such as the Czech Republic, Poland and Estonia.

Taken together, it showed that countries along the B&R had lower levels of grain security, with the number of insecure countries being greater than the number of secure countries, and that the grain security situation varied considerably across countries and regions (Figure 7c). Thirty-five countries, or 58.3%, were consistently grain insecurity, the largest number of countries in this category. Some countries in Southeast Asia, such as Indonesia and the Philippines, as well as countries in West Asia-Middle East, were in a state of grain insecurity, and the grain security situation was not optimistic. Furthermore, 18 countries have always been under grain security, accounting for 30%. Some Central Eastern Europe countries such as Ukraine and Poland, some South Asian countries such as India and Pakistan, and the Russian Federation and Kazakhstan all belonged to this category, and the grain security situation was relatively optimistic. However, a few countries, such as China, Türkiye and Viet Nam, were transitioning from grain security to insecurity, where grain security was poor, with the smallest number of countries in this category at 8.3%. Only two countries, Serbia and Slovakia, were in a state of transition from grain insecurity to security, and the number of countries in this category is 3.3%, with an improved grain security situation.

3.4 Exploring the drivers of grain supply-demand

Ordinary least square (OLS), geographically weighted regression (GWR) and spatiotemporal geographically weighted regression models (GTWR) were used to quantify the extent of influence of different drivers on the grain supply-demand relationship under different points in time, respectively. The final

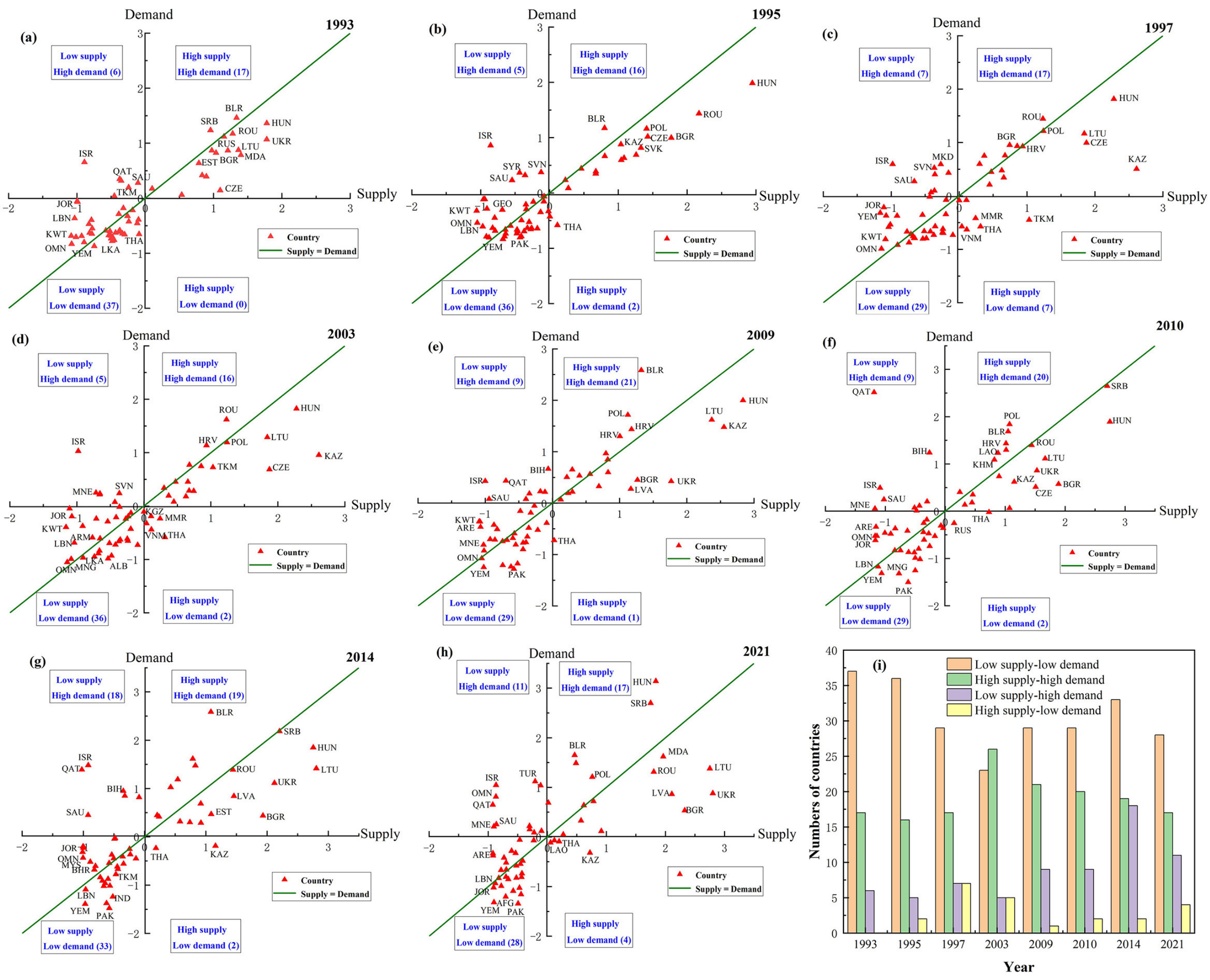

FIGURE 5
Changes in types of grain supply-demand during 1993–2021 **(a–h)** and statistics of types of supply-demand **(i)**, 1993–2021. In **(a–h)**, the horizontal axis represents the standardized results for grain supply, the vertical axis represents the standardized results for grain demand, the red dots represent different countries, and the green solid line represents the linear equation ($y = x$).

comparison showed that the GTWR model has an R^2 of 0.8272, a better fit than the OLS and GWR models (Table 4). Therefore, the GTWR model was chosen for regression analysis.

