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A Dynamic Evolutionary Analysis of the Vulnerability of Global Food Trade Networks

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Abstract: The global food trade network (FTN) is a critical infrastructure for achieving the Sustainable Development Goals (SDGs). The FTN's vulnerability to geopolitical conflicts, public health crises, and climate change events directly impacts food security and the ability to meet the SDGs. This study aims to analyze the dynamic evolution of the vulnerability of FTN, focusing on the period from 2000 to 2022, to aim for strategies for enhancing the resilience and sustainability of the global food system. Based on complex network analysis, we examine the structural characteristics and evolution of FTN for four major crops: soybeans, wheat, rice, and maize. We identify a trend towards increased network density and regionalization, with a decline in average shortest path length (*ASPL*) and an increase in the average clustering coefficient (*ACC*). These changes indicate a shift towards a more interconnected and resilient FTN in response to various shocks, including the COVID-19 pandemic and the Russia–Ukraine conflict. The findings suggest that the global FTN has adapted to increase resilience, which is essential for achieving the SDGs related to food security and sustainable development. The study's insights can guide policy interventions to further strengthen the network against future shocks and promote global food security.

Keywords: global food trade network; sustainable development goals; network vulnerability; complex network theory; food security

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1. Introduction

The Sustainable Development Goals (SDGs), established by the United Nations, represent a comprehensive framework aimed at addressing the most pressing challenges of our time, including poverty, inequality, climate change, environmental degradation, peace, and justice. Among these, SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production) directly relate to the stability and efficiency of global food trade networks (FTNs). These networks are pivotal in ensuring food security, reducing global hunger, and promoting sustainable agricultural practices. The study of the vulnerability and resilience of these networks is crucial for achieving these SDGs and, by extension, the overall sustainability of our global food system.

The spatial imbalance in the distribution of global agricultural production resources has led to a mismatch between food supply and consumption, further generating a food security crisis. The food trading system has become an essential tool for regulating global food supply and demand to reconcile regional food supply and demand conflicts. The FTN is a crucial component of the global food supply system, the stability of which is necessary to address poverty, hunger, inequality, public health, etc. The FTN is a direct determinant of whether or not the Sustainable Development Goals (SDGs) will be achieved in time for 2030. The stability of the FTN is challenged by chronic exposure to shocks from geopolitical conflicts, public health, economic fluctuations, climate change, natural disasters, pests, and diseases [1].

In recent years, public health events and geopolitical conflicts have become important hazards that threaten global food security [2]. The COVID-19 pandemic in 2020 and the Russia–Ukraine conflict in 2022 have further pushed global economic uncertainty to a high level and increased the vulnerability of the global FTN.

The COVID-19 pandemic first directly impacted the global food supply chain, thereby destabilizing the global food network system [3,4]. The COVID-19 pandemic impacted food production, storage, and transportation activities, thus destabilizing the food supply [5,6]; on the other hand, countries tended to restrict exports to safeguard their food supply [7,8], and studies have shown that the COVID-19 pandemic has seriously undermined the global food trade system [9,10], and the risk of global external cereal supply index has risen by 65%, with 80% of net food-importing countries in a high position [11]. The impact of the COVID-19 pandemic on food shortages in developing countries, particularly in the least developed countries, has been significant [12,13]. Developing countries with less mechanized agriculture cannot sustain food production when hit by shocks [14,15], and the negative impact on employment [16], incomes [17], and price inflation are even greater [18,19], further reducing the ability of people in these regions to access food [20,21]. According to statistics, the global number of underfed people as a result of the COVID-19 pandemic increased by 27.8% in 2020 [11,22].

The Russia–Ukraine conflict has severely disrupted the global food trade network. Before the conflict, Russia and Ukraine were the major grain producers. Between 2017 and 2021, both countries averaged as much as 18 percent of total global production of barley, wheat, and grains annually [23,24]. During the conflict, it was estimated that more than 20% of Ukraine's 2021 winter wheat harvest would be affected [25,26], and nearly half of Ukraine's winter wheat and 38% of its rye would be produced in the war-affected regions in 2022, and Ukraine's sunflower production in 2022 would drop by a significant 35% compared to in 2021 [27]. Before the conflict, both Russia and Ukraine played important roles in the global grain trade. In 2021, Russia was the world's largest wheat exporter, accounting for 30% of total global wheat trade, and Ukraine was the fifth largest wheat exporter, accounting for nearly 10% of global wheat trade. Furthermore, Ukraine was the world's fifth-largest exporter of corn, and Russia was the world's largest exporter of nitrogen fertilizer, the world's second-largest exporter of potash, and the world's third-largest exporter of phosphate fertilizer [28,29]. From when the conflict broke out, grain exports of both countries have been greatly affected; in 2022, for example, Russia dropped sharply to the fifth largest wheat exporter in the world, and Ukraine dropped to the seventh largest, with its global share falling by about a half. This was caused not only by the impact on grain production, but also by the disruption of transportation and the sanctions imposed on Russia. About 95 percent of Ukraine's food exports relied on maritime trade, with the conflict having resulted in serious damage to ports such as Mariupol and Kherson and the closure of all Black Sea ports, thereby resulting in a significant drop in Ukrainian exports [30,31]. The Russia–Ukraine conflict has affected global food prices and further impacted the world's food supply system [32,33] and has caused a shortage of food supply and inhibited the export of Russian fertilizers [34], thus triggering global food price fluctuations and pushing up global food prices [35]. According to statistics, the Russia–Ukraine conflict has affected the prices of maize and barley by 0.62% and 1.96% [36,37].

Over the past few decades, global food trade has grown at a significant rate, essentially forming a complex global FTN [38], with each country having direct or indirect links to the others [39,40], which means that shocks will affect the entire world's food supply through the FTN. To potentially break through the global food security challenge and achieve the Sustainable Development Goals, we focus on the evolution of the vulnerability and resilience of trade networks in periods of high-risk levels and the structural changes in trade networks aftershocks, because characterizing the FTN provides a deeper understanding of the vulnerability of food supply systems.

