The Russia–Ukraine Conflict and Global Staple Agrifood Trade Networks: An Analysis of Structural Changes and Disruptions

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The Russia–Ukraine conflict has generated significant disruptions in global agrifood supply chains, particularly affecting the trade of staple agricultural commodities such as wheat, maize, sunflower oil, and barley. As two of the world's major agricultural exporters, Russia and Ukraine play a crucial role in ensuring global food security and maintaining the stability of international agrifood trade networks. This study examines the impact of the conflict on international staple agrifood trade networks by analyzing changes in trade flows, market connectivity, and network resilience before and after the outbreak of hostilities. Using trade network analysis, the research explores shifts in export-import relationships, the emergence of alternative trade routes, and the redistribution of market influence among exporting and importing countries. The findings indicate that the conflict has increased trade uncertainty, raised food prices, and intensified vulnerabilities in countries heavily dependent on imports from the Black Sea region. At the same time, new trade partnerships and diversification strategies have emerged, reshaping the structure of global agrifood networks. The study highlights the importance of strengthening supply chain resilience, promoting trade diversification, and enhancing international cooperation to mitigate the effects of geopolitical shocks on global food systems. The results provide valuable insights for policymakers, international organizations, and stakeholders seeking to improve food security and sustainable agricultural trade in an increasingly uncertain geopolitical environment.

Keywords: Russia–Ukraine Conflict, Agrifood Trade Networks, International Trade, Food Security, Staple Agricultural Commodities, Wheat Trade

Introduction:

Concern over the Russia-Ukraine war is rising globally [1][2]. Economic development [3][4], the regional environment [5][6], international trade [7][8], food supply chains [9] and food security [10][11][12] are only a few of the socioeconomic areas that have been significantly impacted, in addition to the political and security fronts. Given that Russia and Ukraine are already major participants in the world's energy and agricultural markets, the conflict has created significant regional and global food and energy security issues in recent years [13][14][15]. According to UN Comtrade (accessed on July 15, 2023; see https://comtradeplus.un.org/) and FAO (accessed on July 15, 2023; see https://www.fao.org/faostat/en/), Russia and Ukraine together accounted for a sizable portion of the world's exports of wheat, maize, and sunflower oil, at roughly 34%, 17%, and 73%, respectively [16].

Furthermore, they contributed almost 27% and 17%, respectively, to the worldwide barley and maize trade, holding significant market shares [17]. These exports, which account for about 12% of all calories traded globally, are vital to diets and global consumption. Additionally, Russia is a large exporter of potash and nitrogen fertilizers, accounting for around 15% of the

world's nitrogenous fertilizer trade. About 33% of the world's potash fertilizer exports come from Belarus and Russia combined [18].

Global food systems depend on food trade [19][20]. Global food trade networks are formed by economies and trade connections [21][22]. Trade helps achieve the objectives of global food security by bridging the gap between areas with excess food production and those with deficits. However, pandemics [23], climate change [24][25], geopolitical strife [26][27], and the financial crisis [28] will all work together to put the global food trading system under unprecedented strain. There will be shortages, price increases, and heightened susceptibility to hunger and malnutrition when economies that are major food producers or exporters see a decline in food production [29] as a result of catastrophic occurrences or the imposition of trade restrictions. Consequently, the significance of Russia and Ukraine in international food trade and food security is highlighted by their robust participation in agricultural industries [30].

Econometric equilibrium models, such Computable General Equilibrium (CGE) models, are commonly used to examine how external shocks affect commerce and food security. By capturing interactions between various sectors and locations, these models replicate how economies react to changes in technology, policy, and other external influences. CGE models have been successfully applied in earlier research to investigate the impacts of several global disturbances. Significant regional differences in the economic effects of climate change on global agriculture were found in certain research that used a CGE model [31][32]. Demonstrated the crucial significance of productivity gains in reducing food insecurity by using a CGE model to evaluate the effects of possible yield improvements and trade liberalization on global food security.

The effects of the Russia-Ukraine conflict on global food security, agricultural productivity, trade dynamics, and greenhouse gas emissions have been measured using CGE models. For instance, a study uses a CGE model to look at how China's energy-economic-environment system is affected by changes in global oil prices and carbon tax laws. The CGE model is used by Liu et al. to evaluate the economic and environmental effects of the European Union's embargo on Russian fossil fuel imports.