3.4.1 Volatility in the level of impact of grain supply-demand

The degree of influence of different indicators on grain supply and demand over time is characterized by two types of fluctuations: large fluctuations and relatively stable changes, respectively (Figure 8).

The influencing factors with greater fluctuation are: fertilizer use, grain yield and GDP. Specifically, the impact of fertilizer use on grain supply-demand has gradually turned from negative to positive, and the positive impact has gradually increased; the positive impact of grain yield on grain supply-demand has gradually weakened; and the negative impact of GDP on grain supply-demand has been gradually intensifying.

The influencing factors with relatively stable fluctuations are PGDP, precipitation change, temperature change, water resource, sown area, and urbanization. The effects of temperature and precipitation change on grain supply-demand are negligible, always close to zero; the effects of urbanization rate and water resource fluctuate between 0 and 1; and the positive effect of sown area is always close to 1, indicating that it has a strong and stable positive effect on grain supply-demand.

3.4.2 Spatiotemporal variability in the nature of the impact of grain supply-demand

Firstly, the factors that showed mainly negative impacts on grain supply-demand were GDP, PGDP, and urbanization, in descending order of influence degree. In particular, urbanization had a negative effect on grain supply and demand until 2009, when it gradually changed to a positive effect.

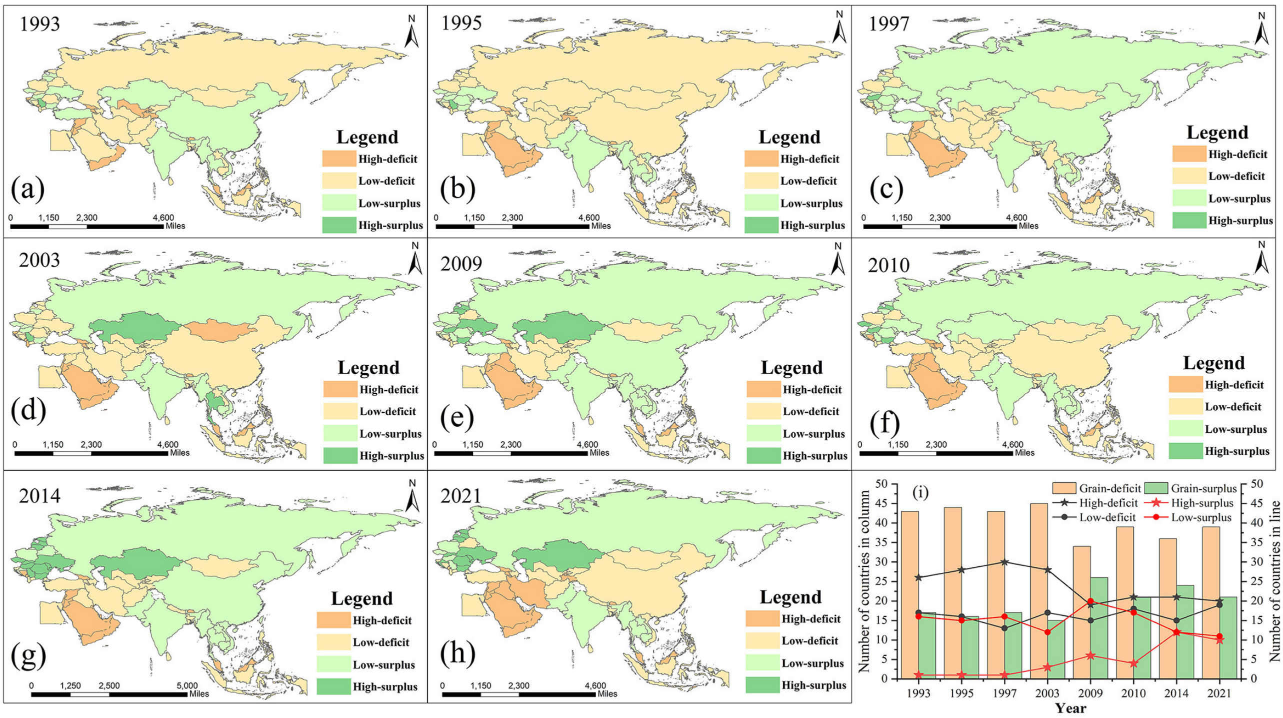

FIGURE 6
Changes in grain deficit and surplus in the B&R region (**a–h**: spatial evolution, **i**: temporal evolution).