The rest of the paper is as follows. Section 2 describes the analytical framework based on complex network theory, the statistical indicators, and the sources of data. Section 3 analyses each of the four main crops (rice, maize, wheat, and soybeans), while Sections 4 and 5 discuss the results and give theoretical explanations.

2. Materials and Methods

2.1. Complex Network Analysis Framework

Complex network theory is based on the structure and features of networks that are composed of a large number of interconnected nodes (people, computers, cells, companies, etc.), which usually have complex topologies [41,42]. Because of the topological character of international commodity flows, complex network theory has an extensive application in international trade [43–46]. According to complex network theory, the global agricultural trade network is weighted and directed [38,41]. In the food trade network, each country involved in trade is represented by a node. The link between a pair of nodes is directed by the direction of trade flows. We set network weights based on the monetary value of products exported and imported by each country, to construct food trade networks G with four main food crops (soybeans, wheat, rice, and maize) over the period 2000 to 2022:

$$G = (V, W, C, T) \tag{1}$$

where V represents the set of all food trade-participating countries (nodes) and W represents the set of all bilateral trade flows (edges). C represents the different crops and T is the set of years for each of the global food trade networks. Then, based on the four different networks, we construct network analysis indicators based on networks and nodes. For networks, the main four basic ones measure global efficiency, average clustering, average shortest path length, network density, degree centrality, and closeness centrality for nodes.

2.2. Centrality Measures

2.2.1. Degree Centrality

Degree centrality (DC) refers to the sum of the number of trade links a country has with other countries, and this indicator reflects whether the country is in the center or the periphery of the trade network, and the larger the value indicates that the position is closer to the center [47,48]. For the given network G, the degree centrality of country i can be expressed as follows:

$$DC(G)_i = \sum_{j \in V} W_{ij} \tag{2}$$

where N is the number of countries in the network G, W_{ij} represents whether or not there is a trade flow between country i and country j in network G, $W_{ij} = 1$ if trade occurs between country i and country j, and $W_{ij} = 0$ otherwise.

2.2.2. Closeness Centrality

Closeness centrality (CC) explains the average distance between country i and all countries in the trade network, reflecting the influence of country i in the trade network [49,50]. According to network theory, we define the geodesic path (γ_{ij}), which means the shortest trade flow path from country i to country j, with the closeness centrality of country i being described as follows:

$$CC(G)_i = \frac{1}{N} \sum_{j \in V} \gamma_{ij} \tag{3}$$

2.3. Network Measures

2.3.1. Network Density

Network density (ND) describes the proportion of existing trade links to the total of all possible trade links in network G. It can be used to reflect the density of the trade network [51,52], with larger values indicating that the countries involved in international trade are more closely linked.

$$ND(G) = \frac{L}{N(N-1)} \tag{4}$$

In Equation (4), L is the sum of the number of edges existing in all nodes in the network G, and $N(N-1)$ represents the maximum value of edges in the network G.

2.3.2. Network Efficiency

Network efficiency (NE) refers to the efficiency of information transfer in a network [42,53,54]. An efficient network is able to transfer information from the source node to the target node quickly and with minimal loss in the transfer process, and the stability of a network is the ability to maintain its structure and functionality. In international trade studies, larger and more concentrated commodity value flows between countries (nodes) may imply higher trade efficiency [55,56]. In network research, redundancy refers to the presence of redundant connections or paths in a system that provide alternative efficient paths when the primary path breaks down [56,57]. A stable network can quickly return to its normal state or keep the critical functions unaffected during an attack. Stability is closely related to the robustness and resilience of a network and is commonly assessed by modeling the network's performance under different perturbations [55–57]. Therefore, adding redundancy (i.e., adding alternate paths or nodes) improves the stability of the network, but it may reduce the efficiency of the network because it may involve longer or more trade paths [58].

Network efficiency (NE) reflects the effectiveness and the strength of the interconnection between nodes, to understand the stability and resilience of the trade network G [48,49]. The lower the network efficiency, the higher redundancy that exists in the network system, indicating that the stability of G is likely to be higher.

$$NE(G) = \frac{1}{N(N-1)} \sum_{\substack{i,j \\ (i \neq j) \in V}} \frac{1}{W_{ij}} \tag{5}$$

2.3.3. Average Shortest Path Length

In network analysis, efficiency can be measured by various efficiency metrics, such as shortest path length, Maximum Flow, Min Cut, etc. [54]. Average shortest path length ($ASPL$) counts the average number of steps of the shortest path between every two nodes in a trade network. γ_{ij} in Equation (6) corresponds to that in Equation (3), which means the shortest trade flow path from country i to country j. $ASPL$ is used to measure the overall transmission efficiency of the network [59,60], with shorter values indicating higher circulation efficiency.

$$ASPL(G) = \frac{1}{N(N-1)} \sum_{\substack{i,j \\ (i \neq j) \in V}} \gamma_{ij} \tag{6}$$

2.3.4. Average Clustering Coefficient

Average Cluster Coefficient (ACC) describes the clustering properties of the network G. High ACC means that nodes in a network tend to form tight groups or communities, which is a common feature of networks [61,62]. ACC is the average of all nodes, and the local clustering coefficient (LCC), specifically, for a given node, is computed as the number of edges that actually exist between the nodes that are neighbors of that node divided by the maximum number of edges that may exist between those neighboring nodes [61,62]. If all the neighbors of a node are connected to each other, then the local clustering coefficient of this node is 1, indicating a fully connected local network; if there are no connections between the neighbors, then the clustering coefficient is 0.

$$ACC(G) = \frac{1}{N}\sum_{i\in V}\frac{e_i}{d_i(d_i-1)} \tag{7}$$

where $d_i = DC(G)_i$ to simplify the equation and e_i denotes the number of edges among the nodes (connected to country i).