Recent research has focused on analyzing the possible effects of the conflict between Russia and Ukraine on food security from a variety of angles. A subset of this literature examines how the conflict affects food yields. The lack of workers,

Wheat production in Ukraine may be significantly impacted by transportation suspensions, disruptions to the supply of chemical fertilizers, and pest and disease control measures.

The impact of the conflict on international food prices, trade, and the food supply chain has also been the subject of numerous research. According to these studies, the conflict would result in severe food insecurity, a drop in commerce, and steep increases in food prices, especially for countries that heavily depend on grain imports from Russia and Ukraine. Additionally, experts have looked into how the conflict's shocks spread throughout the world's food commerce network. Some of these researches have used models and algorithms to estimate the effects of the Russia-Ukraine conflict on the food chain, or they have used historical data from before 2023. International food trade networks, however, are dynamic, and few studies have used post-war food trade data to analyze the impact of the conflict. In this research, we create three separate international crop trade networks and an aggregated worldwide food trade network using monthly trade data for wheat, rice, and maize from January 2016 to December 2023 from the UN Comtrade Database. We seek to examine the impact of the Russia-Ukraine conflict on the global food commerce network by contrasting the changes in network structure and features before and after the conflict. The majority of economies, including Russia and Ukraine, have not released food trade data after 2023 due to the inherent delays in data collection and updating. Only a few economies in North and South America, as well as a portion of the

economies in Europe, have provided accurate and timely trade statistics. We use bilateral trade statistics from the reporting economies to fill in the gaps in order to overcome this restriction. We can record the trade connections between Russia, Ukraine, and a few other economies using this method. Our study fills a research gap by examining the real impact of the Russia-Ukraine conflict using current data, even though we are unable to create a comprehensive global food commerce network. We highlight the impact of the Russia-Ukraine conflict on the three international crop trade networks, the overall international food trade network, and economies using network building and topological indicators.

Table 1. Global export shares of Russia and Ukraine before the conflict

Commodity	Combined Share of Global Exports (%)
Wheat	34
Maize	17
Sunflower Oil	73
Barley	27
Nitrogen Fertilizers	15
Potash Fertilizers (Russia + Belarus)	33

Information and Approach:

Description of the Data:

We examine three crops that provide the majority of the world's population with calories: wheat, rice, and maize. Our study uses monthly import and export data from the UN Comtrade database for these crops from January 2016 to December 2023. Many economies have not yet released monthly trade data for these crops since 2023 due to data reporting delays. We have implemented a technique that uses information from trade partners to fill in the gaps in the data. We rely on data published by other nations, like Brazil, that have shared their crop export data with China over the same period when a specific economy, like China, fails to disclose its crop import data for a given month (e.g., April 2022). We calculate China's crop import volume for that particular month by extrapolating from Brazil's data. Similarly, we use import and export data from Russia's trading partners to fill in the gaps and get a complete picture of Russia's crop trade activities during the period when it hasn't published any crop trade data since April 2022.

We create trade connections between trading partners and reporting economies. In order to maximize coverage of the economies included in our study, we conduct quarterly analysis of the international crop trade networks instead of monthly analysis due to significant monthly swings. Due to the fact that many economies do not release trade statistics for 2024 and prior to 2016, we only take into account data on global food trade from 2016 to 2023.

Table 2. Reporting economies included in international crop trade networks

Crop	Reporting Economies
Maize	42
Rice	43
Wheat	25
Common Economies Used for Aggregation	24

After cleaning up the data, we concentrate on the economies that consistently supplied data between January 2016 and December 2023. These economies comprise 42 reporting economies for maize, 43 for rice, and 25 for wheat (see Table 1). We eventually employ three forms of crop trade data provided by 24 reporting economies to compare and aggregate various crop trade data (see the reporting economies for crops indicated in Table 1). Crop trade flows for the chosen economies are the only ones included in our dataset. Because of this, we are unable to examine how the Russia-Ukraine war affects certain economies, which would understate the conflict's influence on the world crop trading system. However, using the data at

hand, we might still create global food trade networks that would enable us to evaluate the impact of the conflict on the crop trade in specific economies.

