Argumenta Oeconomica
Year 2026, Vol. 56, No. 2
ISSN 2720-5088
journals.uew.pl/aoe

Complex network perspectives on global grain trade: The role of the Black Sea Grain Initiative

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Quote as: Filiz, T., & Topuz, H. (2026). Complex network perspectives on global grain trend: The role of the Black Sea Grain Initiative. *Argumenta Oeconomica. 56*(2), 55-72.

DOI: 10.15611/aoe.2026.2.04

JEL: Q18, R40, F14

Abstract

Aim: The aim of this article was to analyse the structural impacts of the Black Sea Grain Initiative (BSGI) on wheat and corn trade networks and to develop policy-relevant insights to enhance the resilience of grain supply chains in the face of geopolitical shocks.

Methodology: Using trade data from the United Nations (UN), the study applied complex network analysis to investigate the structure, connectivity, and clustering of wheat and corn trade networks. The analysis focused particularly on how the Russia–Ukraine war reshaped trade hubs, flow dynamics, and overall network efficiency.

Results: The findings revealed that global wheat and corn trade networks presented an oligopolistic structure, with Ukraine occupying a central role. The conflict led to substantial transformations in network structures, altering both the direction and intensity of trade flows. These changes underlined heightened vulnerabilities, particularly for import-dependent countries in Africa, the Middle East, and Europe.

Implications and recommendations: The article highlights the necessity of strengthening maritime trade routes, implementing international security measures for maritime transportation, and fostering regional cooperation. In addition, it emphasises the importance of reactivating or replacing the BSGI through a new international framework to ensure the continuity of grain flows under conditions of ongoing conflict.

Originality/value: By integrating complex network analysis into the study of grain trade, the article fills a gap in the literature on the structural effects of the BSGI. It contributes to both academic debates and policymaking by identifying fragile points in global supply chains and outlining strategies to enhance resilience against geopolitical shocks.

Keywords: Black Sea Grain Initiative (BSGI), food security, grain trade, complex network analysis, Ukraine

1. Introduction

For thousands of years, grain products have been a vital component of human nutrition and have played a significant role in shaping human civilization. The survival of billions of people worldwide depends on foods derived from rice, wheat, corn, sorghum, and millet. Grain consumption accounts for more than 50% of the daily caloric intake of humans (Awika, 2011). Challenges in accessing these fundamental food resources have led to the emergence of the concept of food security. Food security is defined as a condition in which all individuals always 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 (Peng & Berry, 2019). In this perspective, global grain trade is crucial to food security, since it is not simply an economic activity but also a multifaceted issue inextricably linked to international relations, sustainable development, and public health.

Several fundamental causes of food insecurity manifest themselves across different regions. Unplanned population growth places pressure on limited resources, undermining equitable distribution through poverty, weak purchasing power, and poor access (Ahmad et al., 2021). Climate change further exacerbates these pressures by reducing agricultural productivity and complicating global supply chains (IPCC, 2021; Duchenne-Moutien & Neetoo, 2021). Armed conflicts and political crises worsen the situation by destroying farmland, irrigation systems, and infrastructure, while displacing communities and leaving populations vulnerable to prolonged hunger and malnutrition (Kemmerling et al., 2022). Moreover, climatic and geographical disparities create regions of surplus and scarcity, giving rise to complex and interdependent grain trade networks (Zhu & Gong, 2023). Heavy reliance on a limited number of suppliers makes import-dependent countries particularly vulnerable to market fluctuations, as disruptions from key exporters pose direct risks to food security (Wang et al., 2023).

The role of Ukraine and Russia in the global grain market has become particularly evident during the ongoing war. As major suppliers in the global grain trade, these two countries have a significant impact on global food security, and together account for approximately 30% of global wheat exports and 20% of global corn exports (OECD, 2022a). The heavy dependence on these two suppliers, combined with the severe disruptions caused by the war, have created an urgent need for an international mechanism to stabilize grain flows. These conditions paved the way for the establishment of the BSGI United Nations of 2022.

The BSGI emerged in July 2022 as an international agreement brokered by the UN and Turkey to address the food security crisis triggered by the Russia-Ukraine conflict (United Nations, 2024a). The agreement was signed in Istanbul by the UN, Turkey, Ukraine, and Russia, with Turkey and the UN acting as guarantors, Ukraine responsible for resuming grain shipments, and Russia ensuring that its ports and inspection mechanisms facilitated safe passage. The agreement, signed for an initial period

of 120 days, was subsequently extended several times until Russia's withdrawal in July 2023 (United Nations, 2024b). The initiative aimed to safely resume Ukraine's grain exports which were severely disrupted by the war and posed significant risks to global food security. Given Ukraine's critical role as a major grain producer − often referred to as the "Breadbasket of the World" − the BSGI sought to prevent supply chain disruptions by establishing security guarantees to ensure the safe passage of vessels through the Black Sea (Borrell Fontelles, 2023; United Nations, 2022). These measures included ship inspections and coordinated navigation routes to minimise risks (OECD, 2022b). During its one--year duration, the initiative facilitated the export of approximately 33 million tons of grain, reportedly contributing 20 billion USD to Ukraine's national budget (Kormych & Averochkina, 2023). However, one of the major shortcomings of the BSGI was its lack of direct reference to the Russia-Ukraine war, which, combined with persistent geopolitical tensions, led to recurrent disruptions in its implementation (Ekleme & Yercan, 2025).

Figure 1 provides an overview of Ukraine's wheat and corn trade trends between 2010 and 2023. The data show sharp variations, with wheat exports peaking at 4.7 billion USD in 2021 and corn exports reaching their highest value, 6 billion USD, in 2022. Wheat exports then fell sharply to 2.7 billion USD in 2022, before recovering slightly to 2.9 billion USD in 2023, while corn exports declined from their 2022 peak to 5 billion USD in 2023. These shifts illustrate the volatility of Ukraine's agricultural exports and highlight the impact of recent geopolitical developments, particularly the Russia–Ukraine war, on grain trade.

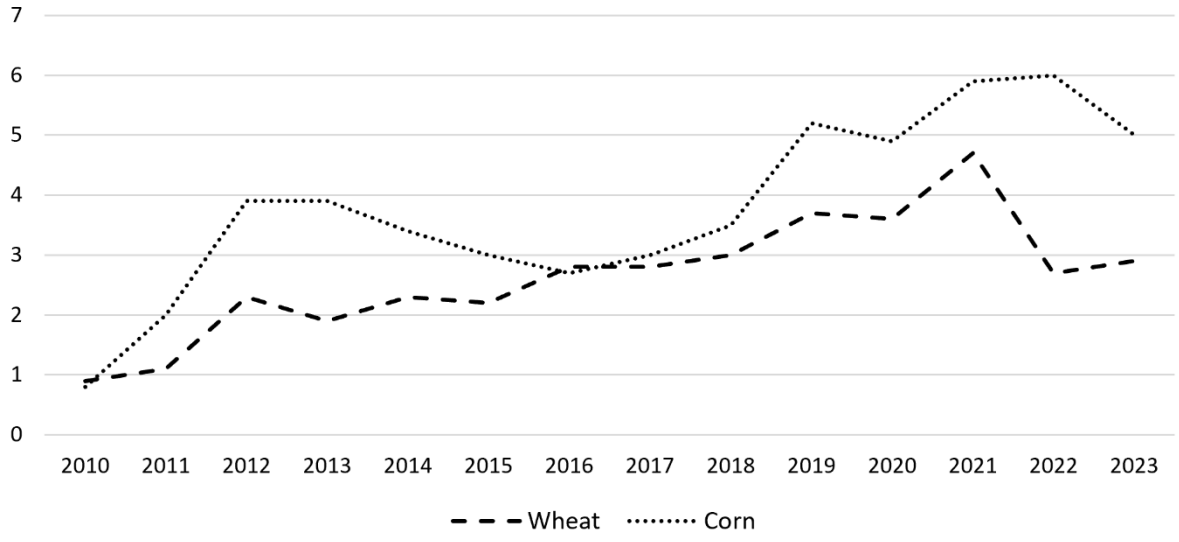

Fig. 1. Ukraine's Wheat and Corn Exports (in billions USD)

Source: United Nations, 2024b.