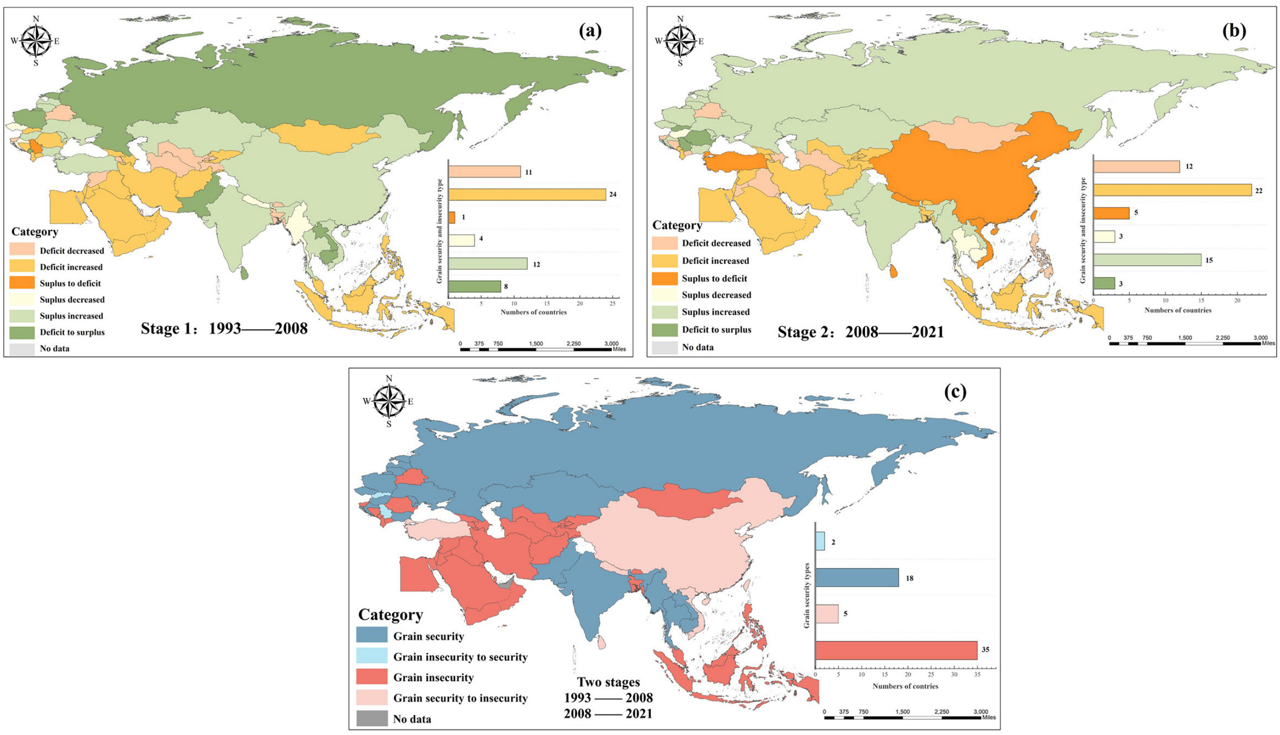

FIGURE 7
Classification of grain security at different stages **(a, b)** and changes in grain security **(c)**.

TABLE 4 Comparison of regression results of GTWR, OLS and GWR models.

Model	GTWR	GWR	OLS
R^2	0.8272	0.7805	0.1644
AICc	671.69	682.79	1,075.94

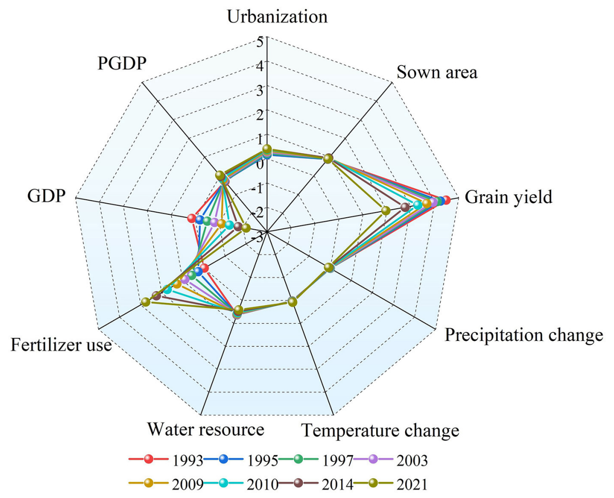

FIGURE 8
Temporal changes in the impact of different indicators on grain supply-demand.

GDP had the largest negative impact on grain supply-demand, with more significant spatial differences in the magnitude of the impact (Figure 9A). Overall, the factor coefficients were predominantly positive in 1997 and before, and predominantly negative overall after 1997. Since 1993–2021, there has been a relative increase in the number of countries negatively affected by GDP and a relative decrease in the number of countries positively affected by GDP. In particular, countries in Central Asia showed a larger change in the influence degree of GDP, while countries in other regions showed a smaller change. The countries most negatively affected by GDP are Ukraine and Türkiye, with regression coefficients <-3.8796. The countries positively affected by GDP were concentrated in Central Asia, South Asia and Southeast Asia, such as Kazakhstan, India and Myanmar.