2.4. Data Sources

The agricultural bilateral trade data for the four major crops (rice, maize, wheat, and soybeans) from 2000 to 2022 are obtained from the Food and Agriculture Organization's Statistics Division (FAOSTAT, https://www.fao.org/faostat/en/#data/TM, accessed on 10 March 2024). We have harmonized the use of reported data from importing countries to mitigate the effects of statistical omissions and data asymmetries [38].

3. Results

3.1. Evolution of Global Food Trade Networks

Based on the complex network analysis framework, we analyze the evolution of global food trade flows, and we focus our attention on comparing the changes that have occurred in the structure of global food trade. It should be mentioned that, to simplify the elements and highlight the features of trade structure changes, we have excluded negligible trade flows (below 20 tons). Referring to related studies, we constructed food trade networks using global trade data of food crops. To avoid statistical errors, we selected import flows [38]. Through the form of the directed chordal graph, we presented the trade flows and the structure. The outermost part of the circle represents the countries participating in the trade, and the inner part of the circle represents the flow of specific crops (smooth edges indicate export flows; sharp edges indicate import flows).

As shown in Table 1, during the study period, there is no dramatic change in the list of top import and export countries for selected crops. Land-scarce countries remain major importers, such as China, India, and Japan, and land-abundant countries remain major exporters, such as the USA, Russia, and Canada.

Table 1. Top 10 exporter and importer countries for the selected crops during the study period (on average).

Soybean		**Rice**		**Wheat**		**Maize**	
Top 10 Importers							
2010~2016	2017~2022	2010~2016	2017~2022	2010~2016	2017~2022	2010~2016	2017~2022
CHN	CHN	MEX	MEX	IDN	IDN	JPN	JPN
MEX	MEX	VEN	VEN	DZA	EGY	MEX	MEX
DEU	ARG	TUR	NPL	EGY	TUR	KOR	CHN
JPN	NLD	NIC	VNM	ITA	DZA	ESP	KOR
ESP	JPN	NPL	CRI	JPN	ITA	EGY	VNM
NLD	DEU	GTM	PHL	BRA	CHN	NLD	ESP
TWN	EGY	PAK	HND	KOR	PHL	TWN	EGY
THA	THA	HND	NIC	ESP	JPN	COL	IRN
IDN	ESP	CRI	COL	TUR	BRA	ITA	NLD
TUR	TUR	SLV	GTM	MEX	NGA	VNM	ITA
Top 10 Exporters							
2010~2016	2017~2022	2010~2016	2017~2022	2010~2016	2017~2022	2010~2016	2017~2022
USA	BRA	USA	USA	USA	RUS	USA	USA
BRA	USA	CHN	BRA	CAN	USA	BRA	BRA
ARG	ARG	BRA	IND	AUS	CAN	ARG	ARG
PRY	CAN	IND	CHN	FRA	AUS	UKR	UKR
CAN	PRY	RUS	URY	RUS	FRA	FRA	FRA
UKR	UKR	ARG	PRY	DEU	UKR	HUN	ROU
NLD	URY	URY	GRC	UKR	ARG	ROU	HUN
URY	NLD	GUY	RUS	ARG	DEU	IND	RUS
CHN	RUS	ESP	ITA	KAZ	ROU	RUS	ZAF
BOL	HRV	PRY	BGR	ROU	KAZ	ZAF	IND

There are still some important changes. Firstly, Brazil has replaced the United States as the largest soybean exporter, mainly due to the Sino-US trade war. In order to get rid of over-reliance on U.S. soybeans, China has expanded its import of soybeans from other countries. Secondly, Argentina has become the third largest soybean importer, while at the same time, it is the third largest soybean exporter. It is inferred that due to the Sino–U.S. trade war, China tends to import soybeans from markets other than the United States, so Argentina imports a large number of soybeans from the United States and re-exports them to China. Thirdly, Russia has become the world's top wheat exporter. Furthermore, Ukraine remains one of the most important wheat exporters.

3.1.1. Global Soybean Trade Networks

Increased systemic risk has led to the extension of the soybean supply chain to more countries, with trade flows becoming significantly more intensive, although the main structure still comprises the United States, Brazil, and China [63–66].

Figure 1 shows the characteristics of soybeans with a high concentration in production and trade. The United States, Brazil, and Argentina are the world's largest producers of soybeans, China is the world's largest consumer of soybeans, and China's imported soybeans account for 83.7% of the total consumption in 2022. Brazil, the United States, and Argentina almost monopolize the global soybean export trade, and their exports to China account for about 60% of the world's total. The share of soybeans imported by China from Brazil increased significantly from 2010 to 2022. The trade friction between the United States and China has led China to avoid dependence on the United States, and stabilizing China's soybean supply [67,68] is the motivation for the large growth of the Brazilian share.

