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RESEARCH ARTICLE

Constructing a composite index to evaluate multidimensional variations in food security over different regions

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Abstract Understanding food security level on a large scale is crucial for grasping global food security and issuing timely warnings about regional food systems risks. Current regional spatiotemporal distribution and multidimensional comparisons of global food security are insufficient. Therefore, this paper proposed a weighting technique combing the subjective AHP method with the objective CRITIC method, and developed a new composite index to measure food security multidimensionally. Using the food security composite index (FSCI), this study explored the spatiotemporal evolution of food security in different dimensions at both global and regional levels, based on panel data from 2001 to 2020. The variation of FSCI remained stable in the quantity dimension across all regions, with significant improvements in economic security observed in Europe and Latin America and Caribbean, and Asia showed an upward trend in resource dimension. Compared to the global average, Europe had a pronounced advantage, whereas Sub-Saharan Africa had a significant disadvantage.

Keywords Composite index · Food security · Indicator system · Spatiotemporal variation · Sustainable development

INTRODUCTION

Food security is a complex scientific issue comprehensively reflected by multiple dimensions and indicators (Pinstrup-Andersen 2009; FAO 2013; Caccavale and Giuffrida 2020). The United Nations 2030 global sustainable development goals (SDGs) and “Vision 2025 for the Future Earth” list achieving food security and promoting agricultural sustainability are key research topics (ICSU 2013; UN 2015). In the twenty-first century, various global events such as climate shocks (Hasegawa et al. 2018), the COVID-19 pandemic (Chiwona-Karltun et al. 2021), and the Russia-Ukraine conflict (Behnassi and El Haiba 2022) have led to negative consequences such as reduced food production, labor shortages, soaring food prices, inadequate food supply, difficulty in obtaining food, and disrupted trade (Osendarp et al. 2022; Poertner et al. 2022). It is estimated that by 2030, more than 8% of the world’s population will face hunger issues (FAO 2022). These challenges present greater uncertainty and instability in the face of global environmental changes, which will alter the equilibrium of global grain security (Chen et al. 2021; Myers et al. 2022; Schneider et al. 2023). The food security situations in Africa, Asia, and Latin America and Caribbean deteriorated severely (Ma et al. 2020; FAO 2022), while the food security level in Sub-Saharan Africa was significantly lower than the global average (Connolly-Boutin and Smit 2016; EIU 2022; Wudil et al. 2022). The food security issues in these areas have long been a focus of attention for the international community. A comprehensive understanding of the current status and developmental trends of regional food security is essential for ensuring the stability of global food system and achieving the SDGs.

With the increasing salience of global food security issues in recent years, scholars have conducted numerous studies to quantitatively assess food security among different countries or regions (van Dijk and Meijerink 2014; Stephens et al. 2018; Zhao and Zhong 2020). A question that has drawn much attention from scholars worldwide is: What indicators should be used to assess the status of food security, and what

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level of food security is considered acceptable (de Haen et al. 2011; Headey and Ecker 2013; Xie et al. 2021)? Using the dimensions of availability, access, utilization, and stability, FAO (2013), EIU (2012), Yao et al. (2015), and Ma et al. (2020) constructed a food security indicator system to evaluate and monitor the food security and nutritional status of different countries. Different weighting approaches such as principal component analysis, I-Distance weighting, a hierarchical data envelopment analysis, and an entropy weight TOPSIS model were employed by Izraelov and Silber (2019), Chen et al. (2019), Caccavale and Giuffrida (2020), and Zhang et al. (2022) to calculate the food security indices, which measure the overall level of food security at the national level. Most existing studies in constructing food security indicator systems and composite indices consider multiple dimensions, which involve both macro- and micro-elements (Pinstrup-Andersen 2009; Poudel and Gopinath 2021; Viana et al. 2022). Nevertheless, there was a clear mutual influence between indicators at both macro- and microscales, potentially masking the trends and features they were meant to reveal. Since the 21st century, as there remains much room for further exploration in comprehensive evaluations at global and regional levels and in multidimensional analyses of variations in food security, there is an urgent need to examine the spatial–temporal patterns of food security variations across different regions of the world.

Food security, being a worldwide issue, is intricately impacted by multiple factors, highlighting pronounced variations across distinct regions (Lu et al. 2015; Guo et al. 2021; Ray et al. 2022). The objectives of this paper are to (1) establish an evaluation indicator system for food security and develop a food security composite index (FSCI) by integrating the subjective weighting method of AHP with the objective weighting method of CRITIC, (2) employ the FSCI at both global and regional scales to assess the spatiotemporal dynamic variations in food security across different dimensions in various regions worldwide from 2001 to 2020 (20 years), and (3) assess the comparative advantages and disadvantages of different regions' overall food security levels in comparison with the global average by the comparative advantage index method. From a regional perspective, this study contributes to a holistic understanding of large-scale food security trends, with significant implications for policy formulation, mitigation challenges, and the achievement of the SDGs. The innovation lies in proposing a new method for developing a composite index that integrates the advantages of subjective weighting (using the AHP method) and objective weighting (using the CRITIC method), introducing the AHP-CRITIC mixed weighting technique, and utilizing this technique to construct the FSCI, offering a reliable tool to support regional food security assessment.

Construction of a food security evaluation indicator system

Amidst the current global warming scenario, the issue of food security has become more urgent and multifaceted. Given the pressing global targets of the 2030 SDGs, establishing a macro-evaluation indicator system for food security offers an effective means to accurately monitor and evaluate progress toward food security in alignment with the SDGs on a broader scale. This approach enables us to gain insights into disparities and trends among different regions, thereby providing scientific justification for formulating an overarching macro-strategy toward achieving global food security.

The universally acknowledged definition of food security, proposed by FAO, asserted that "A situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life". It encompasses multiple aspects including the availability, access, utilization, and stability of food. We selected quantity, economy, and resource securities as the three dimensions to establish a macro-evaluation indicator system for food security. Firstly, quantity security, a fundamental requirement for food security, is essential for the basic life support of the general populace (Cui and Nie 2019; Lei et al. 2022; Zhang et al. 2022). The sufficiency and stability of food supply can be determined through assessments of production yield, inventory stockpiles, and import/export volumes, enabling timely detection of potential supply-related pressures and risks. Secondly, economic security is crucial for food security, as it ensures the healthy operation of food production and supply chains (Cui and Nie 2019; Guo et al. 2021). Assessing economic indicators such as per capita GDP, agricultural orientation index, and food price index helps understand the economic feasibility of these chains. This enables timely detection of economic pressures and risks, promoting the development of food production, stability of supply chains, and ultimately ensuring sustainable food supply and access (Benton et al. 2011; Chaudhary et al. 2018). Finally, resource security is considered a fundamental prerequisite for food security, as the production of food relies on various resources such as land, water, transportation, and the political environment (de Amorim et al. 2018; Gil et al. 2019; Singh et al. 2022; Xu et al. 2023). By evaluating indicators such as arable land area, agricultural water usage, and transportation infrastructure, the utilization of resources and environmental impacts in food production can be understood. Ensuring resource security aids in optimizing resource allocation and management, thereby enhancing the efficiency and sustainability of food production (Lei and Qiu 2022; Liu et al. 2023). The interrelationship and compatibility between the quantity, economy, and resource securities of food are often observed in practice. The balance among these three dimensions is crucial in ensuring comprehensive food security and offers a significant direction for the conceptualization of the macro-framework of food security.