Table 3. Networks constructed in the study

Network	Description
iWTN	International Wheat Trade Network
iRTN	International Rice Trade Network
iMTN	International Maize Trade Network
iFTN	Aggregate International Food Trade Network

Network Construction:

We limit ourselves to the case of quarterly trade evolution because monthly trade data exhibits notable variations. We transform the trade volumes into trade calories using food conversion statistics from the Food and Agriculture Organization of the United Nations (FAO) in order to exclude the effects of crop prices and quality. We obtain the quarterly trade matrix Wcrop(t) for each crop in each quarter t (crop = maize, rice, and wheat, t = 2016/Q1, 2016/Q2, · ·, 2023/Q4) based on the monthly trade data supplied by the 24 economies chosen. Here, w crop ij (t) represents the caloric trade volume of crop exported from economy i to economy j. We create a time-varying international crop trade network (iCTN), G crop(t) = (V crop(t), Wcrop(t)), for every crop in every quarter between January 2016 and December 2022. V crop(t) represents the set of network nodes, which consists of reporting economies and their trading partners. The international wheat trade network (iWTN), the international rice trade network (iRTN), and the international maize trade network (iMTN) are the three iCTNs that result from this. By combining the three crops, we simultaneously create the aggregate international food trade network (iFTN), G(t) = (V (t), W(t)).

To eliminate seasonal effects, we compare the global crop trade networks and the whole global food trade networks during the same quarter but in separate years. The three global crop trading networks for maize are shown in Table 1 wheat, rice, and the whole global food commerce network in the fourth quarter of 2016 and 2023. Trade flows for each crop and food (aggregate crops) in the fourth quarter of 2016 and 2023, respectively, are displayed in the rows. We only display connections with trade volumes that rank in the top 2%, medium 1%, and bottom 2% for each crop in order to improve clarity. Compared to the fourth quarter of 2016, we discover that the total international food commerce network in the fourth quarter of 2023 has more links with large trade volumes (see Table 1g,h). It signifies the formation of new commercial ties.

The structure of the global rice trade network encompassing a few economies has stayed comparatively steady, as seen in Table 1 c , d. Additional topological indicator-based analysis is needed.

Node Attributes:

Node Degree:

The node degrees present the number of trade partners of economies. In a directed network, we define both in-degree and out-degree of a node to count incoming links and outgoing links, respectively. The in-degree of a node is defined as follows:

$$k \text{ in } i = \sum j \in V - \{i\} \text{ IE } (eji) = NV \sum j=1 \text{ IE } (eji), (1)$$

where IE (eji) is the indicator function:

$$\text{IE } (eji) = (\ 1, \text{if eji} \in E\ 0, \text{if eji} \in / E\ (2)$$

The out-degree of a node is defined as follows:

$$k \text{ out } i = \sum j \in V - \{i\} \text{ IE } (eij) = NV \sum j=1 \text{ IE } (eij). (3)$$

Node Strength:

Since the networks are weighted, we quantifynode strengths, including in-strength s in i and out-strength s out i , which are defined as follows:

$$s \text{ in } i = \sum j \in V - \{i\} \; wji = NV \sum j=1 \; wji, \quad (4)$$

$$s \text{ out } i = \sum j \in V - \{i\} \; wij = NV \sum i=1 \; wij, \quad (5)$$

PageRank:

The PageRank algorithm was developed in 1997 to rank web pages in the Google search engine, and it was later used in many different fields to measure the importance of nodes in a directed network. Here, we apply PageRank to measure the influence of an economy in the international crop trade networks, omitting the calculation process.

Network Metrics:

Average Node Degree:

To display the average trade partners of all economies in the global food trade networks.

In order to rank webpages in the Google search engine, the PageRank algorithm was developed in 1997. Later, it was applied to determine the significance of nodes in a directed network in a variety of fields. To determine a node's relevance, the PageRank computation is repeated recursively. Here, we use PageRank to gauge an economy's impact on global crop trading networks without going through the computation process.