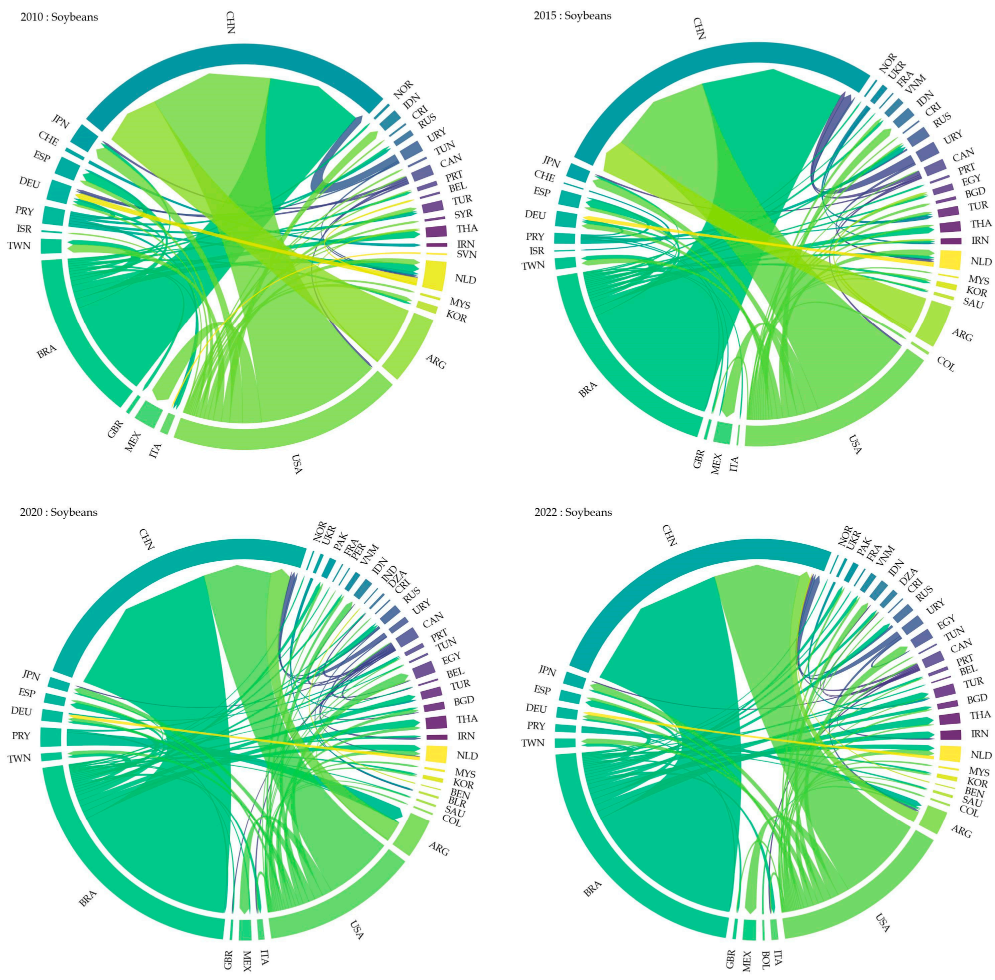

Figure 1. Global soybean trade flows structure for chosen years.

Food trade can be influenced by political factors, thus affecting the sustainability of the international food supply chain [69,70]. The structural characteristics of international trade in soybeans provide direct evidence of the role that international trade plays in globalizing and redistributing unbalanced agricultural production resources. China's domestic production is insufficient to satisfy the consumption of soybeans, essentially exchanging agricultural production resources through trade [43,44].

3.1.2. Global Rice Trade Networks

In the global rice market (Figure 2), major exporters are clustered in the Americas and Asia, particularly the U.S., China, Brazil, Thailand, Vietnam, India, and Pakistan, because of their resources for agricultural production and policy support. Importing countries are mainly located in Africa, the Middle East, Southeast Asia, and Latin America, which rely on imports to fulfill their domestic needs due to their limited agricultural production capacity [45,46].

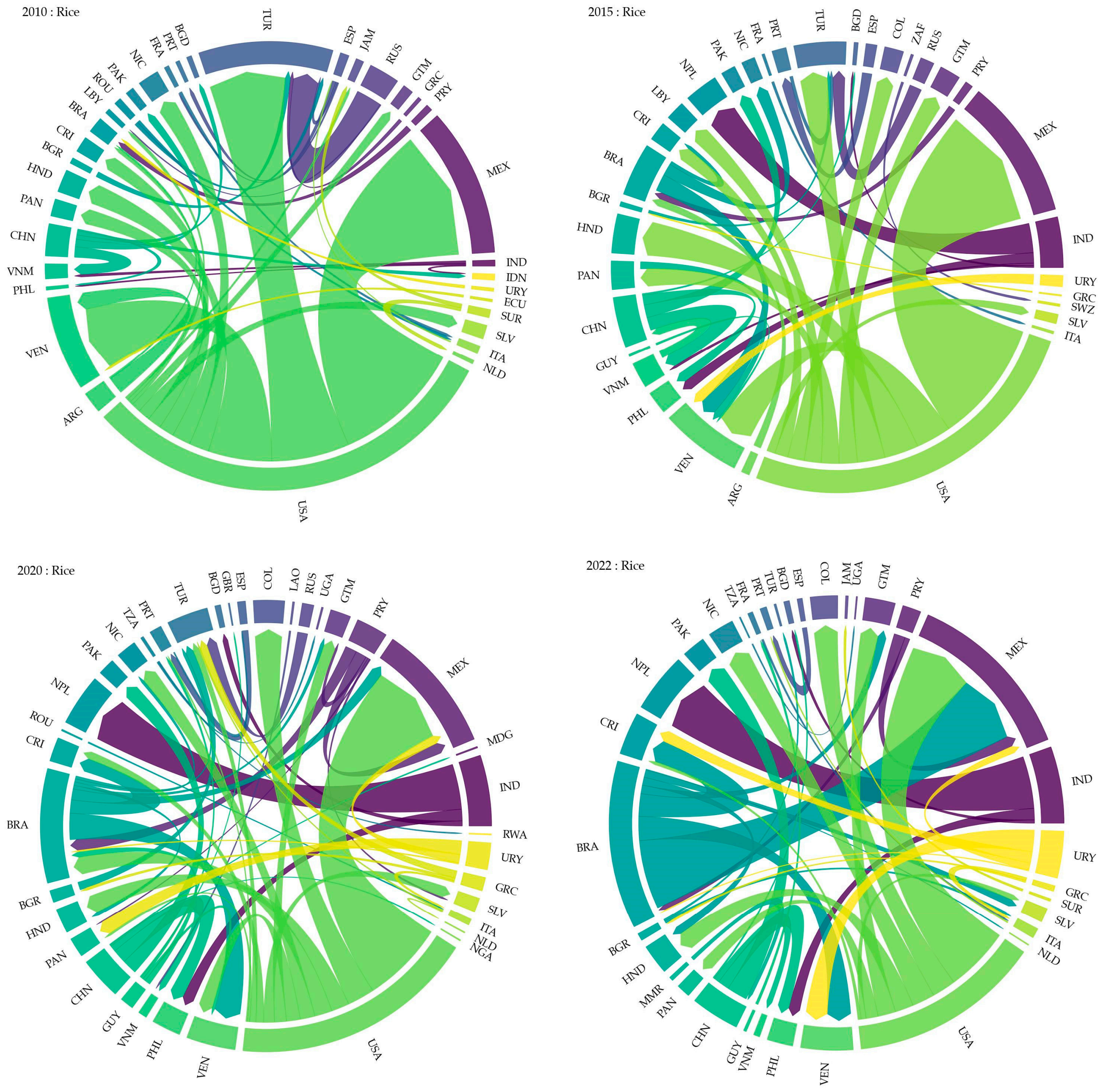

Figure 2. Global rice trade flows structure for chosen years.