In July 2023, Russia officially announced its withdrawal from the BSGI, arguing that the agreement's provisions on facilitating Russian agricultural exports and fertilizer access to international markets had not been fulfilled. Moscow stressed that Western sanctions remained in place and continued to harm its agricultural sector, undermining its economic interests (Atlantic Council, 2023). Security concerns, particularly risks to grain shipments amid the ongoing war, also influenced its decision. Russia further contended that the deal largely benefited Ukraine and other countries while failing to meet its own commercial expectations, prompting its withdrawal. This development once again brought global food security to the forefront, reflecting escalating geopolitical tensions (Liefert, 2024; IFPRI, 2023). As of 2025, the war persists, and uncertainty remains over Ukraine's capacity to sustain grain exports.

Researchers have conducted academic studies to analyse the effects of the Russia–Ukraine war on agricultural trade, price fluctuations, and food security. Xu et al. (2024) applied complex network theory to reveal the vulnerability of global food trade networks and stressed the importance of

diversification and cooperation to withstand shocks such as COVID-19 and the conflict. Similarly, Zhang et al. (2024) identified structural changes in the wheat trade network, leading to significant fluctuations in trade intensity and efficiency. Trucmel and Vintila (2023) reported that some low--income countries were excluded from European grain export destinations, while Robu et al. (2024) documented short-term declines in trade connectivity and Jafari et al. (2023) highlighted the mixed effects of regional trade agreements. Braun et al. (2023) further stressed the broader implications of the war for energy, agricultural products, and iron, underlining heightened threats to food security in the Middle East and Africa. Devadoss and Ridley (2024) also indicated that these threats have already materialised, highlighting that import-dependent regions such as Africa and the Middle East are experiencing worsening food insecurity and malnutrition due to reduced Ukrainian grain supplies. Recent research has highlighted market-level consequences, particularly volatility in global grain prices after the suspension of the BSGI. Martins (2024) reported that agricultural commodity prices spiked at the onset of the war, eased temporarily with the implementation of the initiative, and rose again following Russia's withdrawal. Goyal and Steinbach (2023) emphasised that speculative pressures amplified fluctuations in grain futures markets, increasing uncertainty. Steinbach and Yildirim (2024) noted subsequent stabilisation, as investors anticipated limited long-term disruption due to the emergence of alternative export routes. Global wheat prices rose by 28% at the onset of the war, triggering food crises worldwide, especially in developing economies (Poursina et al., 2024).

Following Russia's withdrawal from the BSGI, considerable attention has been directed toward Ukraine's search for alternative export routes. Among these, the EU's Solidarity Lanes initiative, launched in May 2022 by the European Commission in cooperation with Poland, Romania, and Bulgaria, significantly enhanced Ukraine's connectivity with the EU (Beluhova-Uzunova et al., 2024; Rabinovych, 2025; European Commission, 2025). Initially conceived as an emergency response, the initiative soon evolved into a strategic export corridor, ensuring the continuation of grain flows to global markets and contributing to the stabilisation of agricultural commodity prices during the conflict (Goyal & Steinbach, 2023). Between May 2022 and August 2025 these routes enabled the export of more than 189 million tonnes of goods, including nearly 87 million tonnes of grain, while facilitating around 81 million tonnes of imports. The total trade value through this period reached approximately €225 billion, with €161 billion in imports (European Commission, 2025). Nevertheless, persistent challenges − particularly high transportation costs and limited infrastructure − constrained its overall effectiveness, imposed economic pressures on farmers in border states, and fuelled debates over the future direction of EU agricultural policy (Countryman et al., 2024).

In recent years the global food supply chain has faced multiple risks, including climate change, geopolitical crises, and logistical disruptions. The Russia–Ukraine war has caused particularly severe interruptions in the trade of essential grains such as wheat and corn, driving up food prices and worsening food insecurity worldwide. Earlier research has examined the effects of the conflict on agricultural trade flows, price volatility, and regional food security. Despite these contributions, relatively little is known about how the BSGI affected the structure of international wheat and corn trade networks. This gap highlights the need for a systematic analysis of how the BSGI influenced network structures and trade relations. This study aimed to address this gap by applying complex network analysis to assess the effects of the BSGI on wheat and corn trade networks, with a particular focus on changes in structure, connectivity, and clustering. In addition to advancing the literature on grain trade, the authors also sought to draw attention to potential policy implications for enhancing the resilience of supply chains in the face of future geopolitical crises.

Therefore, the following key research questions were posed:

- Which countries can be identified as strategic nodes within global wheat and corn trade networks?
- What are the impacts of the Russia-Ukraine war on wheat and corn trade networks?
- How has war influenced the cluster structures of grain trade networks?
- What effects arise from the inability to export Ukrainian grain on wheat and corn trade networks?

2. Data and methodology

This study utilised international trade data provided by the UN for the years 2021, 2022, and 2023. The dataset covered products classified under the Harmonised System codes 1001 (Wheat) and 1005 (Corn). For the analysis process, Gephi software was employed, with the Yifan Hu force-directed algorithm applied for network visualisation, which enhances visual clarity by arranging nodes in a well--structured manner, particularly in large and complex networks. Its ability to minimise edge crossings and optimise the distances between nodes enabled a clearer representation of the structural properties of the network (Yifan, 2006).

In the network analysis process, trade flows below USD 100 million were excluded. This threshold was selected to focus on identifying significant and central actors within the trade network. Given that the global trade network consists of numerous small-scale transactions, these minor flows can introduce noise into the network structure and complicate the interpretation of analytical results. Moreover, large-scale trade flows are of greater strategic importance and play a more decisive role in assessing the impacts of food security risks and disruptions in trade flows. Thus, the analysis was conducted exclusively on significant trade flows exceeding 100 million USD.

This article examines how the BSGI affects global grain trade using complex network analysis, based on Leonhard Euler's 18th-century graph theory, which helps social scientists, economists, and engineers understand the structural properties of interconnected systems. This study described countries as nodes and trade relationships as edges based on grain exchange prices. The average degree measures the extent of trade interactions among countries, with higher values indicating a more integrated network; network density shows the proportion of actual connections to all possible links, highlighting trade breadth and distribution; and in-degree and out-degree metrics identify key importers and exporters, respectively, revealing central grain trade system nodes.