The construction of a systematic, scientific, guiding, and actionable food security indicator system should adhere to the following principles: firstly, regarding food security as an organic system, where each element and hierarchy are independent yet closely interconnected. Secondly, the selection and weighting of evaluation indicators should be scientifically reasonable and evidence-based, with the chosen indicators having both guidance and directionality, in order to offer guidance for food security development. Moreover, it is crucial that the evaluation indicators can be quantified and the data can be easily obtained. Therefore, following the principles outlined above and drawing on the research by FAO (2015), EIU (2022), Chen et al. (2019), Cui and Nie (2019), Ma et al. (2020), Su et al. (2022), Zhang et al. (2022), and Xu et al. (2023, 2024), we identified 15 indicators from the perspectives of quantity, economy, and resource securities, including per capita grain production, per capita GDP, and the proportion of arable land area, among others. These indicators were utilized to establish a macro-food security evaluation indicator system. The specific details of the indicators are provided in Table 1.

MATERIALS AND METHODS

Study area

Geographical zoning were utilized from the FAO's "The State of Food Security and Nutrition in the World 2022" report (FAO 2022), focusing on Asia, Europe, Latin America and Caribbean (LAC), and Sub-Saharan Africa (SSA). The selection of specific countries within these regions followed the M49 global geographical region standard provided by the United Nations Statistics Division[1] and considering data availability. A total of 86 countries were selected. It should be emphasized that all selected countries ensured data availability over the research period was continuous. The geographical distribution is shown in Fig. 1, and a list of countries included is shown in Appendix S1 and Table S1.

Data source and preprocessing

To begin with, we selected internationally recognized and authoritative institutions that regularly update data related to food security, such as the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT[2]), the World Bank (DataBank[3]), the Agricultural Market Information System of the United Nations (AMIS[4]), the UN Comtrade Database[5], and the United Nations Statistics Division's database (UNdata[6]). For each of these data sources, we filtered out indicators related to quantity, economic, and resource security dimensions based on the food security indicators provided which encompassed grain production, trade volumes, price fluctuations, agricultural inputs, and other aspects. Subsequently, the relevant data were downloaded from each source and were preliminary processed and cleaned to ensure their accuracy and uniformity. The dataset, which covered cross-sectional data from 86 countries over 2000 to 2021, was organized into three dimensions: quantity security, economic security, and resource security, consisting of a total of 15 indicators. The specific information is available in Table 1.

In terms of data preprocessing, we followed the data statistical principles of FAO. To eliminate the impact of abnormal trend fluctuations, all indicator data underwent a preprocessing step of three-year moving average, with the time frame restricted to 2001–2020 (20 years). After that, linear interpolation was employed to handle missing data and fill in the gaps, ensuring data integrity and accuracy. Finally, to improve the accuracy of data processing and facilitate unified calculations, all data were further subjected to normalization preprocessing using the range method, mapping its values to the range of 0–1. However, data that were inherently relative ratios were not normalized. The descriptive statistical results for various indicators across 86 countries globally from 2001 to 2020 are presented in Appendix S2 and Table S2.

Construction of composite index of food security

The composite indexes of food security in different dimensions were constructed using a multi-indicator evaluation approach based on the established indicator system (Table 1). This approach adopted the method of

[1] https://unstats.un.org/unsd/methodology/m49.

[2] https://www.fao.org/faostat/zh/#data.

[3] https://data.worldbank.org/.

[4] https://www.amis-outlook.org/home/en/.

[5] https://comtrade.un.org/.

[6] http://data.un.org/Host.aspx?Content=About.

Table 1 Food security evaluation indicator system and its description

First-layer index	Second-layer indices	Third-layer indicators	Unit	Description	Properties	Data resource
Food security composite index (FSCI)	Quantity security index (QSI)	X_{11}: Cereal production per capita	Tonnes/1000 persons	Cereal production/total population number	Positive	FAOSTAT
		X_{12}: Domestic cereal supply quantity	1000 tonnes	Cereal production + cereal imports—cereal exports + changes in cereal stocks	Positive	FAOSTAT, UN Comtrade Database
		X_{13}: Net cereal imports	Tonnes	Cereal imports—cereal exports	Negative	FAOSTAT, UN Comtrade Database
		X_{14}: Food loss	Tonnes	The quantity of food lost or wasted during storage and transportation processes	Negative	FAOSTAT
		X_{15}: Per capita food production value variability	Dimensionless	Standard deviation of the per capita food production value/average per capita food production value	Negative	FAOSTAT
	Economy security index (ESI)	X_{21}: Gross domestic product per capita, PPP	$ (constant 2017 international $)	Gross domestic product converted by purchasing power parity/total population number	Positive	FAOSTAT, DataBank
		X_{22}: The agriculture orientation index for government expenditures	Dimensionless	Share of agriculture in government expenditures/share of agriculture in GDP	Positive	FAOSTAT
		X_{23}: Food consumer price index (CPI)	Dimensionless	A measure of the monthly change in international prices of a basket of food commodities (2015 = 100)	Negative	FAOSTAT, UNdata, AMIS
		X_{24}: Food price inflation	%	Fluctuation of grain commodity price series in a certain period	Negative	FAOSTAT
	Resource security index (RSI)	X_{31}: Percentage of arable land area	%	Arable land area/land area	Positive	FAOSTAT
		X_{32}: Rail line density	km/(100 km^2)	The total length of railway routes/land area	Positive	FAOSTAT
		X_{33}: Port container traffic	TEU: 20-foot equivalent	Port container traffic measures the flow of containers from land to sea transport modes	Positive	DataBank
		X_{34} : Political stability and absence of violence index	Dimensionless	One of the Worldwide Governance Indicators	Positive	DataBank
		X_{35}: Control of corruption index	Dimensionless	One of the Worldwide Governance Indicators	Positive	FAOSTAT
		X_{36}: Percentage of agricultural freshwater	%	Annual agricultural freshwater/total freshwater	Positive	FAOSTAT, DataBank

A positive indicator indicates a positive influence on food security, meaning that the greater the value is, the higher the food security level. A negative indicator indicates a negative influence on food security, meaning that the greater the value is, the lower the food security level

transforming multiple statistical indicators that describe different aspects of the evaluated objects into dimensionless relative evaluation values and combining these evaluation values to obtain an overall evaluation of the objects (Li et al. 1999; Cai et al. 2020; Xu et al. 2023). The following steps were followed:

Indicator data normalization processing

To minimize the influence of variable dimensions, units, and ranges, the three-year moving average and the extreme-range method were employed to normalize all indicators values before data analysis (Caccavale and