In Figure 2, the decline in U.S. rice exports is very significant and accelerating, from 70.92% of global rice exports in 2010 to 42.65% in 2020 to 31.93% in 2022. U.S. rice has almost captured the market in Mexico in 2010 and 2015; however, due to the high risk of food supply from the epidemic, Mexico has increased rice imports from Brazil and Paraguay. In 2022, the share of U.S. rice exports declined again due to the Russia–Ukraine conflict, with Mexico importing half of the rice from the U.S. and half from Brazil. Thus, by comparing the rice trade network over time, it is quite evident that the highly concentrated bilateral trade flows have gradually evolved towards the less concentrated multilateral trade flows since the uncertainty in the world economy has remained at a high level. Countries' import policies have increasingly opted for multilateral trade to reduce the risks associated with excessive concentration [71,72].

3.1.3. Global Wheat Trade Networks

As shown in Figure 3, the global wheat trade network is relatively decentralized, with very low trade concentration compared to that of the other three crops for imports, and the share of world import trade accounted for by the countries with the highest imports is consistently lower than 7 per cent from 2010 to 2022.

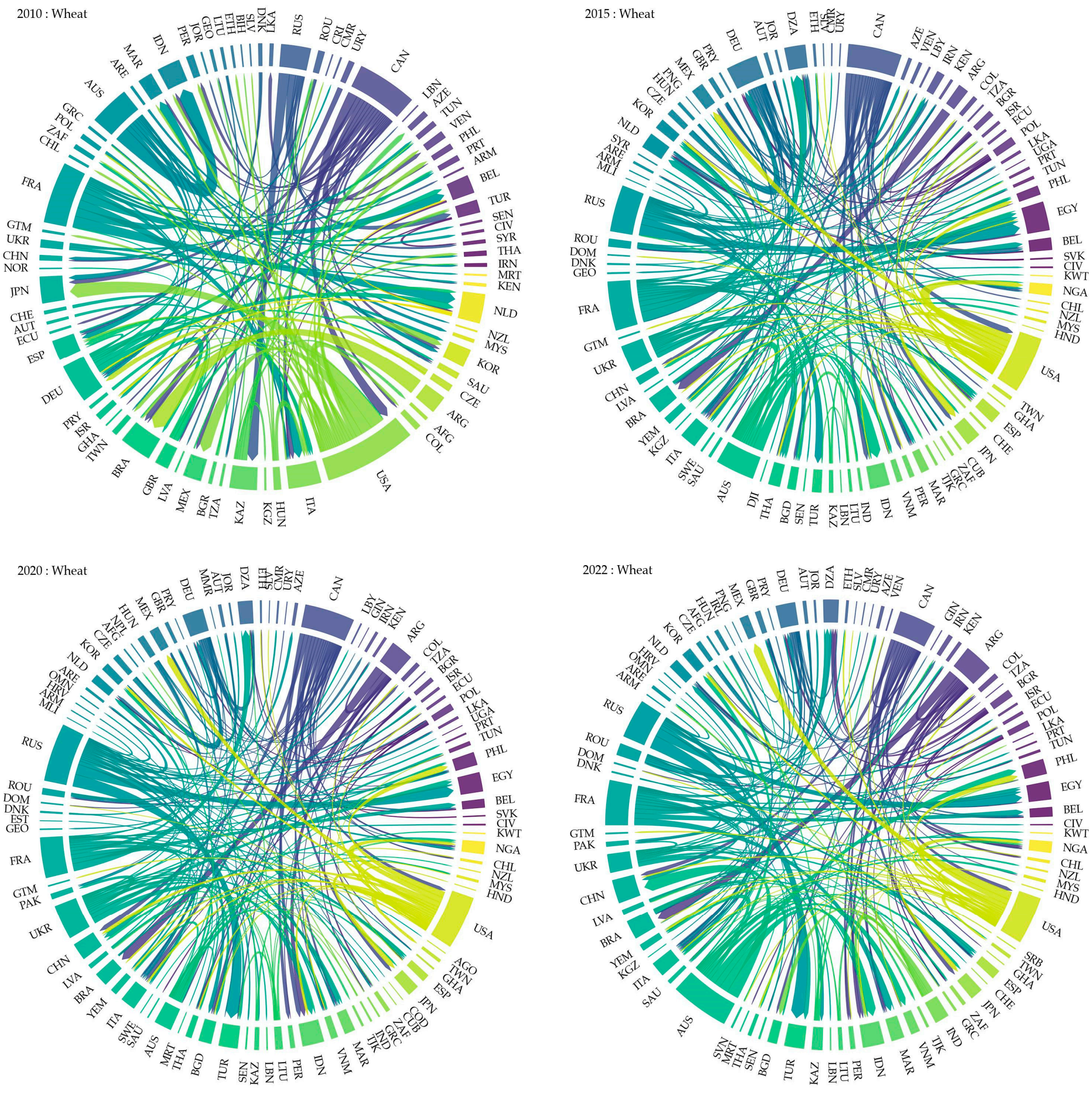

Figure 3. Global wheat trade flows structure for chosen years.

The wheat export trade network is more concentrated than the import one, mainly in a few land-rich countries such as the United States, Australia, and Canada. However, there is also a certain downward trend in export concentration from 2010 to 2022, with major exporters such as the United States, Canada, and France all showing a clear downward trend in their share of world exports from 2010 to 2022.

The wheat trade network is more complex; compared to that of other crops, it is more complete and more resilient, with a lower degree of concentration [73,74]. Thus, it is less negatively affected by the impact of the COVID-19 pandemic and the Russia–Ukraine conflict.