The extent of PGDP's impact on grain supply-demand was second only to GDP, with a predominantly negative effect (Figure 9B). Since 1993–2021, there has been a relative increase in the number of countries positively affected by PGDP and a relative decrease in the number of countries negatively affected by PGDP. Among them, countries in Central Eastern Europe showed more drastic changes in the influence degree of the factor. In contrast, countries in other regions showed more moderate changes. Countries negatively affected by PGDP were concentrated in West Asia-Middle East, Central Eastern Europe and South Asia. Russian Federation, Myanmar, Thailand and Laos were the most negatively affected countries. The countries most affected by the positive impact of PGDP are mainly China, Mongolia and Kyrgyzstan.

Urbanization had a predominantly negative impact on grain supply-demand, with a lower degree of influence than other negatively affected factors. Since 1993–2021, the number of countries where urbanization had a positive impact on grain supply-demand is increasing (Figure 9C). Countries positively affected by urbanization were concentrated in the West Asia-Middle East, Central Eastern Europe, and South Asia, with the larger positively affected countries concentrated in Central Eastern Europe, such as Ukraine and Romania, with regression coefficients >0.3672. Countries negatively affected by urbanization were focused on East Asia, Central Asia, and Southeast Asia, with China, Myanmar and Thailand, being more negatively affected, and the regression coefficients are <-0.3575 in some years.

Secondly, the factors that mainly had a positive impact on grain supply-demand were, in descending order of the influence degree, grain yield, sown area, fertilizer use, and water resource.

Grain yield had the largest positive effect on grain supply-demand, with more significant spatial differences in the magnitude of the effect (Figure 10A). From 1993 to 2021, the change in the influence degree of the factor has been relatively flat, except for countries in Central Asia, which have experienced a large change. The countries more positively affected by grain yield were mainly located in Central Eastern Europe, such as the Czech Republic and Slovakia, with regression coefficients >9.8219. Only a few countries were negatively affected by grain yield in some years, such as in Central and Southeast Asia, for example, Kazakhstan, Myanmar and Laos.

The overall effect of sown area on grain supply-demand was predominantly positive, with the positive effect second only to grain yield (Figure 10B). From 1993 to 2021, only a few countries such as Russian Federation, Pakistan and Oman have been negatively affected by sown area in some years. Except for Russian Federation, where the influence degree of the factor varied considerably, the influence degree of countries in the other regions varied little. The countries more positively affected by the sown area were concentrated in the West Asia-Middle East such as Türkiye, Egypt and Kazakhstan, with regression coefficients >2.2543.

Fertilizer use mainly positively impacted grain supply-demand, second only to the sown area, with more significant spatial differences in the impact degree (Figure 10C). Overall, the factor coefficients were predominantly negative in 1997 and before, and predominantly positive overall after 1997. Since 1993–2021, countries positively affected by fertilizer use have been concentrated in Central Eastern Europe and parts of the West Asia-Middle East, such as Ukraine, Romania and Egypt. Among them, the number of countries positively affected in Central Eastern Europe has gradually increased. The countries negatively affected by fertilizer use were primarily located in Central Asia, East Asia and Southeast Asia.

The overall impact of water resource on grain supply-demand was predominantly positive, with a lower influence degree relative to other positively influencing factors (Figure 10D). After 1997, the extent to which the countries along the B&R were affected by this factor stabilized and changed relatively little. The countries positively affected by water resource were concentrated in West Asia-Middle East, Central Asia and Central Eastern Europe, with Saudi Arabia, Türkiye and Yemen being the main countries most positively affected, with a positive coefficient of >1.2075.