A key tool for studying complex networks, modularity analysis finds groups of nodes in a network where their internal connections are stronger than their external ones. This method examines trade blocs and regional clusters within the BSGI grain trade network, emphasising structural trade relations and their ramifications (Lambiotte et al., 2008; Gautam & Gupta, 2023). In addition to identifying these communities, modularity analysis helps evaluate potential risks and opportunities by recognising dominant trade blocs and assessing their influence on global food security. If a particular bloc dominates a substantial share of the global grain supply, disturbances within it could profoundly impact trade dynamics. Consequently, modularity analysis is essential for pinpointing critical hubs and comprehending the interconnected dynamics of global grain trade.

Table 1 below shows the mathematical formulas for the key metrics and modularity analysis utilised in complex network analysis.

Table 1. Formulaic Representations of the Complex Network Analysis Metrics

Metric	Formula	Interpretation
Average Degree $(\bar{k})$	$\bar{k} = \frac{1}{N}\sum_{i=1}^{N} k_i$	*N* is the total number of nodes in the network. k_i is the total degree of node *i*, representing the total number of incoming and outgoing connections associated with that node.
Density (D)	$D = \frac{E}{N(N-1)}$	*E* is the number of existing directed edges in the network. *N* is the total number of nodes in the network.
Average Shortest Path Length (L)	$L = \frac{1}{N(N-1)}\sum_{i \neq j} d_{ij}$	d_{ij} is the number of edges in the shortest directed path from node *i* to node *j*. N is the total number of nodes in the network.

Metric	Formula	Interpretation
Modularity(Q)	$Q = \frac{1}{m}\sum_{C\in P}\sum_{i,j\in C}\left(A_{ij} - \frac{k_i^{out}k_j^{in}}{m}\right)$	A_{ij} is the weight of the directed edge from node *i* to node *j*. k_i^{out} is the weighted out-degree (sum of outgoing edge weights) of node *i*. k_j^{in} is the weighted in-degree (sum of incoming edge weights) of node *j*. *m* is the total weight of all edges in the network. P denotes the partition of the network into communities, and the double summation is performed over all pairs of nodes *i* and *j* belonging to the same community *C*.

Source: Newman (2010); Newman & Girvan (2004); Leicht & Newman (2008).

3. Results

The analysis indicated that significant structural changes occurred in the wheat and corn trade networks between 2021 and 2023 as a result of the BSGI's influence (see Table 2 for details). In the wheat trade network, the number of nodes (participating countries) increased in 2022 but declined again in 2023. The rise in 2022 reflected the involvement of more countries in trade, whereas the decrease in 2023 indicated a contraction of the trade network and a reduction in participating countries. Similarly, fluctuations in the number of edges (trade relationships between countries) also pointed to these structural transformations. This volatility suggests that geopolitical uncertainties have had a notable impact on the trade network.

The authors observed a similar contraction in the corn trade network. While a greater number of countries were involved in 2021, the network experienced a significant decline by 2023. This indicates that trade became concentrated among fewer countries, reflecting a narrowing of trade relationships.

The low network density and average degree values revealed that the trade networks operate with sparse and limited connections. This indicates that countries maintain trade relations with a small number of partners, limiting alternative sourcing options in the event of trade shocks. Moreover, changes in the average shortest path length over the years suggested that trade routes initially became longer but later shortened again, implying that trade shifted to more indirect routes in 2022.

Table 2. Metrics of Wheat and Corn Trade Networks

Year	Wheat			Corn		
	2021	2022	2023	2021	2022	2023
Node	75	85	75	60	62	56
Edge	124	156	122	94	108	92
Average Degree	3.31	3.67	3.25	3.13	3.48	3.29
Density	0.022	0.022	0.022	0.027	0.029	0.030
Average Shortest Path Length	1.195	1.439	1.316	1.333	1.337	1.308

Source: own calculations based on the UN Comtrade data.

Figure 2 presents the network visualisations of wheat trade for the years under analysis, which determined node sizes based on each country's out-degree value. In other words, the diameter of a node represents the number of export connections that a country has with other nodes, indicating its prominence as an exporter within the network. The direction of arrows shows the export flow, while the thickness of arrows reflects trade volume, with thicker arrows indicating larger export values.

In 2021, Australia, Russia, Canada, the United States, France, and Ukraine stood out as the leading central countries in wheat trade. Canada and the United States operated globally with multi-centred trade networks spanning Asia, Latin America, and Europe. Russia and Ukraine maintained a strong presence in the Middle East and African markets, while Australia held a dominant position in the Asia--Pacific region, particularly in markets such as China, Japan, and Indonesia. France focused on the European and North African markets, whereas Ukraine concentrated its exports on Eastern Europe, the Middle East, and Africa. The United States sustained a broad distribution of trade, engaging with countries such as Canada, Mexico, China, and Japan. Meanwhile, Russia exported to countries in the Middle East and North Africa, such as Turkey, Egypt, and Libya, and maintained strong trade connections with neighbouring countries, e.g. Kazakhstan and Azerbaijan.

In 2022, noticeable changes occurred in the wheat trade network compared to the previous year. Canada maintained its strong trade relations with the United States, China, Italy, and Japan while expanding into new markets in Africa and Europe, establishing trade links with countries including Nigeria and Spain, and strengthening ties with Chile, Colombia, and the Dominican Republic in Latin America. Australia preserved its dominance in the Asia-Pacific region but shifted focus to Africa, establishing new trade relationships with Kenya and South Africa while also reinforcing its ties with Bangladesh and Saudi Arabia. France sustained its deep trade relations within Europe (Germany, the United Kingdom, the Netherlands) and North Africa (Egypt, Algeria) while increasing its influence in Africa through new connections with countries such as Senegal and Cameroon. The United States expanded its trade network in Asia and Latin America by adding new markets such as Brazil, Vietnam, and Egypt, alongside its existing strong partnerships with Canada, Mexico, China, Italy, and Japan. Russia, in addition to its established trade ties with Turkey, Egypt, Libya, and Bangladesh, expanded into new markets such as Brazil, Kenya, and Pakistan, strengthening its presence in Africa and South America. These developments demonstrate that, in 2022, global wheat trade networks expanded and became increasingly multi-centred.

For Ukraine, 2022 was a year of significant change driven by geopolitical events. While it had a broad export network focused on Eastern Europe, the Middle East, and Africa in 2021, it was forced to narrow it in 2022. However, its trade relations with Turkey remained strong. Furthermore, Ukraine increased its trade connections with European countries such as Poland, Romania, and Spain. Overall, Ukraine's trade network became more geographically concentrated, with a shift toward Europe and a reduction in the number of trade partners.

The 2023 wheat trade network showed further noticeable changes compared to the previous year. Canada extended its exports to Africa and Latin America, establishing new trade relationships with Ghana, Venezuela, and Guatemala while maintaining its connections with Bangladesh in the Asian market. Australia continued its strong presence in the Asia-Pacific region, expanding its exports to China and Indonesia and strengthening its ties with Southeast Asian countries such as Vietnam and South Korea. France sustained its influence in the European and North African markets while increasing its activity in Africa through new connections with Senegal and Cameroon. The United States expanded into new markets in Latin America, such as Ecuador and Guatemala, and solidified its trade relations in Asia with South Korea and the Philippines. Russia focused heavily on Africa and the Middle East, extending its trade with Egypt and Türkiye while maintaining its presence in countries like Brazil and Nigeria.