3.1.4. Global Maize Trade Networks

In Figure 4, the export concentration of maize decreases sharply from 2010 to 2022. In 2010, the global maize export trade mainly came from the United States, which accounted for nearly half of the global maize export.

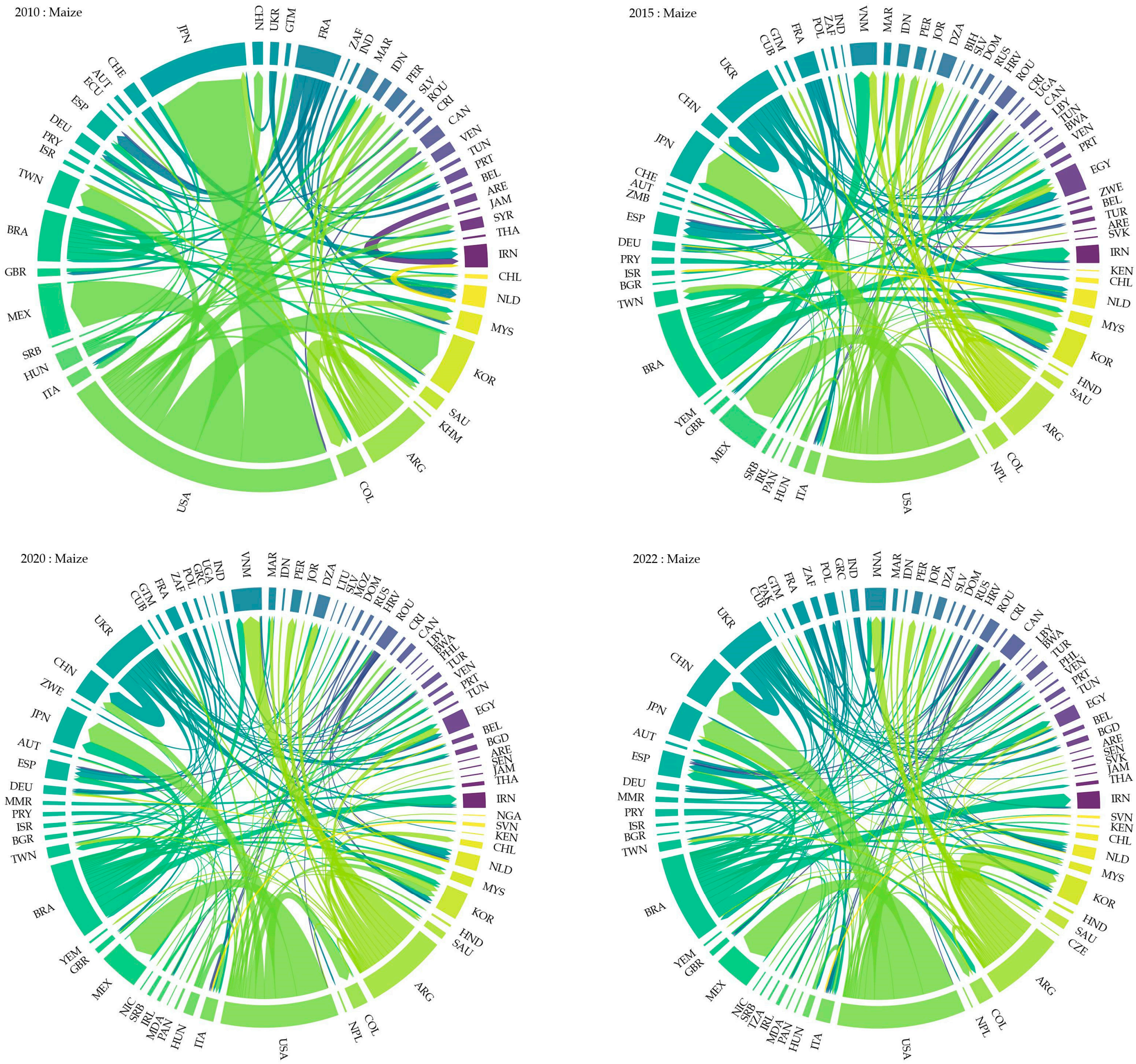

Figure 4. Global maize trade flows structure for chosen years.

The export share of the USA decreased significantly from 42.41% in 2010 to 26.09% in 2020 to 30.27% in 2022, while Brazil's export share increased from 9.33% in 2010 to 19.51% in 2022. In the period 2010–2022, the increased complexity of the global maize trade network shows that trade diversification is an effective way to cope with uncertainty.

3.2. Food Trade Network Topology Analysis

Figure 5 shows the dynamic trend of the network indicators of the FTN from 2000 to 2022, and the long-term trend of the FTN indicators of the four crops is clear; moreover, it is worth mentioning that the change is very significant after entering the high-risk period (2017–2022). The overall connectivity of the FTN demonstrated a rising trend: with the development of the global economy, countries are cooperating more closely on food trade for the four main crops, which has significantly increased the efficiency and density of food distribution, while dependence on the FTN is gradually increasing [75,76].

Figure 5. Evolution of average clustering, average shortest path length, network density, and global efficiency of FTN.

Network density (*ND*) and global efficiency (*GE*) of the four crops showed an overall increasing trend, indicating increased dependence on food imports. Since 2000, the globalization of food trade has developed rapidly, and while showing characteristics of regional trade cooperation, the trade structure is affected by shocks and enters a period of adjustment after 2017. The rise in the average clustering coefficient (*ACC*) indicates the probability of interconnection between neighboring nodes of a node in a network, and a high average clustering coefficient implies the existence of a tight community structure in the network (e.g., Regional Trade Agreements). A decline in the average shortest path length (*ASPL*) is a symbol of enhanced national food availability, and the *ASPL* explains the average length of the shortest path between any two nodes in the network, reflecting the closeness of the network and the speed of information dissemination.