Metrics for Networks:

Node Degree Average:

We compute the average node degree to display the average trading partners of all economies in the global crop trade networks and the global food trade network.

$$D \; k \; inE = k \; out = NE \; NV \quad (6)$$

And

$$\langle k \rangle V = D \; k \; in + k \; outE = 2NE \; NV \; . \quad (7)$$

Average Node Strength:

The average in-strength of nodes ($i \in V$) is expressed as follows:

$$D \; s \; inE \; V = 1 \; NV \; NV \sum j=1 \; s \; in \; j = 1 \; NV \; NV \sum i=1 \; NV \sum j=1 \; wij1 = W \; NV \; , \quad (8)$$

Similarly, the average out-strength of nodes is expressed as follows:

$$s \; out \; V = 1 \; NV \; NV \sum i=1 \; s \; out \; i = 1 \; NV \; NV \sum i=1 \; NV \sum j=1 \; wij1 = W \; NV \; . \quad (9)$$

Therefore, we have

$$D \; s \; inE \; V = s \; out \; V = W \; NV \quad (10)$$

And

$$\langle s \rangle V = D \; s \; in + s \; outE \; V = 2W \; NV \; . \quad (11)$$

Network Density:

We use density to describe how connected nodes are in the network, which is defined as the portion of the potential links that are actual links, as follows:

$$\varrho = NE \; NV \; (NV - 1) \; , \quad (12)$$

Link Reciprocity:

Link reciprocity plays a pivotal role in shaping directed networks and is crucial for comprehending the observed network topology. In conventional terms, the reciprocity of a node i is defined as the ratio of the number of reciprocal links k R i to the total number of links ki , associated with node i:

$$Ri = \sharp \, j : eij \in E \; \& \; eji \in E \;\; \sharp \, j : eij \in E \text{ or } eji \in E \;\; = k \; R \; i \; ki \; , \quad (13)$$

where

$$k \; R \; i = \sharp \, j : eij \in E \; \& \; eji \in E \;\; = \sum j \neq i \; wijwji0 \quad (14)$$

is the number of reciprocal links node i has. In Equation (14), we pose 0 0 = 0. Link reciprocity research offers important insights into the underlying dynamics and structure of complex networks, leading to a deeper comprehension of their behavior. 2.4.5. Network Efficiency Network efficiency is computed as the average reciprocal of the shortest path lengths between pairs of nodes within a network. Here, we compute the efficiency as follows: We pose 0 0 = 0 in Equation (14). Link reciprocity research offers important insights into the underlying

processes and structure of intricate networks, enabling a deeper comprehension of their behavior.

Effectiveness of the Network:

The average reciprocal of the shortest paths between node pairs inside a network is used to calculate network efficiency. In this case, the efficiency is determined as follows:

$$E = 1\ NV\ (NV - 1)\ \sum i \neq j\ 1\ dij\ , \quad (15)$$

where dij is the shortest path between node i and node j. In the international crop trade networks, efficiency serves as a measure of how effectively crops are transported.

Organic Interconnectedness:

By focusing on the network's intrinsic structure rather than complicated calculations, natural connection provides an effective method for researching network resilience.

Its main use is to measure how redundant alternate paths are inside the network. To do this, a weighted sum of closed walks of various durations is calculated. The initial natural connection has the following mathematical definition:

$$NC = \ln SC\ NV\ = \ln \sum NV\ i=1\ e\ \lambda i\ NV\ !\ , \quad (16)$$

where

$$SC = \infty \sum l=0\ \mu l\ l! = NV \sum i=0\ \infty \sum l=0\ \lambda\ l\ i\ l! = NV \sum i=1\ e\ \lambda i\ , \quad (17)$$

where λ is the eigenvalue of the adjacency matrix A, μl is the number of closed walks of length l, and SC is the initial weighted sum of the numbers of closed walks. 2.5. Percentage Change in Metric To better understand the structural changes in the international crop trade networks before and after the Russia-Ukraine conflict, we compute the percentage change r(t) to compare the network's structure between two consecutive quarters spanning the period from 2016 to 2023.