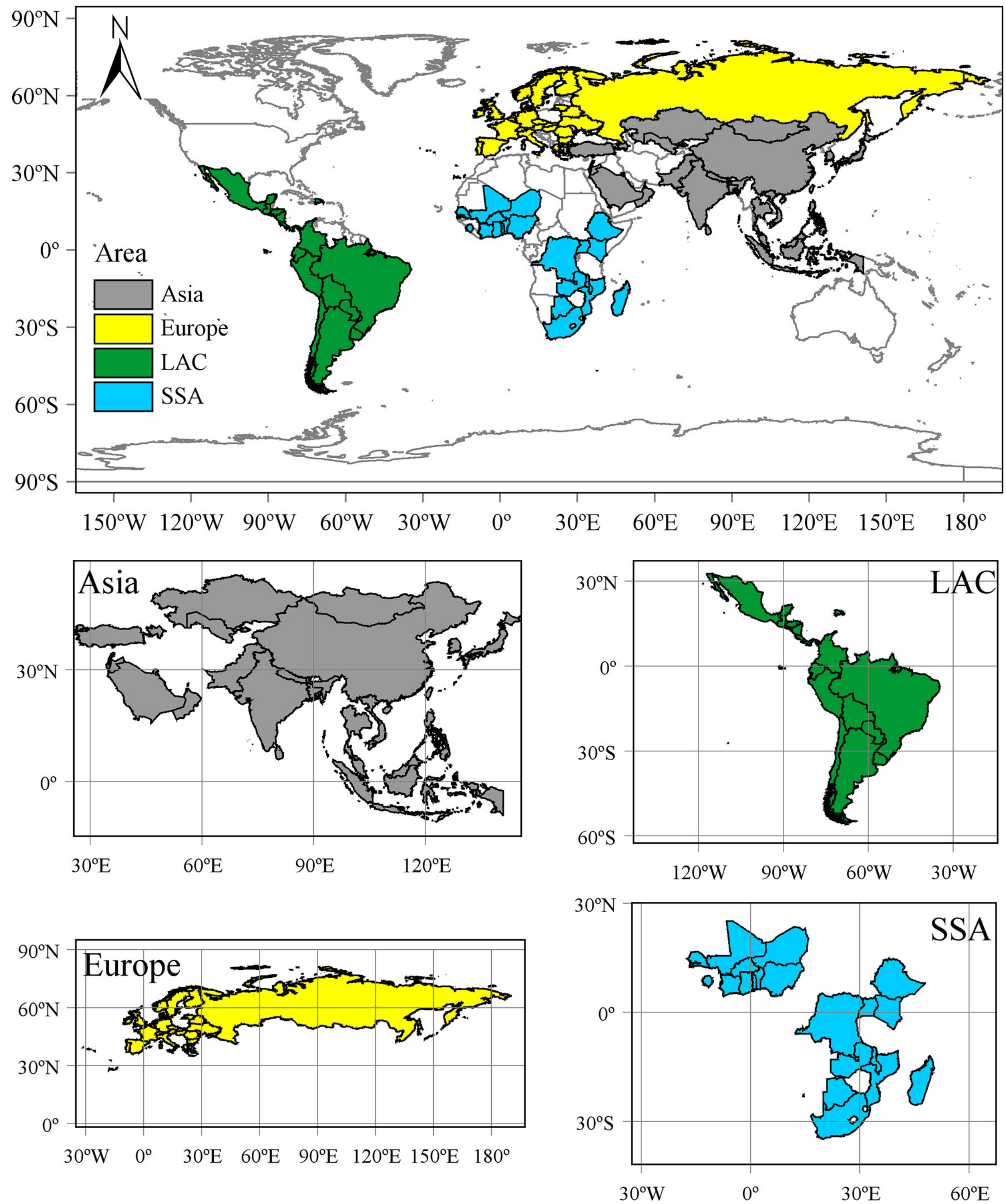


Fig. 1 Maps of the study area (Considering the availability and temporal continuity of data, 86 countries were selected in accordance with the M49 global geographical region standard provided by the United Nations Statistics Division. These countries covered four regions: Asia, Europe, LAC, and SSA.)

Giuffrida 2020; Xu et al. 2023). Indicators were expected to have a positive impact on grain security used Eq. 1a, while indicators had a negative impact used Eq. 1b. X_{ij} is the original data of the j-th indicator of the i-th region. $X_{ij}\prime$ is the corresponding normalized value, and $max\left(X_{ij}\right)$ and $\min\left(X_{ij}\right)$ represented the maximum and minimum values of the j-th indicator, respectively.

$$X_{ij}\prime = \begin{cases} \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})} (a) \\ \frac{\max(X_{ij}) - X_{ij}}{\max(X_{ij}) - \min(X_{ij})} (b) \end{cases} \quad (1)$$

The indexed weights were calculated based on the AHP-CRITIC mixed weighting method

To balance the subjective judgment of decision-makers and the objective characteristics of the evaluation object, this research employed a mixed weighting method that integrated the analytic hierarchy process (AHP) and the criteria importance through intercriteria correlation (CRITIC) methods. Firstly, the AHP method was used to calculate the subjective weight of the index. This method subjectively decomposed the evaluation goal into different levels and indicators, compared and calculated the indicators at the same level, and determined the weights of different indicators (Kim 2009; Li et al. 2018). Pairwise subjective comparisons were made for the food security indicators, based on the research conducted by Yao et al. (2015), Cui and Nie (2019), Cai et al. (2020), EIU (2022), and Su et al. (2022), as shown in Appendix S3 and Table S3. The weights of the indicators were then calculated using the geometric mean method, as indicated in Eq. 2. C_{ij} represented the matrix element and w_i represented the subjective weight value of the i-th indicator. After that, the CRITIC method was used to calculate the objective weight value of the index. This method was objectively based on the comparison strength of the evaluation indicators and the conflicts between the indicators (Diakoulaki et al. 1995; Krishnan et al. 2021). The standard deviation of the indicator data represented the comparison strength by measuring the fluctuation size of it, and the correlation coefficient of the indicator data represented the conflicts by measuring the correlation between the indicators. The main calculation formula was shown as Eq. 3. w_j represented the weight of indicator j, r_{ij} was the correlation coefficient between indicator i and j, and σ_j was the standard deviation of indicator j. Finally, the mixed weighting method of AHP-CRITIC was used to calculate the composite index weight. The subjective weights calculated by the AHP method were combined with the objective weights calculated by the CRITIC method to obtain the composite indices weights. The calculation formula was shown as Eq. 4. ω_{ij} represented the composite indices weights.

$$w_i = \frac{\sqrt[n]{\prod_{j=1}^{n} C_{ij}}}{\sum_{j=1}^{n} \sqrt[n]{\prod_{j=1}^{n} C_{ij}}} \quad (2)$$

$$w_j = \frac{\sigma_j \sum_{i=1}^{n} (1 - r_{ij})}{\sum_{j=1}^{m} \sigma_j \sum_{i=1}^{n} (1 - r_{ij})} \quad (3)$$

$$\omega_{ij} = \frac{\omega_i \omega_j}{\sum \omega_i \omega_j} \quad (4)$$

Calculating the composite index of food security in different dimensions

The dimensional indices and the food security composite index (FSCI) for various regions were obtained by applying the weighted function, with the index weights calculated according to the constructed macro-indicator system for food security, as demonstrated in Eq. 5–6. The weight values of each indicator are shown in Appendix S4 and Table S4.

$$Y_{it} = \sum (\omega_{ij} \cdot X_{ijt}) \quad (5)$$

$$\mathrm{FSCI}_t = \sum (\omega_{ij} \cdot Y_{it}) \quad (6)$$

Uncertainty analysis based on Monte Carlo method

During the construction of FSCI, uncertainties such as the selection of indicators and weighting method could induce errors and exert an impact on the simulation results (Saltelli and Tarantola 2002). To ensure that the evaluation model simulation results of the FSCI were more robust and reliable, it was necessary to conduct an uncertainty analysis on them. The Monte Carlo approach was adopted to simulate real situations through a large number of random samples and perform statistical analysis on these sample results so as to obtain the possible range and probability of outcomes (Caccavale and Giuffrida 2020; Ocampo et al. 2022). Therefore, it was employed to test the robustness of the simulated results of the FSCI by repeatedly replacing indicator variables, changing weighting methods, and generating a large number of random FSCI values, which were then sorted and compared.

The uncertainty analysis results of FSCI values in different regions from 2001 to 2020 are presented in Appendix S5 and Table S5. The results indicated that, after 640 repetitions by replacing each method, although the frequency and probability of rank occurrences might vary across different regions, there was no overall impact on the regional ranking of FSCI. This suggested that the initial FSCI values calculated using the AHP-CRITIC mixed weighting method for the 15 indicators were robust.