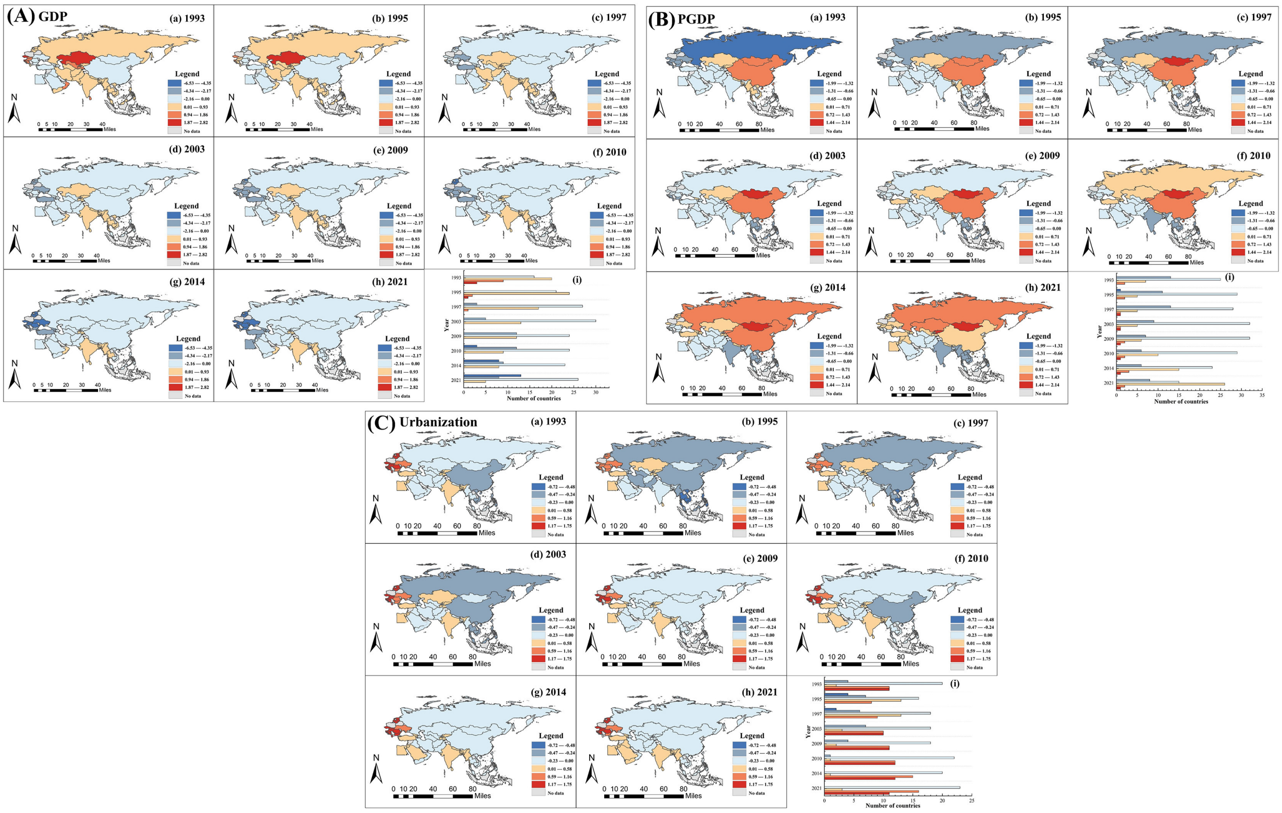

FIGURE 9
Spatial distribution of GTWR regression coefficients for GDP **(A)**, PGDP **(B)** and urbanization **(C)** in 1993–2021 (a–h) and the number of countries with different coefficients (i).

Fewer countries were negatively affected by water resource, and the negative effect was small, with a negative regression coefficient >-0.4449. These countries were concentrated in East Asia, South Asia and Southeast Asia, such as China, Mongolia, India and Myanmar.

Lastly, two factors, temperature change and precipitation change, had a relatively small impact on grain supply-demand.

Temperature change had the least impact on grain supply-demand, with regression coefficients ranging from −0.1808 to 0.1979, respectively, and showing an overall positive impact (Figure 11A). Countries with relatively significant positive impacts of temperature change include Romania, Ukraine and Kazakhstan. Only a few countries showed a negative impact in some years, such as Russian Federation, India, and countries in West Asia-Middle East, such as Egypt, Türkiye and Saudi Arabia.

Precipitation change affected grain supply-demand to a slightly greater extent than temperature change, but also to a relatively lesser extent, affecting regression coefficients in the range of −0.5315 to 0.3365 (Figure 11B). There has been little overall change in the extent to which countries along the B&R were affected by precipitation change since 1993–2021. Positively affected countries were concentrated in South Asia, Southeast Asia and East Asia. In contrast, negatively affected countries were primarily located in West Asia-Middle East and Central Eastern Europe.

4 Discussion and conclusion

4.1 Discussion

4.1.1 Spatiotemporal patterns of grain supply-demand and the state of grain security

The B&R region has shown a significant increase in total grain production, with grain yield contributing more to total production than sown area. Losses in the process of grain consumption and the use of seeds showed a downward trend. This is due to the optimization of agricultural structure and the ongoing advancements of agricultural technology, which have correspondingly enhanced agricultural production efficiency. At present, the B&R region is still in the primary stage of grain demand, which was based on "food-based and feed-supplemented," and grain consumption accounts for a large proportion of the global consumption, but the average grain consumption level was lower than that of the world, which was in line with the findings of Zhang C. et al. (2021). This reflected the overall low level of economic development in the B&R region, posing greater challenges for grain security and nutritional diversity. However, the B&R region was crucial to the global supply-demand balance and had a significant part in the flow of trade in the global grain market and the stable maintenance of grain security. With further economic development