Metric Change Percentage:

We compute the percentage change r(t) to compare the network's structure between two consecutive quarters from 2016 to 2023 in order to have a better understanding of the structural changes in the international crop trade networks before and after the Russia-Ukraine conflict.

$$r(t) = x(t) - x(t - 1)\ x(t - 1)\ (18)$$

Table 4. Topological indicators used in trade network analysis

Metric	Symbol	Interpretation
In-Degree	Kin	Number of import partners
Out-Degree	Kout	Number of export partners
In-Strength	Sin	Import trade volume
Out-Strength	Sout	Export trade volume
Density	ϱ	Network connectedness
Reciprocity	R	Mutual trade relations
Efficiency	E	Trade flow efficiency
Natural Connectivity	NC	Network resilience
PageRank	PR	Influence of economy

Results:

In order to better understand the impact of the Russia-Ukraine conflict, we examine the evolution of the structural characteristics of three international crop trade networks and the aggregate international food trade network from January 2016 to December 2023. Russia and Ukraine are major global producers and exporters of crops, with their crops, such as maize and wheat, holding significant positions in the global food trade. We concentrate on topological measures that have changed significantly since the crisis between Russia and Ukraine.

Russia and Ukraine are major global producers of foodstuffs worldwide, and their crops, such wheat and maize, play important roles in the global food trade.

The protracted conflict between Russia and Ukraine is likely to make the world's food supply shortfalls worse, raising food prices and jeopardizing food security. In this study, we examine how the overall international food trade network and three international crop trading networks' structural features changed between January 2016 and December 2023. We concentrate on two time periods prior to and following the start of the Russia-Ukraine conflict in order to better comprehend its effects (the second, third, and fourth quarters of 2021 and 2023, respectively).

Effect on Global Networks for Crop Trade:

We show how three worldwide crop trade networks changed between the first quarter of 2016 and the fourth quarter of 2023, emphasizing different network characteristics, as illustrated in Table 2, including the quantity of nodes, edges, total edge weight, average degree, average strength, density, clustering coefficient, efficiency, and natural connectedness. From 2016 to 2022, the three international crop trading networks' structures exhibit notable seasonal variations, but they also show an upward trend, particularly after 2016. The numbers of nodes and edges do not significantly vary, as seen in Table 2a, b, and d. It suggests that there is stability in the trade connections among these 24 economies in the global crop trade networks. It is in line with the general trend of the average in-strength and total link weights. However, during the first quarter of 2022, there was a notable decline in the density of both the international wheat and rice trading networks. It would show how the conflict between Russia and Ukraine has affected the global commerce in wheat and rice. The characteristics of bidirectional trading linkages between economies in the global crop trade networks remained constant during 2016 but displayed a declining tendency following the first quarter of 2022. Table 2 shows that the international crop trade networks' efficiency declined following the conflict, suggesting that there are fewer effective ways to spread crop trade flows. Additionally, natural connectivity is generally steady. The effectiveness of the global crop trading networks declined following the conflict, as shown in. It suggests that there are less effective strategies to spread crop trade flows. Moreover, natural connection is generally stable.

In the short term, the worldwide wheat trade network has been more significantly impacted by the Russia-Ukraine war than the international rice and maize trading networks. Table 3 gives a summary of the percentage change in density, efficiency, average in-degree, and number of edges between the first and second quarters of 2016 to 2023. The average in-degree and % changes in the number of edges of the international rice trade network and the international maize trade network were both positive in 2022/Q2. This shows that the average degree and number of edges in the global networks for rice and maize trade continued to rise. Even if these networks saw more significant drops in these two indicators prior to 2022, it is still unclear if the Russia-Ukraine conflict had a direct impact on these developments. Nonetheless, the average in-degree and density of the global wheat trade network significantly decreased in 2022/Q2 compared to 2022/Q1, indicating a detrimental effect of the conflict on global wheat commerce. Additionally, there were notable declines in the density of the global wheat trade network in 2018/Q2 and 2022/Q2. This suggests that the global wheat trading network's connectedness declined. The 2018 decline was caused by wheat crop losses in Northern and Eastern Europe as a result of severe weather. In the meantime, the international wheat trading network's structure has been upset by the dispute.

Within six months of the battle, there were disruptions in all three international crop trade networks. Table 4 illustrates the negative percentage changes in the three international crop trading networks' average in-degree, density, efficiency, and number of edges. This suggests that just after the Russia-Ukraine conflict, the worldwide crop trading networks' structure was upset.

It's interesting to see that, rather than declining in 2023/Q3, the density and number of edges grew. During this quarter, the average in-degree, density, and efficiency of the global wheat trading network significantly increased. On the other hand, there were fewer edges in the global crop trade networks. These results imply that although the conflict affected the networks' connectedness and structure, it had little effect on economies' involvement in international crop commerce.