Comparative advantage index approach

The revealed comparative advantage index (RCA) was proposed by American economist Balassa to quantitatively measure the competitiveness and relative advantage of a country or region in the international market by assessing the economic efficiency in producing similar goods relative to other countries or regions (Balassa 1965; Cai and Leung 2008; Stellian and Danna-Buitrago 2019). The comparative advantage approach has been widely applied in the field of agricultural production and food security (An et al. 2008; Benesova et al. 2017; Bahta and Mbai 2023). This research employed the comparative advantage index approach to construct indices for quantity security comparative advantage, economic security comparative advantage, resource security comparative advantage, and comprehensive food security comparative advantage. These indices were used to assess the comparative strengths and weaknesses of food security in different regions.

The quantity security comparative advantage index (QAI) was a measure of the proportion of the quantity security index in a specific region during a certain period to the FSCI of the same region during the same period, compared to the global average level. It revealed the relative contribution and security advantage of the quantity security index to the food security of that region. The QAI was calculated as shown in Eq. 7, where QAI_{it} represented the comparative advantage index of the quantity security dimension in region i during period t, which measured the contribution of regional quantity security to food security. QSI_{it} is the QSI of region i during period t, while QSI_{gt} is the QSI on a global scale during period t. $FSCI_{gt}$ is the global FSCI during period t. If $QAI_{it}>1$, it signified that region i during period t had a comparative advantage in quantity security relative to the global average level. A larger value indicated a more pronounced advantage in quantity security. Conversely, if $QAI_{it}<1$, it indicated that region i during period t had a comparative disadvantage in quantity security compared to the global average level. A smaller value indicated a more pronounced disadvantage in quantity security. Likewise, the EAI and RAI were expressed in Eq. 8 and 9.

$$\mathrm{QAI}_{it} = \frac{\mathrm{QSI}_{it} / \sum_j \mathrm{FSCI}_{it}}{\mathrm{QSI}_{gt} / \sum_j \mathrm{FSCI}_{gt}} \tag{7}$$

$$\mathrm{EAI}_{it} = \frac{\mathrm{ESI}_{it} / \sum_j \mathrm{FSCI}_{it}}{\mathrm{ESI}_{gt} / \sum_j \mathrm{FSCI}_{gt}} \tag{8}$$

$$\mathrm{RAI}_{it} = \frac{\mathrm{RSI}_{it} / \sum_j \mathrm{FSCI}_{\mathrm{it}}}{\mathrm{RSI}_{gt} / \sum_j \mathrm{FSCI}_{gt}} \tag{9}$$

FCAI was the comprehensive result of QAI, EAI, and RAI, which measured the degree of advantage in food security for a region from multiple dimensions. It was calculated as shown in Eq. 10, where $FCAI_{it}$ represented the FCAI of region i during period t, and it comprehensively reflected the indicators of food security level in region i. If $FCAI_{it}>1$, it indicated that the food security level of region i during period t had a more significant comprehensive comparative advantage in this region. The larger the value, the more pronounced the comprehensive comparative advantage. Conversely, the more pronounced the disadvantage.

$$\mathrm{FCAI}_{it} = \sqrt[3]{\mathrm{QAI}_{it} \times \mathrm{EAI}_{it} \times \mathrm{RAI}_{it}} \tag{10}$$

Based on the above equations, the FCAIs in different regions of the world from 2001 to 2020 were calculated using a panel dataset. According to the actual data characteristics of FCAI values, FCAI was divided into six levels using an equal interval grading method: extremely strong advantage ($1.3 \le$ FCAI), strong advantage ($1.15 \le$ FCAI < 1.3), general advantage ($1.0 \le$ FCAI < 1.15), general disadvantage ($0.85 \le$ FCAI < 1.0), strong disadvantage ($0.7 \le$ FCAI < 0.85), and extremely strong disadvantage (FCAI < 0.7).

RESULTS

Temporal and spatial variations of the different dimensions constituting food security

Over the past two decades, there was an upward trend in the global QSI, ESI, and RSI, with growth rates of 0.023/(10 years), 0.006/(10 years), and 0.021/(10 years), respectively (Appendix S6 and Fig. S1). Turning to regional differences, the QSI in Europe, LAC, and SSA regions showed an increasing trend, with growth rates of 0.06/(10 years), 0.064/(10 years), and 0.004/(10 years), respectively (Appendix S6 and Fig. S2). Moreover, both Europe and LAC had growth rates exceeding the global rate of change. In contrast, Asia showed a decreasing trend by 0.037 per decade. The ESI in Asia, Europe, and LAC regions showed an upward trend over the past 20 years in terms of economic security, with growth rates of 0.012/(10 years), 0.023/(10 years), and 0.015/(10 years), respectively, all surpassing the global rate of change. On the other hand, SSA showed a decreasing trend by 0.024 per decade. Regarding resource security, the RSI in all four regions showed an upward trend over time, with growth rates of 0.065/(10 years), 0.011/(10 years), 0.008/(10 years), and 0.0004/(10 years), respectively, with only Asia exceeding the global rate of change.

To examine the temporal variations of food security in three dimensions, the period from 2001 to 2020 was divided into 4 time periods: 2001–2005, 2006–2010, 2011–2015, and 2016–2020 for analysis. Figure 2 presents the trends of food security in three dimensions in Asia, Europe, LAC, and SSA regions during these 4 time periods. In Europe and LAC, QSI, ESI, and RSI showed a continuous upward trend every 5 years. The levels of