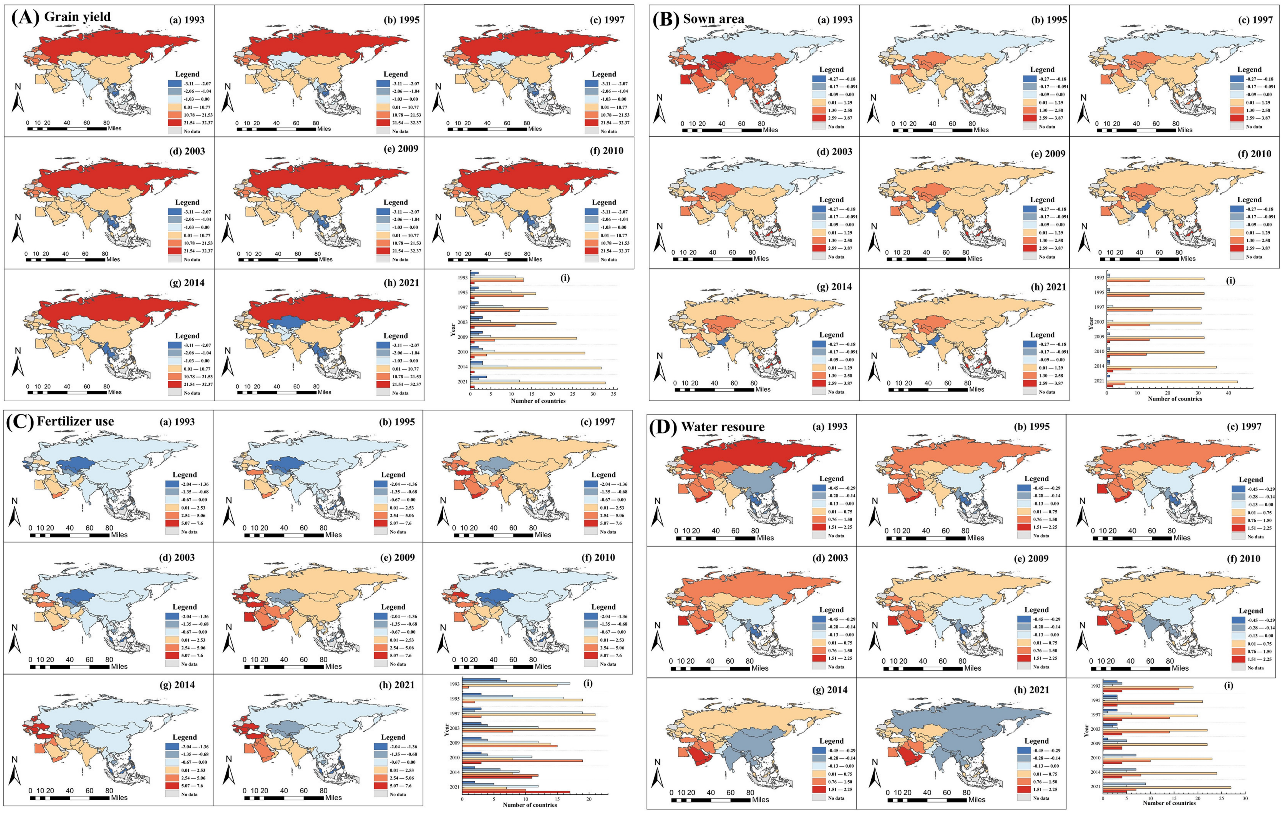

FIGURE 10
Spatial distribution of GTWR regression coefficients for grain yield **(A)**, sown area **(B)**, fertilizer use **(C)** and water resource **(D)** in 1993–2021 (a–h) and the number of countries with different coefficients (i).

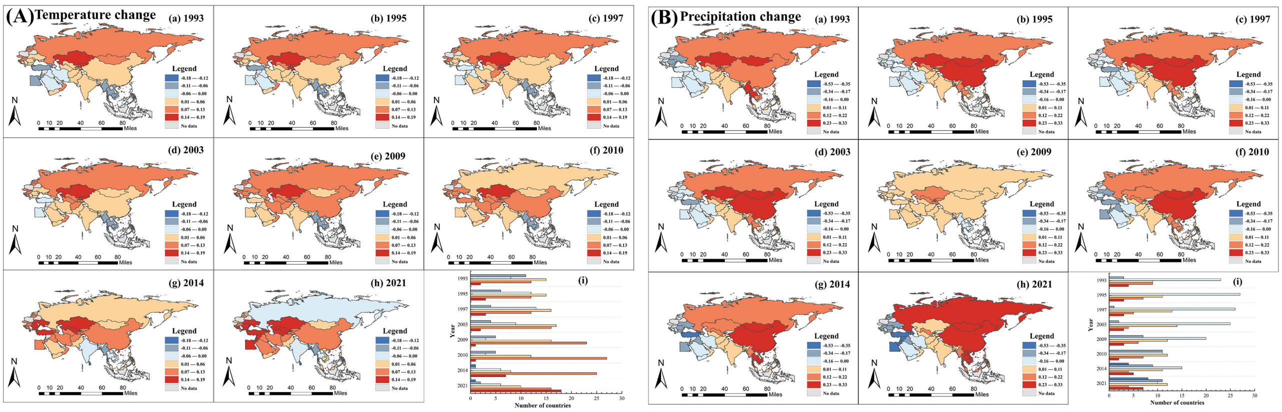

FIGURE 11
Spatial distribution of GTWR regression coefficients for temperature change **(A)** and precipitation change **(B)** in 1993–2021 (a–h) and the number of countries with different coefficients (i).

and rising income levels, grain demand will gradually shift toward diversification and high quality.