Furthermore, 2023 marked a significant rise in Romania's role within the European trade network, as it emerged as a central node and became a prominent exporter contributing to regional trade. For Ukraine, 2023 showed greater regional diversification within its trade network. After shifting more toward Europe in 2022, Ukraine maintained strong trade ties with countries such as Romania, Egypt, and Bangladesh in 2023. Additionally, Ukraine further strengthened its trade with Romania and Italy, increasing its export volume to these two countries.

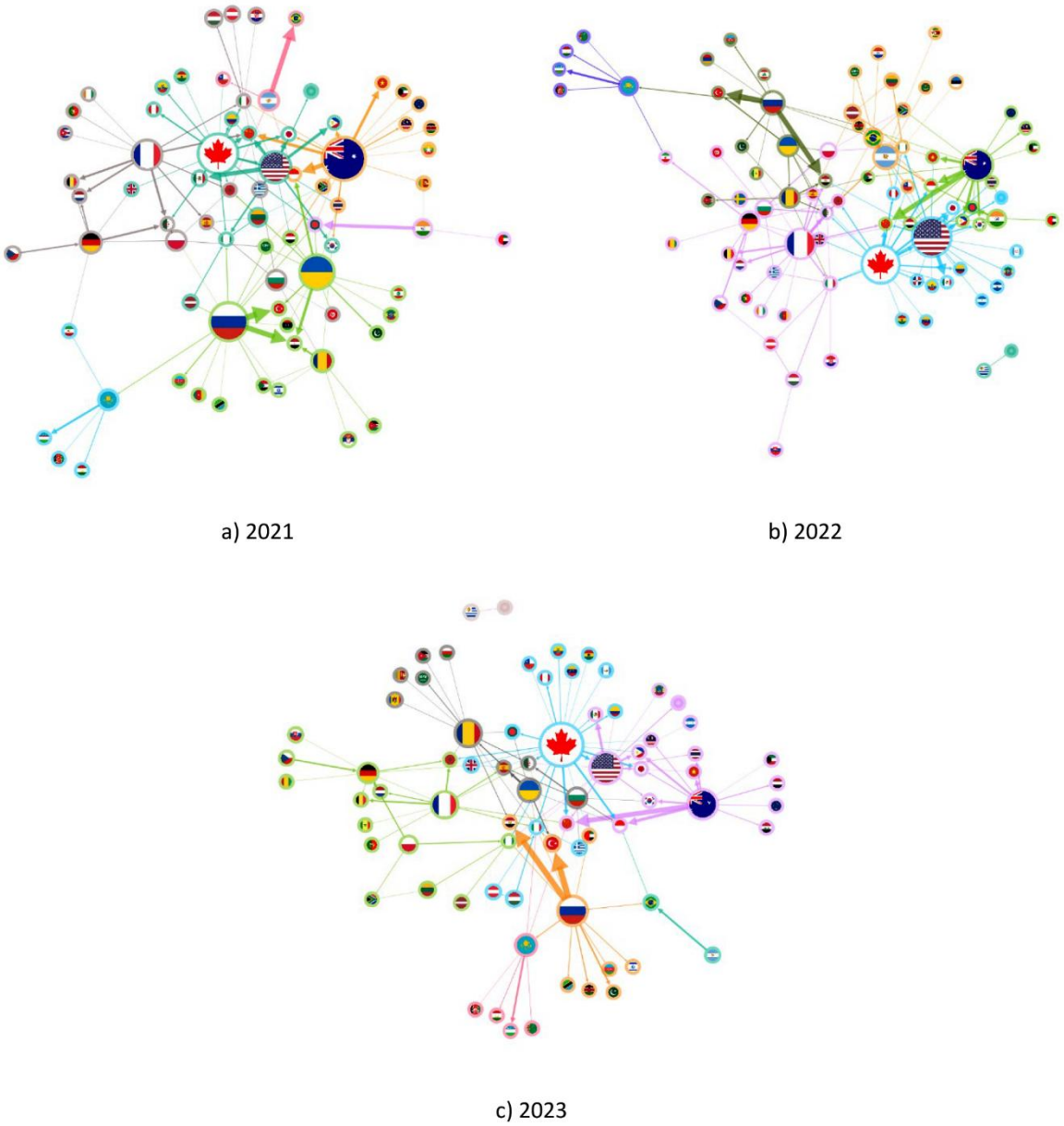

Fig. 2. Wheat Network Graph

Source: own calculations based on the UN Comtrade data.

Figure 3 illustrates the structure of the global corn trade network, in which node sizes are proportional to each country's out-degree, reflecting the number of distinct export destinations and indicating its relative centrality within the network. The direction of the arrows represents the flow of corn exports, while arrow thickness is proportional to trade volume, with thicker arrows corresponding to higher export values.

In 2021, Argentina, Brazil, the United States, and Ukraine emerged as the leading exporters in the corn trade, playing active roles across Asian, European, and Latin American markets through their extensive trade networks. Argentina and Brazil concentrated primarily on the South American and Asian markets, whereas the United States and Ukraine focused their exports on Asia, the Middle East, and Europe. Argentina established strong trade connections with countries such as Brazil, Malaysia, and Saudi Arabia, expanding its influence across Africa, Asia, and Latin America. At the same time, Brazil maintained a robust position with significant exports to countries including Egypt, South Korea, and

Spain, as well as sustaining an extensive trade network throughout Europe and Latin America. The United States operated with a broad distribution across key markets, continuing trade with countries such as Japan, Mexico, and China, thereby reinforcing its global trade presence.