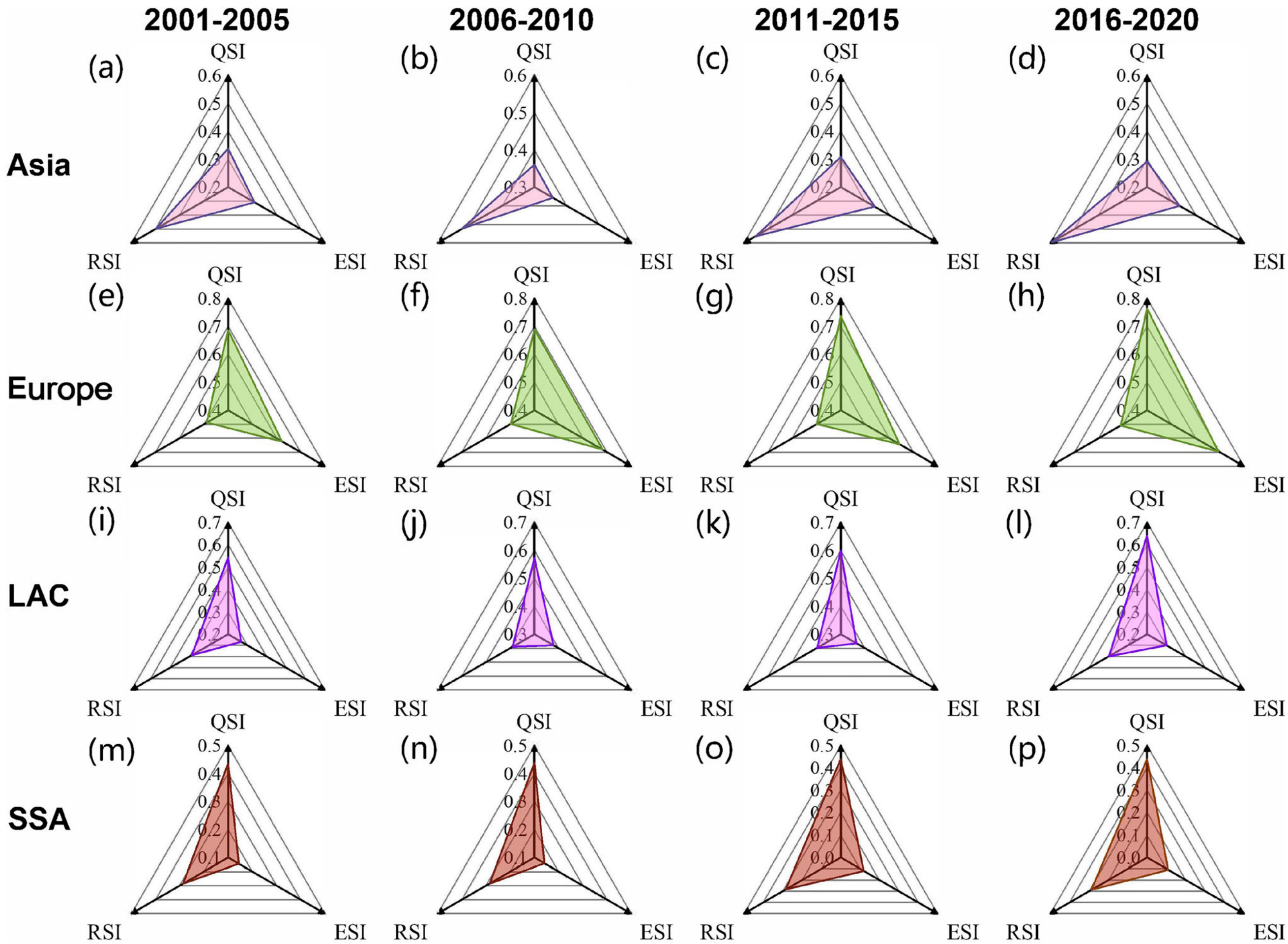


Fig. 2 The variations in food security in the three dimensions across different regions of the world from 2001 to 2020

quantity, economic, and resource security for food in these regions improved over time, contributing to the overall assurance of food security. In Asia, only ESI and RSI showed a similar trend, varying from 0.31–0.335 to 0.499–0.597, respectively. In SSA, only QSI and RSI demonstrated similar changing characteristics, ranging from 0.435–0.441 to 0.287–0.288, respectively. The resource security dimension played a dominant role in Asia, while the quantity security dimension played a more significant role in the other three regions.

Figure 3 displays the spatial distribution and index value differences in food security across various dimensions in each region for the periods of 2001–2005 and 2016–2020. There were no significant changes in the spatial distribution of QSI over the four regions from 2001–2005 to 2016–2020. Europe remained in the high-value zone, while the low-value zone was mainly distributed in Asia (Fig. 3a–c). By contrast, Europe and LAC showed significant changes in magnitude, while the changes in Asia were relatively small. In terms of ESI, there were no significant changes in the spatial distribution of Asia and SSA, while the average values in Europe and LAC increased during the period of 2016–2020 (0.695 and 0.3, respectively), compared to the average values in the initial period (2001–2005) (0.623 and 0.268) (Fig. 3d–f). During the past five years, the high-value zone of ESI was mainly distributed in Europe, while the low-value zone was in SSA. Europe showed a larger extent of change, while SSA showed smaller changes. Regarding the RSI, there were no significant changes in the spatial distribution of Europe, LAC, and SSA, while the average value in Asia increased to 0.597 during the period of 2016–2020, compared to the average value of 0.499 in the initial period (2001–2005) (Fig. 3g–i). During the past 5 years, the high-value zone of RSI was mainly distributed in Asia, while the low-value zone was in SSA. Among them, Asia showed a larger degree of change, while SSA showed weaker changes.

Spatiotemporal variations in the FSCI

Figure 4 illustrates the trend of FSCI over different regions from 2001 to 2020. From a global perspective, the FSCI