The gravity center of grain supply-demand was concentrated in East Asia. This is because China, as one of the countries in East Asia, is the most populous in the world (Fei et al., 2023) and has a large area of land suitable for growing grain crops. As a result, this makes China's grain supply and demand in the B&R region relatively large, both at about 35%. Moreover, the reason for the contraction in both the standard deviation ellipse space size of grain supply and demand is that, with the upgrading of economic levels and the exchange of agricultural trade and cooperation among the countries along the B&R (Alhussam et al., 2023), the differences in grain supply and demand among these countries have decreased. In particular, there has been a greater contraction in grain demand relative to grain supply. This is due to the fact that the natural conditions for grain production are more constrained, and the basic natural conditions for grain production still vary significantly between countries. However, with globalization, the improvement in economic performance across these countries has led to a further reduction in the differences in grain demand.

Since 1993–2021, the grain supply and demand levels in most countries along the B&R have remained largely consistent. However, different grain supply-demand types of countries face different grain security problems, and therefore different types of countries should adopt appropriate targeted policies. High supply-high demand countries should build resilient and diversified grain supply chains and continue to strengthen agricultural technological innovations to lead other countries to increase their grain production capacity. Countries with low supply-low demand should seek more international assistance and cooperation to strengthen agricultural infrastructure. Countries with high supply-low demand should expand their agricultural export markets and focus on sustainable grain production. Countries with low supply-high demand should invest more in agricultural technology, diversify their sources of grain imports, promote the diversification of their populations' diets and reduce their dependence on grain imports.

In terms of changes in the grain supply-demand gap in the B&R region, in 2008 and beyond, the grain security situation has been evolving in a more sustainable direction, and grain supply gradually meeting demand. Grain supply-demand changes are closely linked to social environment and policy developments. In 2003, the grain supply-demand gap reached its largest negative value. This may have been due to the heatwave in Europe in 2003 (Velde et al., 2010), which significantly reduced grain supply in Central Eastern European countries such as Ukraine, Romania, and Hungary. Additionally, economic growth and population increases led to higher grain demand, resulting in a supply-demand imbalance. In 2014, the grain supply-demand gap reached its largest positive value. This was due to a significant increase in grain-surplus countries, with 71% of countries, such as China, Russian Federation, and Romania, experiencing an increase in grain supply.

The overall grain security situation in the B&R region was poor, with more than 58% of the countries being grain insecurity and grain-deficit, which were concentrated in Southeast Asia near the equator, as well as in West Asia-Middle East. The environment for growing grain in this type of country was relatively poor and is not suitable for growing grain crops. Grain-insecurity countries should strengthen trade cooperation with other countries along the B&R that have more surplus grain to meet their grain needs through grain imports and should also strengthen agricultural technology innovation. Around 30% of the countries in the B&R region were grain secure. According to the regional cooperation and win-win situation proposed by the "Belt and Road" Initiative, grain-security countries can appropriately provide emergency grain aid to surrounding grain-deficit countries, support agricultural technology, which will not only help grain-deficit countries to alleviate short-term grain crises, but also promote long-term agricultural development and regional grain security.

4.1.2 Drivers of grain supply-demand

Grain supply-demand was mainly negatively affected by PGDP. This is due to rapid economic development, industrial and technological transformation, reduced agricultural investment, all of which have led to a decrease in grain supply. At the same time, with economic growth and people's standard of living improving, the purchasing power of grain rises, and the demand for grain increases, leading to a decrease in the ratio of grain supply to demand. Fertilizer use had a predominantly positive effect on grain supply-demand, suggesting that fertilizer use increases grain yield, which leads to an increase in grain supply. One study showed that global fertilizer usage per hectare increased from 60 kg in 1960 to 110 kg in 2002, contributing to increased grain production (Khan et al., 2009). However, a few countries were negatively affected by fertilizer use, and these countries were concentrated in Central Asia. The main reason is that high fertilizer use has caused soil pollution and soil quality degradation (He et al., 2022), leading to a decrease in grain productivity and grain supply, resulting in a decrease in the supply-demand ratio. Therefore, such countries should strengthen technological innovation, use fertilizers scientifically, reduce the pollution of fertilizers in the soil (Lu et al., 2020), and promote green grain production.

Urbanization had a mainly negative impact on grain supply-demand, which indicated that the increase in the rate of urbanization, the gradual transformation of many villages into towns and cities, the transfer of a large number of rural population to cities, the abandonment of some land, and the increase in demand for grain, all of these make the supply-demand ratio smaller. Therefore, the expansion of urbanization in such countries should be accompanied by a basic balance between grain supply-demand to ensure grain security.

Water resource had a mainly positive effect on grain supply-demand. This is because water is the basic guarantee of grain supply. Therefore, all countries along the B&R should rationally develop and utilize surface water resource, promote water-saving irrigation techniques, improve water use efficiency (Mainuddin et al., 2020) and improve agricultural water management.