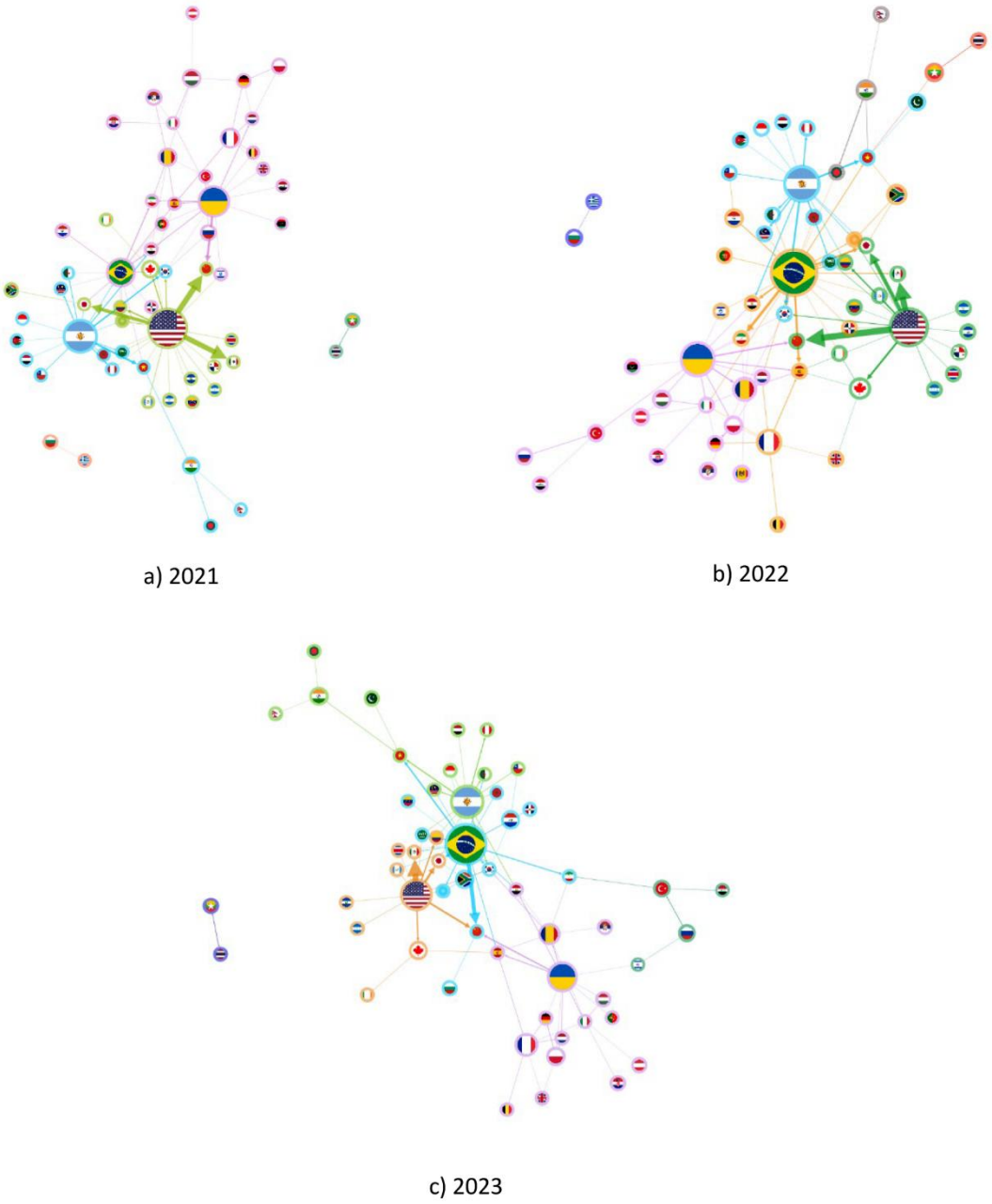

Fig. 3. Corn Network Graph

Source: own calculations based on the UN Comtrade data.

Building upon these established trade patterns, the corn trading network further expanded in 2022, with the United States, Argentina, Brazil, and Ukraine strengthening their positions in international markets. The United States maintained strong export connections with major markets e.g. Japan, Canada, Egypt, and China, while deepening its influence in Latin America through intensified trade with Venezuela, the Dominican Republic, and Colombia. Argentina continued its existing trade relationships with Malaysia, Egypt, and Saudi Arabia, while expanding into new markets such as Japan, Colombia, and Vietnam, thereby increasing its presence in Asia and Latin America. Similarly, Brazil broadened its trade network across Latin America, the Middle East, and Asia, maintaining relations with Egypt, Saudi

Arabia, and Spain, and diversifying its exports with increased trade to Asian countries e.g. Bangladesh and Vietnam. Despite geopolitical challenges, Ukraine focused on intensifying trade within Eastern Europe through connections with Romania and Poland while sustaining strategic relations with China and South Korea in the Asian market.

By 2023, Ukraine's corn trade network demonstrated a notable recovery compared to the previous year, reflecting the resilience of its export sector. The country successfully maintained exports to European and African countries such as Romania, Poland, and Egypt while reestablishing its trade relations with China. Furthermore, Ukraine expanded its connections with Spain and Romania and made notable efforts to enter new markets e.g. Israel. Overall, despite ongoing challenges in 2023, Ukraine displayed adaptability by diversifying its trade relations and preserving critical trade routes.

In parallel, the United States sustained its broad geographical reach in 2023, following a trend consistent with previous years. The country strengthened its commercial ties with Saudi Arabia, Colombia, and Mexico while maintaining a strong presence in key Asian markets including South Korea, Japan, and China. Additionally, the expansion of trade networks within Latin America and reinforced relations with Canada helped maintain the United States' central role in global corn trade.

Similarly, Argentina pursued further expansion of its trade network in 2023 by increasing exports to Asian and Middle Eastern markets. Strong trade relations were established with Vietnam, Egypt, and Saudi Arabia, alongside diversified exports targeting the broader Asian region. This diversification strategy enhanced Argentina's competitive position in global corn trade, while sustained exports to Malaysia, Algeria, and Peru further solidified its ability to serve multiple geographic regions.

Brazil also continued to expand its presence in both Latin American and Asian markets in 2023, maintaining strong export flows to major markets e.g. China and Egypt. At the same time, the country strengthened its trade relationships with Vietnam, Venezuela, and Saudi Arabia. Compared to 2022, Brazil's trade network became more diversified, supported by the development of new market connections. The continuation of trade with markets such as Iran and Spain further reinforced Brazil’s strong position in global corn trade.

Modularity analysis groups countries into communities based on the density of their trade relations. In this approach, countries that maintain stronger trade connections with each other than with the rest of the network are classified within the same community. Accordingly, in Figures 4 and 5, countries in the same colour represent modularity-based communities, indicating groups of countries that were more closely connected in trade during the respective year.

According to the modularity analysis results for 2021, geographical proximity played a decisive role in shaping wheat trade networks (see Figure 4). Latin American countries (namely Argentina, Brazil, Chile) and North American countries (the United States, Canada, Mexico) were classified within the same modularity group. Similarly, European and Asia-Pacific countries formed distinct clusters within their respective geographic regions, maintaining trade relations primarily within a regional framework. During this period, Ukraine and Russia were part of the same modularity group, demonstrating strong trade relationships, particularly with North African countries and those in the Arabian Peninsula. As of 2021, regional alliances and geographical proximity largely shaped wheat trade.

By 2022 the outbreak of war between Ukraine and Russia led to significant transformations in the wheat trade network. During this period several countries that had previously shared the same modularity class with Ukraine shifted into different groups. New trade connections emerged among European countries, while some African countries were incorporated into the same modularity class as Latin American and Australian countries, signalling a strengthening of trade networks between these regions.

In 2023, Ukraine’s position within the wheat trade network changed even further. Due to the ongoing effects of the war, Ukraine experienced a noticeable weakening of its trade connections, and its modularity group became significantly narrower, limited to a small number of countries.