Obviously, four types of network indicators show trend changes in 2017–2022. From an integrated perspective, structural shifts in the FTN are taking place in the post-shock period—transitioning from a preference for economic efficiency to a preference for stability.

3.3. Node Feature Distributions of Food Trade Network

To derive more effective and direct conclusions, we have conducted separate statistical analyses for degree centrality (*DC*) and closeness centrality (*CC*) at the national level for four types of crops, and we have created density distribution charts (Figure 6). $D = 1$ indicates the average of *DC* or *CC* for a country between 2012 and 2017, and $D = 2$ indicates the average between 2018 and 2022.

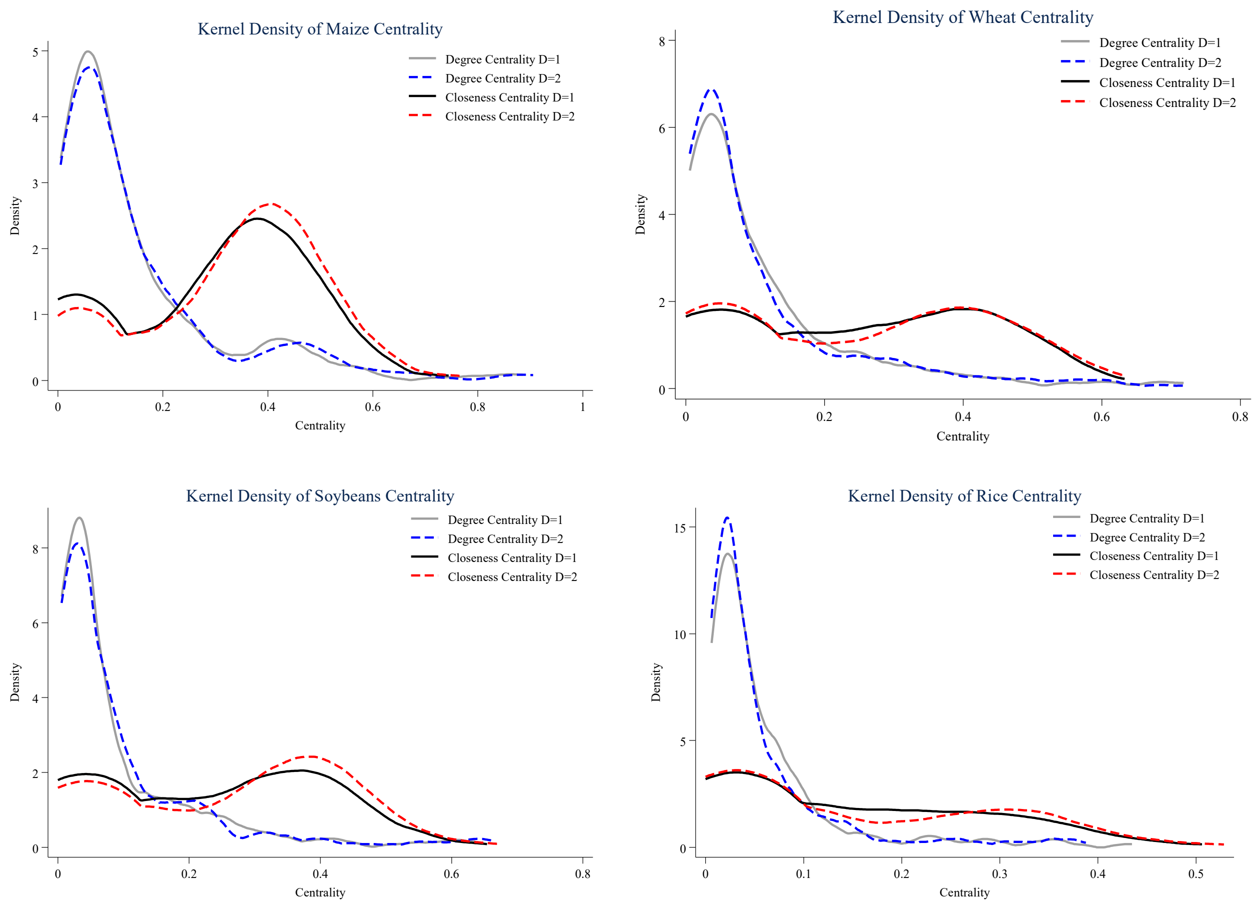

Figure 6. Kernel density distribution of degree centrality and closeness centrality.

For soybeans, rice, and maize, the extreme point on the right side of the $CC(D = 2)$ curve is shifted to the right, implying an increase in the mean value of CC and a significant increase in density, compared to those of the $CC(D = 1)$ curve. This means that countries with high initial values of *CC* are increasingly inclined to expand further and expand their trading partners, as a strategy to defend themselves against damage to the food supply system from external shocks.

For wheat and rice, the increase in countries within the low degree centrality (*DC*) range indicates that small-scale bilateral trade for these grains is becoming more dispersed. During the period ($D = 2$), the international markets for wheat and rice were impacted by a surge in external risks, leading to an increase in the number of connections among countries involved in the trade of these grains, thereby making the network denser. Conversely, despite an increase in connections for soybeans and corn, the density has decreased when observed from the perspective of national distribution. The conflict between Russia and Ukraine had the most significant direct impact on corn, with Ukraine's agricultural production coming to a halt due to the conflict, resulting in a loss of up to 85% of wheat production, which directly led to a decrease in the density of the global corn trade network.

4. Discussion

First, shocks make the global food trade flows increasingly decentralized. With regard to importing countries and exporting countries, trade concentration declined significantly; *ND* showed an upward trend in response to the number of countries involved in food trade; the number of trade flows demonstrated an upward trend; according to the results of the measurement of the degree of centrality of the close degree of *CC* and the degree of centrality of the degree of *DC*, more countries increased the number of trading partners; and the important food categories of small-scale bilateral trade were more dispersed. These results and conclusions are consistent with those of existing research, for instance, *ND*, the number of trade flows, and the number of countries participating in trade are on the rise, and the global grain trade is becoming more and more fragmented [77,78].