International agricultural trade networks, especially the international wheat trade network, have continuously been negatively impacted by the ongoing conflict between Russia and Ukraine. Table 5a,b shows the % changes in the number of edges and average International crop trade networks were beneficial to some extent, but they declined in 2022/Q4. This suggests that while the average degree and number of edges of the global crop trade networks grew, the rate of growth slowed, perhaps as a result of the Russia-Ukraine conflict. The average degree of the global wheat trade network decreased in 2023/Q4, although the number of edges increased. The density and efficiency of the global wheat trade network showed a more significant decline in 2022/Q4 and 2023/Q4, as seen in Table 5 c , d. This is partially due to the growing conflict, which has impeded the growth of free trade. In general, different crop sectors are affected differently by the Russia-Ukraine conflict on global crop trade networks. The network of international wheat trading appears to be the most severely disrupted. Changes in the structure of the global wheat trade network could be explained by wheat yield losses in Ukraine and wheat export limitations. Particularly for the economy of Europe, Russia and Ukraine are important wheat producers and traders. Trade restrictions are among the penalties that Russia and Ukraine have imposed on one another. The availability of wheat in European markets has been impacted by these actions, which have also impeded the movement of wheat and other agricultural products across the economies.

Table 5. Comparative impact of conflict on crop trade networks

Indicator	Wheat Network	Rice Network	Maize Network
Number of Nodes	Stable	Stable	Stable
Number of Edges	Decreased	Slight Change	Slight Change
Density	Significant Decline	Moderate Decline	Moderate Decline
Efficiency	Declined	Declined	Declined
Natural Connectivity	Stable	Stable	Stable
Overall Impact	High	Moderate	Moderate

Effect on the Global Food Trade Network as a Whole:

In order to have some understanding of the effects of the Russia-Ukraine conflict on the global food trade network, we aggregate wheat, rice, and maize trade across crops. The war had no effect on the total number of economies that are part of the global food trade network. In Table 6, we display the quarterly evolution of the whole international food commerce network's structure from 2016/Q1 to 2023/Q4. In contrast to the behavior seen in the individual international agricultural trade networks, we discover that all topological metrics show an overall rising tendency. Notably, in 2022, the average in-strength, the number of nodes, the link weights, and the link reciprocity all showed a steady trend. However, when the fight started, changes were noted in the number of edges, average in-degree, density, efficiency, and natural connectedness.

We are only interested in examining how the overall global food commerce network has changed structurally during the ongoing conflict. By comparing the first quarter to the second quarter and the second quarter to the third quarter, respectively, between 2016 and 2022, Table 7a,b shows the percentage change in the overall structure of the global food commerce network. We do not include these findings because there were no notable structural changes between the third and fourth quarters. It is clear that the number of edges, average in-degree, density,

efficiency, and natural connectivity all significantly decreased in 2019/Q2. Another noteworthy discovery is that, as Table 7a illustrates, these network indicators rose in 2022/Q2 but fell in 2023/Q2. Furthermore, Table 7b demonstrates that in 2023/Q3, these network indicators kept declining. This implies that the conflict originally had little influence on the global food commerce network during a brief period of time, but as the conflict persisted, it finally had a negative impact. This result is somewhat at odds with the findings of the global wheat trade network, which indicate a decline in connection. The substitution impact between wheat, rice, and maize could be one reason for this discrepancy. Since these staple crops can often be used as substitutes for one another in various food products, when the production or exports of wheat decline, consumers and businesses tend to shift their preferences to alternative crops like rice and maize. Higher exports of rice and maize may result from the growing demand for these crops on the global market. As a result, the overall global food commerce network was not negatively impacted in the near run.

Table 6. Structural changes in the aggregate food trade network.

Indicator	Before Conflict	After Conflict
Number of Nodes	Stable	Stable
Link Weights	Increasing	Stable
Reciprocity	Stable	Stable
Density	Higher	Lower
Efficiency	Higher	Lower
Natural Connectivity	Higher	Lower

Impact on Economies In order to better understand how the Russia-Ukraine conflict has affected economies across the board, we perform economy-scale analyses from two perspectives: the topological properties of Russia and Ukraine and the trade relationships between NATO economies and both Russia and Ukraine. Table 8 shows the quarterly percentage change in in-/out-degrees, in-/out-strengths, betweenness centrality, and PageRank for Russia and Ukraine. Table 8a–d shows a partial recovery in 2023/Q4, where some of these properties show an increase.