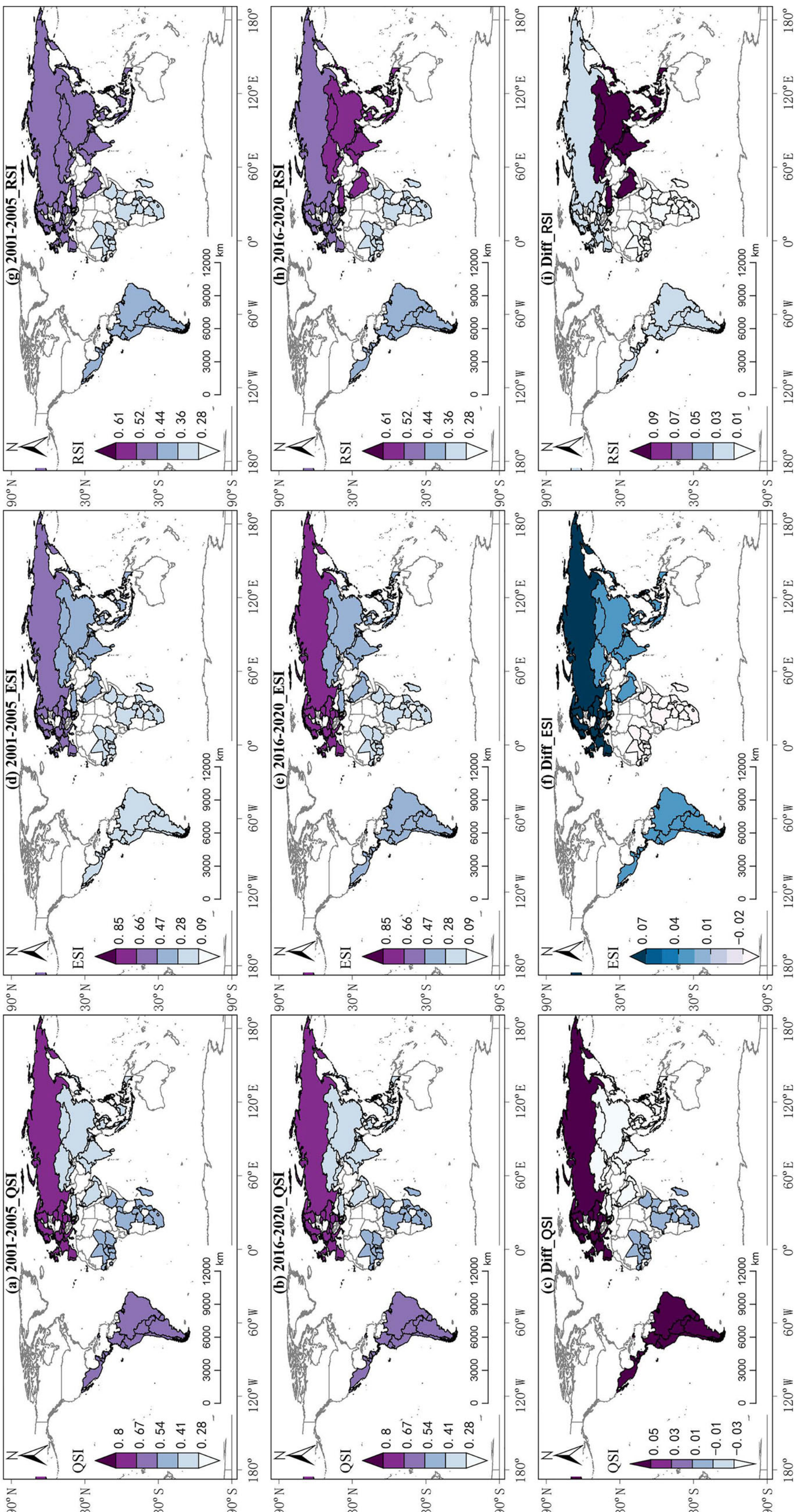
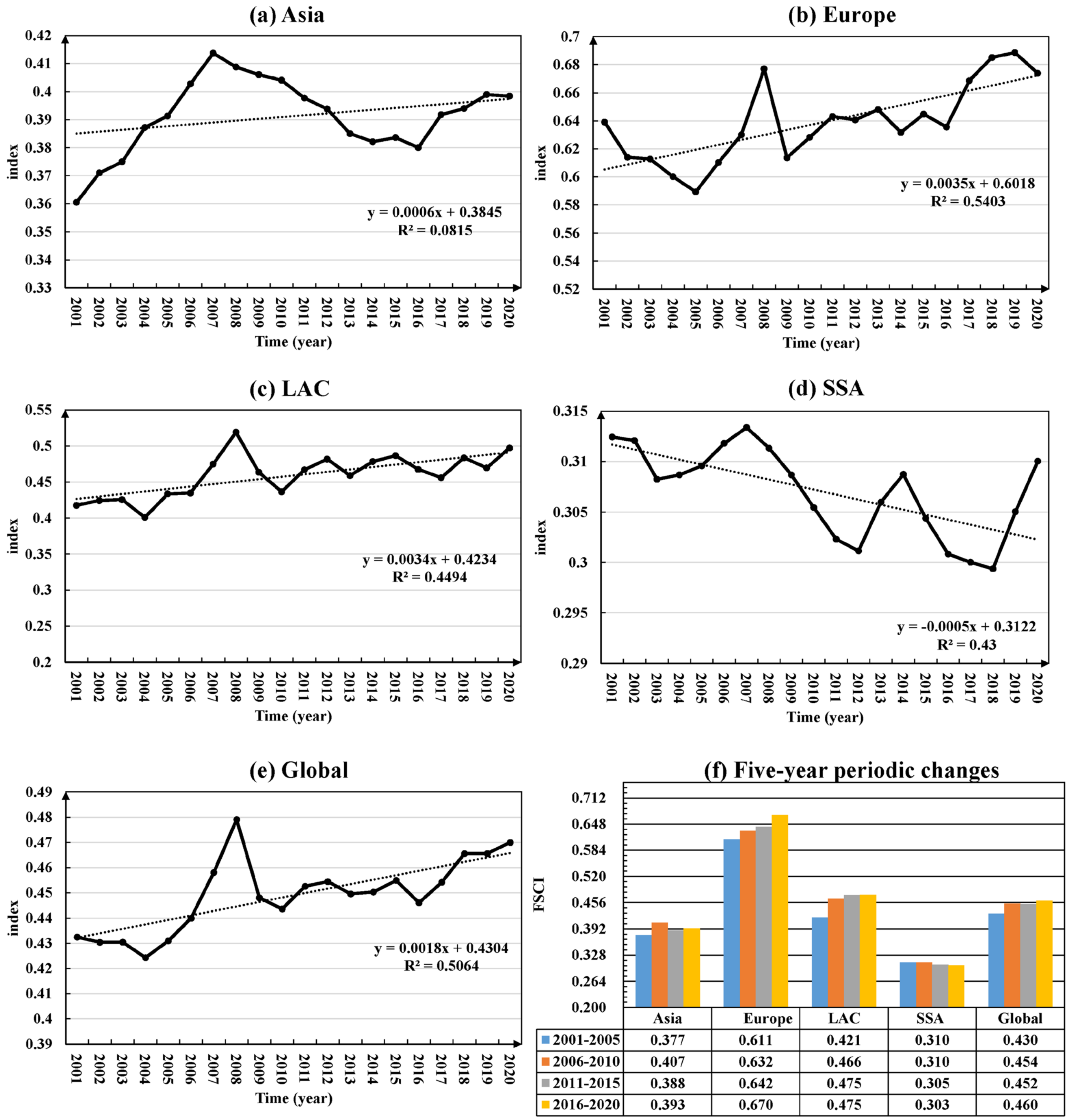


Fig. 3 Spatial distribution and difference of the QSI, ESI, and RSI in different periods across regions from 2001 to 2020



	Asia	Europe	LAC	SSA	Global
2001-2005	0.377	0.611	0.421	0.310	0.430
2006-2010	0.407	0.632	0.466	0.310	0.454
2011-2015	0.388	0.642	0.475	0.305	0.452
2016-2020	0.393	0.670	0.475	0.303	0.460

Fig. 4 Temporal trends of the global food security composite index from 2001 to 2020

displayed an ascending trend over the past 20 years, with a growth rate of 0.018/(10 years), indicating that the level of global food security continuously improved over time. This was mainly due to the high levels of quantity and resource securities, with economy security showing a steady improvement trend, which was conducive to the rapid development of food security. Turning to the regional scale, the FSCI for Asia, Europe, and LAC continuously increased over time, with growth rates of 0.006/(10 years), 0.035/(10 years), and 0.034/(10 years), respectively. Both Europe and LAC showed faster growth rates compared to the global average, indicating an improvement in the food security levels in these regions. In contrast, the FSCI for SSA demonstrated exhibited a downward trend of 0.005/(10 years), highlighting a declining food security level, which demanded urgent attention.

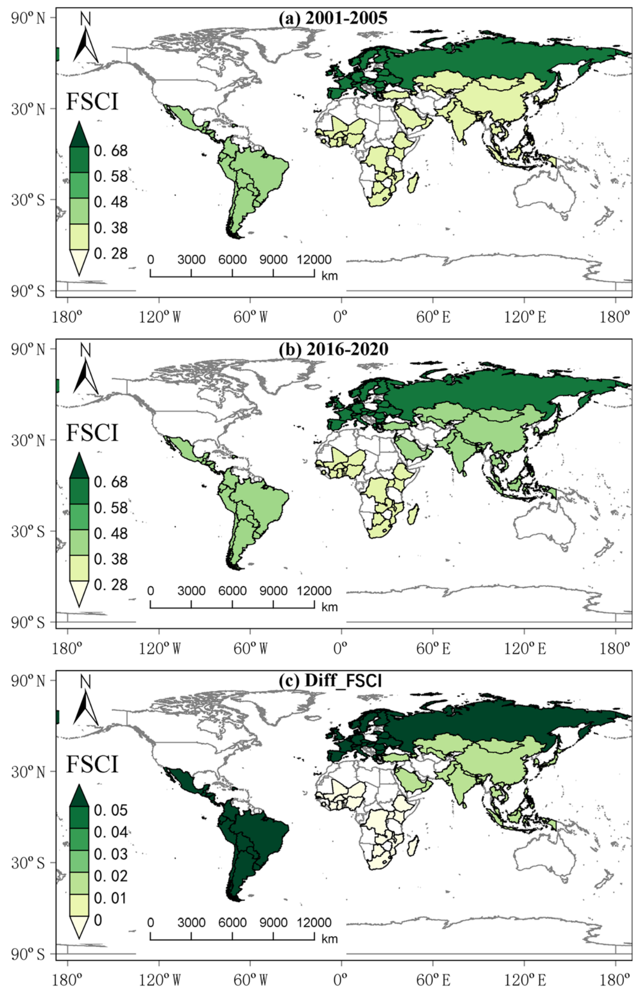


Fig. 5 Spatial distribution (**a–b**) and difference (**c**) of the FSCI in different periods from 2001 to 2020