Temperature and precipitation change had a smaller impact on the ratio of grain supply to demand than other factors, primarily because the temperature and precipitation change were relatively small. Additionally, technological progress has brought about improvements in agricultural production and management measures, which have also weakened the impact of temperature and precipitation on agriculture to a certain extent, and thus the ecosystem of grain crops is more stable and less affected by climate change. However, this does not mean that we can ignore the impacts of temperature and precipitation change on grain production, as the intensity and frequency of extreme weather events are likely to increase as global climate change intensifies, posing a greater threat to grain production (Khalfaoui et al., 2024). Therefore, countries along the B&R should continue to pay attention to the impact of climate change on grain production and take corresponding measures to address those challenges.

The grain supply-demand relationship is a complex system that is affected by the factors mentioned above, as well as by several special external factors. For example, grain supply has not been able to meet grain demand due to the impact of COVID-19, and the grain supply-demand gap has been continuously negative since 2020. Therefore, in the face of certain special factors, countries should strengthen the formulation of contingency plans by focusing on market regulation, technological support, supply chain management, and international cooperation to ensure a stable grain supply and enhance the level of regional integrated defense.

4.1.3 Shortcomings and future prospects

In summary, this paper constructed a multiscale analytical framework for the matching of grain supply and demand in the B&R region from the spatial and temporal dynamics of the relationship between grain supply and demand, and further refined the assessment of the regional grain security situation. The study explored the spatial heterogeneity of the influencing factors of grain supply-demand by introducing natural, economic and social factors. This not only expanded the application of grain supply and demand studies, but also provided scientific support for optimizing grain resource allocation and improving grain security in the B&R region.

Firstly, this paper analyzed grain supply-demand relationship and its influencing factors in the B&R region mainly at the national and regional levels, while there are significant differences in the economic, social, climatic and agricultural conditions of the regions within the countries. Analyses at the national and regional level may not fully reveal these internal differences, leading to limitations in the nuance and applicability of the results. Future research should be further refined to smaller spatial scales, such as the provincial and municipal levels, and regional in-depth studies and comprehensive multi-scale analyses should be carried out to reveal more regional differences and details, so as to provide more precise and effective policy recommendations for regional grain supply-demand management. Secondly, grain trade affects grain supply-demand by influencing, among other things, grain availability and grain prices. Therefore, in the future, changes in grain trade and grain supply-demand could be analyzed in an integrated manner. Finally, regarding the research methodology, the standard deviation ellipse and gravity center model are sensitive to extreme values when characterizing spatial distribution. In the future, these methods could be combined with robust statistical techniques to mitigate the influence of extreme values on the results. Although the GTWR model can reveal spatial and temporal dynamics, it typically assumes a linear relationship. However, the influences on grain supply and demand may involve complex nonlinear relationships. Hence, in the future, it can be combined with other spatiotemporal analysis models (such as spatial autocorrelation models) to form an integrated model that improves the explanatory power of spatial heterogeneity and spatiotemporal changes.

4.2 Conclusion

Based on grain production and consumption data and multi-influence factor data of 65 countries along the B&R from 1993 to 2021, this paper explored the grain supply-demand matching relationship and its influencing factors as well as the state of grain security based on the analysis of the trend of spatiotemporal patterns.

(1) Total grain production significantly increased, with grain yield contributing more to total production than sown area in the B&R region. The gravity center of grain supply and demand was the same, near East Asia. The B&R region was still in the primary grain demand stage of "food-based and feed-supplemented". Although per capita consumption in this region is low and does not reach the global average, the total grain consumption accounted for a large proportion of global consumption and played a key role in maintaining the global balance in grain supply-demand.

(2) The B&R region has been largely self-sufficient since 2007, with grain supply meeting demand, but the level of grain self-sufficiency varied considerably between countries. In terms of matching supply-demand, most countries fell into the category of high supply-high demand and low supply-low demand, with basically the same level of grain supply and demand.

(3) The number of countries with low-surplus and those with high-deficit both showed a downward trend. Among them, the number of countries with high-surplus rose the most, indicating an improvement in grain security situation at the country level. However, the overall grain security situation in the B&R region was not optimistic, and grain insecurity accounted for a relatively large number of countries, mainly in West Asia-Middle East and Southeast Asia.

(4) The effects of fertilizer use, grain yield, and GDP on grain supply-demand fluctuated greatly over time. Grain yield, sown area, fertilizer use, and water resource mainly positively affected grain supply-demand. GDP, PGDP, and urbanization mainly negatively affected grain supply-demand. Temperature change and precipitation change had less impact on grain supply-demand.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

WQ: Funding acquisition, Investigation, Supervision, Validation, Writing – review & editing, Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Resources, Software, Visualization, Writing – original draft. XT: Investigation, Supervision, Validation, Visualization, Writing – review & editing. XZ: Investigation, Supervision, Writing – review & editing. GL: Investigation, Supervision, Writing – review & editing. JZ: Investigation, Supervision, Writing – review & editing. XS: Writing – review & editing. MZ: Investigation, Supervision, Validation, Visualization, Writing – review & editing. RH: Funding acquisition, Investigation, Supervision, Validation, Writing – review & editing, Formal analysis, Visualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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