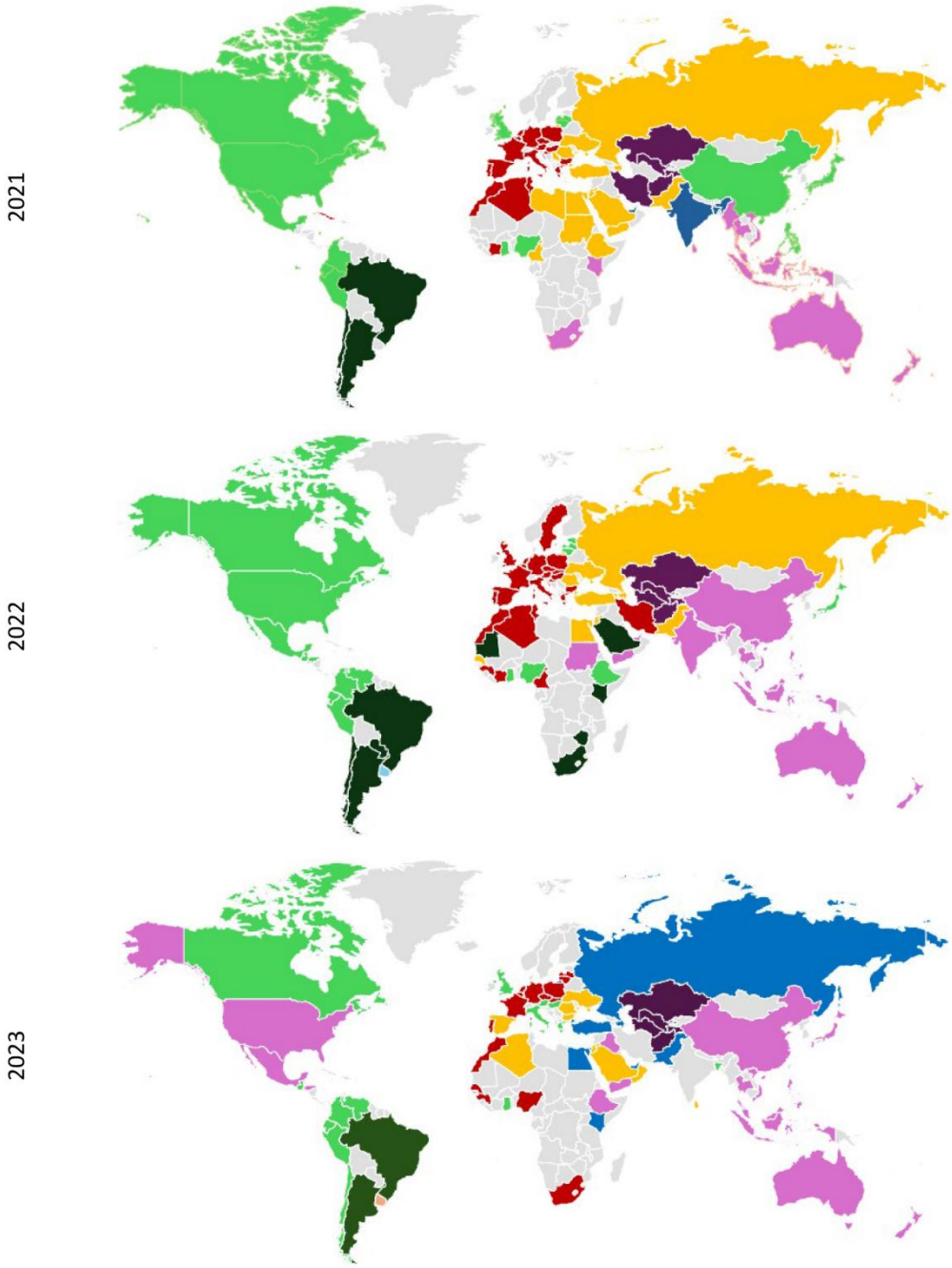

Fig. 4. Modularity Structure of the Wheat Trade Network (2021–2023)

Note: The wheat trade network exhibited modularity values (Q) of 0.551, 0.544, and 0.547 in 2021, 2022, and 2023, respectively. The corresponding numbers of detected communities were 7, 7, and 8.

Source: own calculations based on the UN Comtrade data.

The 2021 modularity analysis indicated that corn trade was strongly based on robust regional connections. During this period, North and South American countries were prominently clustered within their respective regions (see Figure 5), whilst European and Asian countries formed distinct regional groups within the corn trade network. In 2021, Ukraine held a broad sphere of influence in the corn trade network, establishing strong trade relations particularly with countries in Europe, the Middle East, and North Africa. According to the modularity analysis, Ukraine was part of the same modularity group as these regions, functioning as a regional hub within the network.

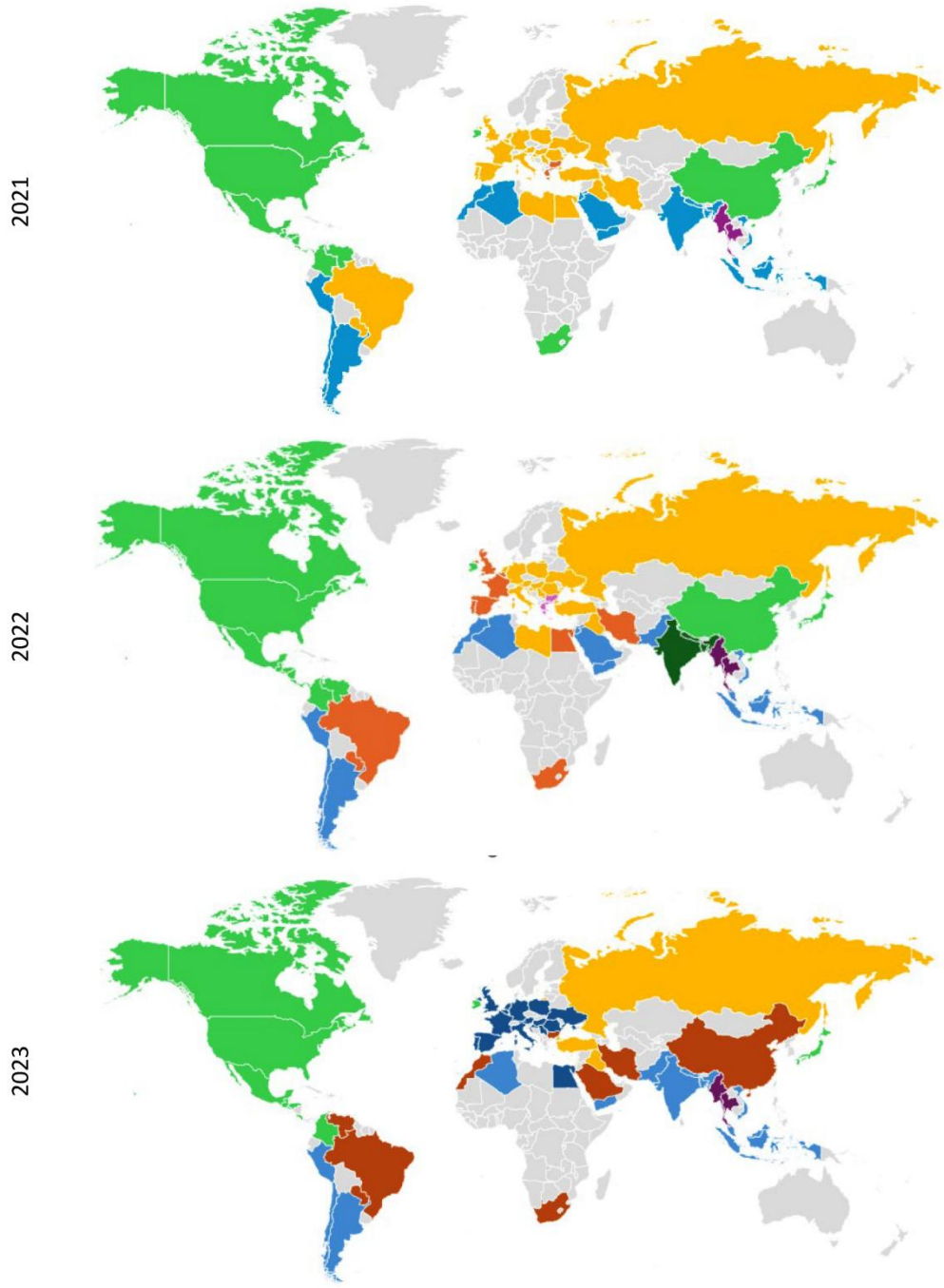

Fig. 5. Modularity Structure of the Corn Trade Network (2021–2023)

Note: The modularity values (Q) of the corn trade network were 0.468, 0.474, and 0.453 in 2021, 2022, and 2023, respectively. The corresponding numbers of detected communities were 5, 7, and 6.