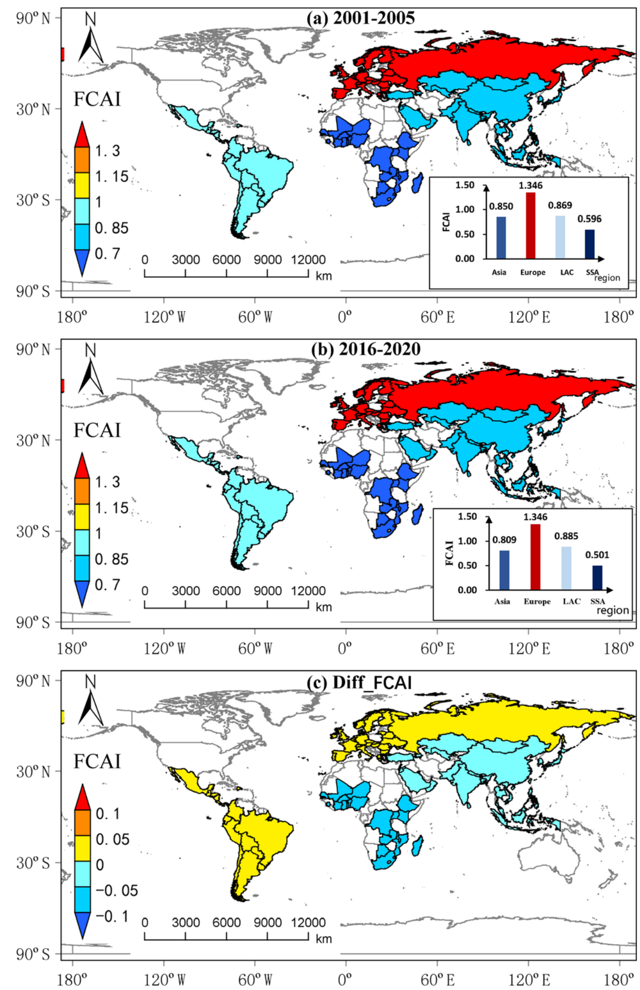


Fig. 6 Spatial distribution (**a–b**) and difference (**c**) of the FCAI in different periods from 2001 to 2020

Figure 5 illustrates the spatial distribution of the FSCI in different regions during the periods of 2001–2005 and 2016–2020, as well as the differences in FSCI between these two periods. The FSCI exhibited similar geographical patterns across different regions during different periods. The high FSCI values were mainly concentrated in Europe (0.611 ∼ 0.67), while the low values appeared in SSA (0.303 ∼ 0.31). Asia and LAC fell between these two extremes, with FSCI ranges of 0.377 ∼ 0.393 and 0.421 ∼ 0.475, respectively. Moreover, Europe and LAC witnessed substantial changes in it, while the changes in LAC were relatively minor. Compared to the global average level, the FSCI values in Europe and LAC were consistently higher in both periods, indicating that these regions maintained a high level of food security and were leaders in terms of food security globally. However, the FSCI values in Asia and SSA were consistently lower than the global average level in both periods, with SSA exhibiting the lowest values.

Comprehensive comparative advantage characteristics of food security

Figure 6 displays the spatial distribution of the FCAI for various regions during the periods of 2001–2005 and 2016–2020, along with the FCAI differences between these two periods. Similar geographic patterns in FCAI values across different time periods were observed, with regions in Europe having FCAI values greater than 1.0, while regions in Asia, LAC, and SSA had values below 1.0. This suggested that only Europe demonstrated a comparative advantage in food security compared to the global average, while Asia, LAC, and SSA were at a disadvantage. Furthermore, the FCAI of Europe consistently remained above 1.3 from 2001–2005 to 2016–2020, underscoring its significant advantage in terms of food security compared to the global average. The FCAI of LAC fluctuated between 0.85 and 1, suggesting a moderate inferiority in this regard. The FCAI of Asia ranged from 0.7 to 0.85, suggesting a pronounced disadvantage compared to the global average. The SSA region, on the other hand, consistently demonstrated FCAI below 0.7, indicating a grave disadvantage in terms of food security compared to the global average.

To further elucidate the relative strengths and weaknesses of regional food security levels compared to the global average over the past 20 years, the multi-year averages were calculated using the FCAI from 2001 to 2020 for each region, and spatial maps were generated (Appendix S6 and Fig. S3). Europe demonstrated an extremely strong advantage in terms of food security compared to the global average (FCAI = 1.322), while LAC experienced a general disadvantage (FCAI = 0.9). Asia faced a strong disadvantage in terms of food security compared to the global average (FCAI = 0.833), and SSA was at an extremely strong disadvantage (FCAI = 0.54).

DISCUSSION

This study firstly proposed a method for constructing a composite index, which integrated the advantages of subjective AHP weighting method and objective CRITIC weighting method, and thus put forward the AHP-CRITIC combined weighting technique. This enhanced the accuracy of the FSCI, providing a powerful support tool for the assessment of regional food security. Secondly, the indicator data selected for constructing FSCI were easily accessible and covered a relatively long period of time (20 years), making them suitable not only for historical assessments of food security similar to this study but also for scenario predictions of future trends (Xu et al. 2023, 2024). Additionally, FSCI enabled a quick grasp of overall food security trends and comparisons across different regions, offering a new theoretical perspective and research approach for comprehensive food security evaluations. Thirdly, the overall level of food security was comprehensively and systematically evaluated through processes such as data collection, indicator selection, evaluation framework construction, indicator system construction, evaluation model construction, calculation of the composite index, and uncertainty analysis of the output results. A more comprehensive and systematic comprehensive evaluation methodology system was provided.

This research assessed the temporal and spatial trends of food security over the last two decades in different regions, namely Asia, Europe, Latin America and Caribbean, and Sub-Saharan Africa. Results indicated that while the Europe had high food security, low food security was concentrated in SSA, which was consistent with Ma et al. (2020) evaluation of food security levels across 172 countries from 2000 to 2014. Additionally, the results of this research were consistent with the rankings of global food security as assessed by FAO and EIU (Appendix S6 and Fig. S4). The regional rankings follow the order of Europe, LAC, Asia, and SSA. However, there were disparities in food security levels between Asia and the global average. The FSCI indicated that Asia was below the global average, while the prevalence of undernourishment (PoU) and global food security index (GFSI) indicated that Asia was above the global average. These discrepancies might be due to differences in the selected indicators and weighting methods, but they did not significantly affect the overall regional ranking. Given its high value in global food security, Europe could continue to play a pivotal role in driving global agricultural technological advancements. In the face of challenges posed by modern agricultural practices to biodiversity and carbon emissions, Europe can promote the research and application of advanced agricultural technologies, including intelligent agriculture, and ecological agriculture, while actively advocating for the development of environmentally friendly agriculture. By improving agricultural production efficiency and resource use efficiency, minimizing environmental harm, and enhancing the quantity and quality of agricultural products, Europe will help achieve the dual objectives of environmental sustainability and food security. Additionally, strengthening international cooperation is crucial to promote fairness and sustainability in grain trade. SSA should adopt technological innovation to proactively address the current and impending challenges in the agricultural sector, which includes drawing from the advanced agricultural experiences of countries with high food security levels and introducing efficient planting technologies like drip irrigation, greenhouse planting systems, and drought-resistant crop varieties, in order to boost agricultural productivity and output, and thus secure sustainable agricultural development. Additionally, bolstering infrastructure is crucial for improving irrigation systems and water usage efficiency. Implementing soil rejuvenation and farmland conservation initiatives will also elevate soil fertility and overall production capacity. Asian countries are encouraged to strengthen cooperation and jointly establish unified food security assessment standards and indicator systems. Through regular assessments and monitoring, issues can be promptly identified and addressed with appropriate measures.