Second, shocks tend to make the global food trade network (FTN) denser. The overall upward trend in the density indicator, which reflects the density of the network, and the continued decline in the *ASPL*, which reflects the distance of bilateral trade paths, indicate that the density of the global trade network is becoming more complex and the links between individual markets are becoming tighter. Most of the existing literature also concludes that the density of the world's food trade network is increasing, for instance, the density indicator and number of nodes of the global food trade network have risen significantly [72,78].

Third, shocks have accentuated the regionalization of the FTN. From 2000 to 2022, the average clustering coefficient (*AC*) has continued to increase, and the average shortest path length (*ASPL*) has persistently decreased, suggesting that regional cooperation in trade has become increasingly evident, and the modularity of the FTN exhibits a distinct upward trend. These results are consistent with existing research, for example, the *AC* and *ASPL* show an upward trend in the global agricultural product network [38,79].

The differences between this study and existing research are as follows. First, the period of this study is extended to 2022, which is the year when the Russia–Ukraine conflict broke out. In this way, changes in the global food trade network before and after the conflict can be directly observed. However, most studies only cover the period before 2022 [43,72]. Second, we focus on wheat, corn, soybeans, and rice, which are food crops that are most closely related to achieving the SDGs. Compared with the existing literature, we focus on these four crops [48,80]. Third, this study makes full use of a complex network analysis framework to comprehensively judge the vulnerability of the global food network, focusing on its impact on sustainable development.

From the evolution of the FTN, we can infer that diversification and regionalization are the key strategies for countries to address food security challenges. Nations are increasingly preferring to broaden the spectrum of their food trade partners, thus mitigating the adverse effects of potential risks. The strategies have given rise to a trade network that is both more decentralized and intricately interconnected. In addition, by promoting the regionalization of food trade networks, countries can build more resilient trading partnerships, thereby contributing to the overall stability and robustness of food trade networks.

Geopolitical tensions and public health crises have catalyzed the FTN's shift towards enhanced resilience. Trend analysis of trade network indicators shows that the changes have been more marked after 2017, with the rebuilding of global trade patterns, the trade war, the COVID-19 pandemic, and the Russia–Ukraine conflict becoming key events. Security and stability have become key issues in the international trade network landscape. As a result, these challenges have prompted countries to adopt strategies such as diversifying their trading partners, thereby accelerating efforts to reduce the vulnerability of their foreign trade networks.

Through decentralization or other paths, the FTN is adjusted in the direction of reducing vulnerability, but there is still a high risk. Rice and maize export trade is still concentrated in a small number of exporting countries, and the number of exporting countries is much smaller than the number of importing countries, and even for wheat, which has a higher degree of decentralization, the degree of export concentration is still much higher than the degree of import concentration, and almost all export trade of soybeans is monopolized by few exporting countries.

The structure of grain trade is significantly influenced by natural resource endowments, and it may be challenging to reduce the vulnerability of trade networks through only the diversification of trade sources. In the case of China's soybean trade, despite efforts to reduce reliance on the United States, the difficulty in lowering risks through diversification of import sources is compounded by the fact that there are only a few primary soybean-exporting countries in the world.

There are still issues that require further exploration. Firstly, what factors can help promote diversification and regionalization in food trade, especially in the context of increasing global instability? Secondly, what factors can promote rapid adjustment of food networks when public health events and geopolitical conflicts occur? Thirdly, what measures can help promote international cooperation among countries in the field of food security, thereby contributing to the global SDGs?

5. Conclusions and Policy Implications

The COVID-19 pandemic and the Russia–Ukraine conflict have played pivotal roles in catalyzing the adaptive process. Amidst the pressing challenges to global food security, nations have mitigated potential risks by embracing trade diversification and regionalization. These strategies have contributed to a general increase in the density and regional integration of the global trade network, thereby enhancing its resilience.

- The global food trade network (FTN) has been changing in the direction of decentralized trade flows, denser networks, and regionalized structures. An important reason for this trend in the FTN is that countries have adopted strategies of diversification of trading partner countries and regionalization of trade in response to food trade security concerns.
- As the pattern of food supply and demand is strongly influenced by natural resource endowment, the extent of reducing the vulnerability of global trade networks through densification and other means is limited. In the future, to further reduce the vulnerability of the FTN, as well as to further promote densification and regionalization, food production, transportation, and storage technologies should be further upgraded, geopolitical conflicts should be mitigated, and research and development inputs should be increased in response to events such as epidemics, outbreaks, climate change, and natural disasters.

In terms of realizing the SDGs, global food trade networks, as important parts of them, have overall been adjusted in a direction with reduced vulnerability but still face major challenges. In addition to the rising global risks, overall high concentration, and difficulty in reducing risks through the diversification of trading partners, the increase in trade network density also means that a single event will have a wider impact on the overall global grain network. For example, the impact of an incident may not be limited to the countries directly involved but may spread to more countries through global trade networks. As a result, the food security of countries around the world is increasingly interconnected. While reducing food security risks through trade diversification, it is particularly important for all countries around the world to unite and jointly reduce global risks to achieve the SDGs.

According to the results of this study, the following methods will help reduce the vulnerability of global food trade networks, thereby helping to achieve the SDGs.

- First, countries around the world continue to promote the diversification and regionalization of the food trade to increase the flexibility of grain trade and reduce potential food risks.

- Second, when risk events such as epidemics and military conflicts occur, countries and relevant international organizations around the world guide world grain trade participants to diversify and regionalize the food trade network.
- Third, as the world is becoming increasingly unstable, countries and relevant international organizations strengthen risk supervision and provide timely warnings.
- Finally, as the density of the global food network is increasing and countries around the world are becoming more interdependent, all countries work together to avoid the occurrence of global geopolitical or public health events, promote scientific and technological progress, improve productivity, and contribute to the realization of the global SDGs.

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Abbreviations

FTN	Food trade network
DC	Degree centrality
CC	Closeness centrality
ND	Network density
NE	Network efficiency
ASPL	Average shortest path length
ACC	Average clustering coefficient

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