Source: own calculations based on the UN Comtrade data.

However the outbreak of the Russia-Ukraine war in 2022 led to significant changes in Ukraine's trade network, and as a result of the conflict several countries that had previously been part of Ukraine's modularity group transitioned into different trade clusters. This shift reflected disruptions among suppliers within the group. In particular, European countries sought alternative sources to compensate for the decline in corn supplies from Ukraine, establishing stronger trade ties with Latin American countries. This development demonstrates the weakening of Ukraine's central role in the Europe––Middle East trade network and highlights the restructuring of trade dynamics within the region.

By 2023 the long-term effects of the war further limited Ukraine's position within the trade network, and its sphere of influence narrowed, with a noticeable decrease in the number of countries within its modularity group. During this period Ukraine's trade network became increasingly isolated within Europe and the Middle East, with its commercial connections confined to a more limited scope. Therefore, as a result of the war, Ukraine became increasingly marginalised in global trade, while new regional hubs emerged to reshape the global corn trade network. Vulnerability analysis measures the resilience of a network by examining the effects of removing specific nodes or connections on the overall structure and functionality of the network. In the context of trade networks the removal of a critical node can have significant implications, which potentially threaten the sustainability of trade and affect other countries. This analysis was conducted to assess the potential impact on dependent countries and to evaluate the effectiveness of alternative trade routes.

Using 2021 wheat trade data, the removal of Ukraine from the network resulted in notable structural changes in both the connectivity and efficiency of the trade network (see Table 3 for details). The number of edges decreased from 124 to 111, highlighting Ukraine's critical role in maintaining the network's integrity. The average shortest path length increased from 1.195 to 1.212, suggesting longer trade paths and reduced efficiency in the flow of goods and information across the network. Finally, the average degree decreased from 3.31 to 3.13, demonstrating a reduction in the average number of trade connections per country within the network.

Table 3. Vulnerability Analysis Results of Wheat and Corn Trade Networks

Metric	Wheat Network (Before Removal)	Wheat Network (After Removal)	Wheat Change (%)	Corn Network (Before Removal)	Corn Network (After Removal)	Corn Change (%)
Number of Edges	124	111	–10.5	94	80	–14.9
Density	0.022	0.022	0.0	0.027	0.025	–7.4
Average Shortest Path Length	1.195	1.212	1.4	1.333	1.37	2.8
Average Degree	3.31	3.13	–5.4	3.13	2.81	–10.2

Source: own calculations based on the UN Comtrade data.

Similarly, the removal of Ukraine from the corn trade network led to noticeable shifts in key structural metrics. The number of edges decreased from 94 to 80, reflecting a decline in trade connections and underlining Ukraine's significance within the network. The network density declined from 0.027 to 0.025, signalling weaker trade relationships and a more fragmented network structure. The average shortest path length increased from 1.333 to 1.370, indicating fewer indirect connections and longer trade paths between countries. Additionally, the average degree fell from 3.13 to 2.81, highlighting a decrease in the average number of connections per country.

These findings demonstrate that Ukraine's absence from the corn trade network diminished the overall connectivity and efficiency of trade relations, significantly undermining the resilience of the global trade network.

4. Discussion

The BSGI stands out as a significant international intervention developed in response to the global food security crisis triggered by the Russia-Ukraine war. The initiative aims to restore Ukraine's grain exports, ensuring the sustainability of global food supplies and preventing extreme price fluctuations. The research findings highlight Ukraine's critical role in global grain trade, particularly revealing the dependency of Turkey, Egypt, and Spain on Ukrainian wheat, and of China and Spain on Ukrainian corn.

Excessive dependence on specific suppliers in food markets makes importing countries vulnerable to unexpected shocks, such as wars and political crises (Devadoss & Ridley, 2024). Poursina et al. (2024) found that Russia's invasion of Ukraine created a significant shock to the global wheat supply, resulting in a 2% average increase in global prices, while domestic prices in Ukraine dropped by 27%. This suggests that price shocks directly affect countries with high import dependency, and the findings further confirm that the dominance of a few key countries in grain trade poses considerable risks during periods of instability.

Beluhova-Uzunova et al. (2024) demonstrated that disruptions in Ukraine's grain exports have altered global trade patterns and warned that food crises will become inevitable without the establishment of new supply routes. Martins (2024) emphasised the regional effects of the Ukraine-Russia war on grain markets, highlighting the importance of developing alternative supply channels to maintain market stability. In line with Goyal and Steinbach (2023), it is believed that without the creation of alternative trade routes for countries dependent on Ukrainian grain exports, supply disruptions during wars and political crises could cause severe economic and social risks. Thus ensuring global food security requires not only short-term trade agreements but also long-term diversified supply strategies.

Trucmel and Vintila (2023) indicated that Ukraine's shift toward exporting to EU countries caused certain price fluctuations within the European internal market but noted that, in the long term, new logistic routes have contributed to the sustainability of trade. This finding demonstrates how Ukraine's increased exports via Romania, Poland, and the Baltic countries have reshaped global trade balances. Furthermore, Ukraine's development of alternative trade routes has not only ensured the continuation of trade but also strengthened regional cooperation among its trade partners. While Xu et al. (2024) stressed the importance of diversified trade relations in enhancing resilience against geopolitical shocks, this study highlights the necessity of regional cooperation in maintaining grain supply.

Romania's and Poland's strategic roles within the European trade network have been critical in enabling Ukraine's grain exports to reach global markets through alternative routes, potentially making trade relations more resilient in the long term. Romania provides logistical support for grain exports via its Black Sea ports, while Poland serves as a key transit hub for land and rail transport into European markets. The study's findings also show that Ukraine's connections with its neighbouring countries have been strengthened during the war. These dynamics paved the way for broader EU-level mechanisms, most notably the Solidarity Lanes initiative.

In this context, the EU's Solidarity Lanes have emerged as an important mechanism, yet high transport costs, limited capacity, and logistical bottlenecks − particularly at border crossings − mean that Solidarity Lanes cannot fully substitute for maritime exports under the BSGI. Land and rail transportation cannot achieve the economies of scale or cost efficiency offered by maritime shipping, which remains the most effective method for high-volume grain flows. Supporting this assessment, Beluhova-Uzunova et al. (2024) highlighted the high costs of transporting grain via Poland and Romania, while Countryman et al. (2024) noted that insufficient railway infrastructure seriously limits the efficiency of these alternative corridors. Hence Solidarity Lanes should be regarded as a vital but complementary corridor that sustains trade flows during crises rather than a long-term substitute for maritime transport.