This study primarily tackled global and regional food security issues, focusing on regions with severe challenges, while excluding North America and Oceania. In fact, this research analyzed them using “import” indicators, effectively integrating these regions into the global context. Future research will enhance global food security assessment by specifically focusing on “grain trade” and giving more attention to these regions and countries. Furthermore, finer spatial research scales and more comprehensive datasets will become feasible, with the rapid advancement of technology,

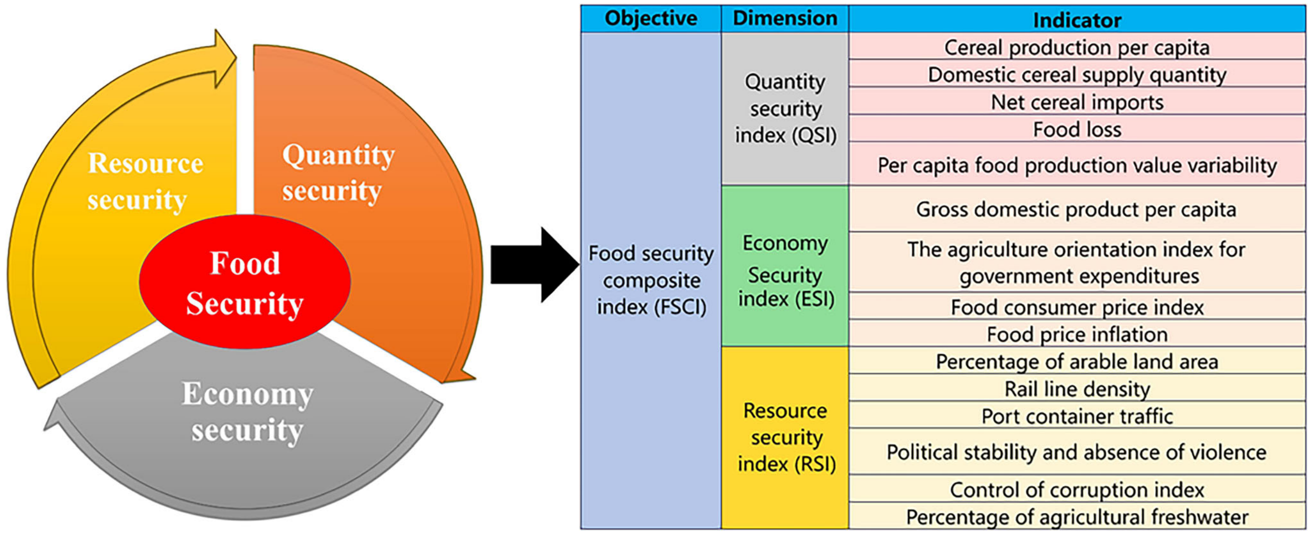


Fig. 7 Framework for the food security assessment indicator system

the widespread utilization of big data, and the continuous expansion of deep learning techniques. For future research, the utilization of a more extensive range of data sources and the exploration of more advanced data collection and analysis methodologies, such as big data analytics and artificial intelligence, will be conducted, to enhance the comprehensiveness and reliability of the data.

Given the pressing global challenges, there is a crucial need to establish stronger connections between agricultural systems analysis and broader food security outcomes due to their interconnectedness (Jones and Ejeta 2016; Stephens et al. 2018; Nicholson et al. 2021). The research's outcomes aim to contribute to food security theories, enabling the optimization of model index parameters and enhancing accuracy in agricultural system modeling. While this research has generated valuable findings, there is room for improvement in the selection of food security indicators and the construction of the composite index. We considered the differences among countries and accordingly chose common indicators with universal applicability, aiming to reduce the uncertainties. Concurrently, we focused primarily on macro-indicators, excluding micro-level nutrition security indicators (like protein, etc.) from our consideration. Hence, in the future, by maintaining the macro-indicators while progressively incorporating and integrating micro-level nutrition security indicators, we will be able to achieve a more comprehensive assessment of food security and nutritional assurance. With the expansion of research perspectives and subjects, a more holistic consideration of the impacts of percentage of agricultural freshwater is essential in future work. While this study primarily focused on its positive aspects, it was also necessary to take into account the issue of overexploitation of water resources. Further exploration is required on how to optimize irrigation technologies and management strategies, as well as how to achieve sustainable water resource utilization and ecological environment protection while ensuring agricultural production.

This study utilized consistent weighting values to evaluate data across diverse regions, aiming to enable comparisons of the FSCI and provide a standardized basis for the international organizations to formulate global food security goals and strategies in line with sustainable development objectives. If the research scope narrows to the national or subregional level, it is important to consider regional disparities in constructing the FSCI and possibly employ distinct weights to better reflect local food security levels, thus supporting the development of policies to ensure national food security.

CONCLUSIONS

Integrating the subjective AHP weighting method with the objective CRITIC weighting method, the composite index was developed to assess food security across multiple dimensions. It revealed the spatiotemporal variations in regional food security and allowed for comparisons of overall regional food security levels. This not only helped enhance our understanding of the current state of global food security from a regional viewpoint but also provided a scientific foundation for the macro-scale layout and planning of SDGs pertaining to global food security. The main conclusions are as follows:

(1) An evaluation indicator system for assessing global food security, incorporating quantity, economy, and

resource security dimensions, was constructed (Fig. 7). This comprehensive approach provided a holistic description of food security. A FSCI was developed for historical and future assessments of food security. Employing the Monte Carlo method, the inherent uncertainties in the composite index were handled, thereby validating the robustness and reliability of the FSCI.

(2) Over the last 20 years, there was a consistent improvement in the levels of quantity, economy, and resource security for food at the global scale, with quantity security playing a dominant role in enhancing global food security. Europe stood out with high average values in both the QSI and ESI, reaching 0.719 and 0.661, respectively. Conversely, Asia and Sub-Saharan Africa exhibited relatively lower values of 0.325 and 0.128, respectively. The RSI showed high average values in Asia at 0.544, while lower values were observed in Sub-Saharan Africa (0.286).

(3) From 2001–2005 to 2016–2020, there were no significant changes in the distribution of QSI in terms of quantity dimension, with Europe being the strong value area and Asia being the weak value area. In terms of economic dimension, ESI significantly improved in Europe and LAC, with Europe witnessing a larger degree of change. In terms of resource dimension, RSI in Asia showed a noticeable upward trend with a significant magnitude of change.

(4) The global food security level demonstrated an upward trend (0.018/(10 years)) from 2001 to 2020, with similar trends observed in Asia, Europe, and Latin America and Caribbean, where the growth rates over each decade were 0.006, 0.035, and 0.034, respectively. In contrast, Sub-Saharan Africa underwent a continuous downward trend (− 0.005/(10 years)). In terms of spatial distribution, the region with high FSCI values was primarily located in Europe (0.639), while low-value region was concentrated in Sub-Saharan Africa (0.307).

(5) Europe had a strong advantage in food security compared to the global average, while Latin America and Caribbean had a moderate disadvantage. Although Asia had a relatively higher level of food security, it still experienced some degree of disadvantage. Sub-Saharan Africa, on the other hand, had a significantly lower level of food security, indicating a strong disadvantage.

Asia and Sub-Saharan Africa had lower food security levels than the global average over the past 20 years, indicating potential risks that may impede progress toward achieving the SDG of zero hunger by 2030. With intensifying global climate change, evaluating the impact of regional food security has become an urgent task and a crucial component of the sustainable development agenda for countries worldwide. Developing a food security evaluation indicator system can offer scientific support for agricultural system modeling and promote sustainable agricultural development.

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Data availability The authors declare that the data supporting the findings of this study are available within the paper and its supplementary information files. Datasets generated during the current study are available from the corresponding author on reasonable request.

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