Although some studies present land and rail routes as strong alternatives, considering trade volumes and cost factors prompts doubts about the long-term sustainability of these approaches. For bulk grain exports, maritime transport remains the most viable option. Ultimately, while the critical roles of Romania and Poland in supporting Ukraine's grain exports cannot be overlooked, the long-term sustainability of land and rail routes remains questionable. Therefore, EU countries and international organizations should prioritise developing lower-cost, maritime-based solutions. In this context, reactivating the BSGI has become increasingly necessary, while convincing Russia to rejoin the agreement through international mediation would be a significant step forward in the short term.

Ukraine plays a critical global role in the export of durum wheat used in pasta and flour production. Interruptions to Ukraine's wheat exports to countries such as Turkey, Spain, and Egypt, which are major exporters of flour and pasta, could cause significant disruptions in these countries' production sectors (S&P Global, 2023). This issue could severely affect not only the pasta industries of these nations but also millions of people in low-income countries by limiting access to essential food sources, thereby deepening the global food crisis. Studies suggest that Ukrainian grain primarily targets developed countries, leaving low-income countries with insufficient benefits (Ekleme & Yercan, 2025). However, this is an incomplete perspective, as some countries e.g. Turkey import Ukrainian wheat and process it into flour and pasta, which are then exported to low-income countries in Africa and the Middle East. Poursina et al. (2024) reported that 65% of grain exported under the BSGI was directed to developing countries, but this did not directly ensure food security, as the ultimate impact was indirect through food processing hubs in importing countries. Therefore, interruptions in Ukraine's wheat exports negatively affect not only the direct importing countries but also the global supply chains that process and distribute these products to low-income regions, exacerbating food security and nutrition crises.

Considering that Russia and Ukraine belonged to the same modularity group prior to the war, the changes in trade networks during 2022–2023 redirected trade flows, with Russia developing closer relations with Turkey and Middle Eastern countries. This finding aligns with other studies (Braun et al., 2023; Kozielec et al., 2024), confirming that geopolitical crises like war can reshape trade networks. This restructuring may result in lasting changes to trade networks in the long term.

Low-income countries aim to increase local agricultural production and achieve self-sufficiency in the event of the corridor's failure, however climate change and population growth exert pressure on agricultural production, complicating this objective. Organizations such as the World Bank (2020) and IPCC (2021) point out that population growth and climate change strain agricultural capacity. In line with these reports, this study stresses the need for climate-friendly agricultural policies and increased international cooperation to ensure food security.

Major grain exporters e.g. the United States, Canada, Australia, Brazil, and European countries may have the potential to compensate for shortages if the corridor collapses. However, grain from these countries may not be economically sustainable for low-income countries due to logistical challenges and costs. As Trucmel and Vintila (2023) also noted, this could increase vulnerability within trade networks. The present findings highlight the importance of regional cooperation mechanisms to secure grain supplies in sensitive regions such as Africa and the Middle East. Furthermore, a limited number of major exporting countries may distort domestic prices, adding further complexity.

To sum up, the analysed trade networks exhibit vulnerability to shocks due to low connectivity, limited trade partnerships, and increased path lengths. Interruptions in the BSGI or its permanent cessation could lead to further contraction of wheat and corn trade and pose severe risks to global food security.

5. Conclusion

The study comprehensively examined the structural impacts of the BSGI on international grain trade, revealing the critical consequences of the Russia-Ukraine war for global food security. The research findings demonstrate that Ukraine is a key player in global grain trade and that the onset of the war has rapidly increased imbalances within trade networks. The disruption of grain supplies from Ukraine following the outbreak of the war has led to significant transformations in global trade structures.

By enabling the export of Ukraine's critical agricultural products to global markets, the BSGI has prevented the deepening of the global food crisis and contributed to price stability. However, the future of the corridor remains uncertain, raising serious concerns about the sustainability of global food supply. The article shows that in a scenario where the corridor ceases to function, low-income countries may become increasingly dependent on imports, making their food security more vulnerable.

The uninterrupted maritime transportation of Ukrainian grain to international markets is of critical importance for global food supply and price stability. Prior to the war, Ukraine exported most of its grain via Black Sea ports, while alternative land and rail routes have remained limited in capacity. If Russia increases its military control and halts the grain corridor, the inability to export Ukrainian grain may lead to spoilage in silos, severely impacting food supplies, particularly in low-income countries, therefore ensuring the continuation of maritime grain exports from Ukraine is essential for global food security and the continuity of humanitarian aid.

Given that Ukrainian grain lacks a fully viable alternative to maritime transportation, concrete steps are needed to secure its continuity. Strengthening international cooperation, increasing diplomatic efforts, and fostering joint action among relevant stakeholders are vital to safeguarding food supply security. Notably, previous initiatives facilitated by the UN and Turkey, which enabled millions of tons of agricultural products to reach global markets, clearly demonstrate the effectiveness of such collaborative efforts.

In this context the UN and the European Union must continue to actively support the transportation of Ukrainian grain. While the UN works to create common ground through negotiations between conflicting parties, the EU should use its funds to strengthen Ukraine's connections with Romania's Constanța Port and develop alternative logistical solutions. Such multilateral collaborations will play a crucial role in ensuring the sustainability of grain supplies.

Diplomacy-based security measures are of great importance to maintain the sustainability of grain trade in the Black Sea. International diplomatic efforts must be enhanced to ensure the safe navigation of grain-laden vessels. In this regard, actors including Turkey, the International Maritime Organization (IMO), and the UN should promote confidence-building measures between conflicting parties and strengthen mediation mechanisms aimed at reducing tensions. Additionally, options such as deploying international maritime escort missions or observer mechanisms to accompany commercial vessels should also be considered when necessary. Protecting trade routes passing through the Black Sea from military tensions is essential not only for the continuity of grain exports but also for shielding global trade from geopolitical risks. In this context Turkey holds a pivotal position as it maintains dialogue with both Russia and Ukraine. Any future framework designed to replace or complement the BSGI is likely to require Turkish mediation, particularly to foster mutual trust between the parties and to support the operational continuity of grain exports.

The article contributes by filling a gap in the literature on grain trade, particularly regarding the structural effects of the BSGI. Methodologically, complex network analysis serves as a useful tool for examining global grain trade dynamics, quantitatively revealing Ukraine’s central position in the grain trade network and how the war has reshaped these connections. This approach contributes to the literature on understanding how conflicts transform the structural features of trade networks. While the authors adopted a structural approach, future research could incorporate econometric methods to explore the causal relationships between trade network disruptions, price volatility, and market efficiency. Further analyses would provide deeper insights into the economic consequences of geopolitical shocks on global food markets.

This research identified fragile points within global supply chains and demonstrated that alternative routes cannot fully replace maritime transportation. While land and rail routes developed through Romania and Poland offer temporary solutions, their limited capacities make them unlikely to sustain Ukrainian grain exports in the long term. This provides policymakers with critical insights, underlining the indispensability of maritime transport in safeguarding supply security during crises and over the long term. Finally, the article also provides a social contribution by highlighting the risks faced by low--income countries regarding food security. Interruptions in Ukrainian grain imports may exacerbate food crises in countries heavily reliant on such supplies. Therefore, the continuity of the grain corridor must be considered not merely as a commercial issue but as a fundamental necessity for global food security and humanitarian stability.

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Received: April 2025, revised: October 2025