We do economy-scale analysis from two perspectives to better comprehend the impact of the Russia-Ukraine war on economies. Among these are the topological characteristics of Russia and Ukraine as well as the commercial ties between the economies of NATO and both countries. Russia and Ukraine are responding to the turmoil in various ways.

The quarterly % change in betweenness centrality, PageRank, in-/out-degrees, and in-/out-strengths for Russia and Ukraine is shown in Table 8. The topological characteristics, with the exception of Russia's strength, declined in 2022/Q2. But in 2023/Q4, there is a modest recovery, with some of these attributes showing an increase.

These results imply that Russia's agriculture trade has suffered in the short term as a result of the conflict between Russia and Ukraine. Table 8e–h illustrates how the Russia-Ukraine conflict affects Ukraine less than it does Russia.

Table 7. Comparative network impacts on Russia and Ukraine

Indicator	Russia	Ukraine
In-Degree	Decreased	Slight Decline
Out-Degree	Decreased	Slight Decline
In-Strength	Declined	Stable
Out-Strength	Declined	Stable
PageRank	Declined	Minor Change
Betweenness Centrality	Declined	Minor Change
Overall Impact	Severe	Moderate

NATO economies have complex ties to both Russia and Ukraine. NATO has continuously criticized Russia's activities and demonstrated support for Ukraine as a political and military partnership. Russia's annexation of Crimea and its role in the crisis in Eastern Ukraine have been fiercely denounced by NATO.

As a result, ties between NATO and Russia have deteriorated, which has serious ramifications for collaboration and trade. As a result, our analysis also shows that the trade structure between Russia and Ukraine is heterogeneous.

The number of NATO economies with economic ties to Russia and Ukraine from 2016/Q1 to 2023/Q4. As seen in Table 9a, trade linkages between Russia and NATO economies for all crops and aggregate food significantly declined when the crisis started. The containment effect of the conflict on trade links between the economies of NATO and Russia is responsible for this reduction. But with time, the conflict's effects diminished. Furthermore, Table 9b demonstrates that after 2016, Ukraine expanded its trade ties with NATO economies for all crops. Although trade ties for rice and maize initially declined after the crisis started, they eventually stabilized, easing the impact on trade relations. On the other hand, following 2022/Q1 and 2022/Q4, trade linkages for wheat and aggregate food showed a minor growth. This implies that agriculture trade ties between Russia and NATO economies were more negatively impacted by the crisis than those between Ukraine and NATO economies.

Table 10 shows the evolution of the proportion of food caloric trade volumes between Russia and NATO economies, as well as between Ukraine and NATO economies, to all 24 economies from 2016/Q1 to 2023/Q4. We find that, after the conflict, the proportion of maize and rice exports between Russia and NATO economies, as well as between Ukraine and NATO economies, did not undergo significant changes, indicating that these crop exports remained relatively stable. On the other hand, the proportion of wheat and aggregate food exports between Russia and Ukraine, indicating a discernible impact of these trade relationships. We discover that after the battle, the share of rice and maize exports between the economies of Russia and NATO, as well as did not experience any notable shifts between the economies of Ukraine and NATO. This suggests that during the conflict, these crop shipments stayed comparatively steady. Nonetheless, it is clear that the share of wheat and total food exports between the economies of Russia and NATO has significantly decreased. With a drop in the relative volume of these exports, this loss indicates a discernible effect of the conflict on these particular economic partnerships. Additionally, from 2016/Q1 to 2023/Q4, the percentage of NATO economies' imports from Russia and Ukraine for the three crops and for total food remained untouched by the conflict.

Table 8. Changes in trade relations with NATO economies

Relationship	Effect of Conflict
Russia–NATO Wheat Trade	Strong Negative
Russia–NATO Maize Trade	Negative
Russia–NATO Aggregate Food Trade	Negative
Russia–NATO Rice Trade	Slight Impact
Ukraine–NATO Wheat Trade	Positive
Ukraine–NATO Maize Trade	Positive
Ukraine–NATO Aggregate Food Trade	Positive

We compare the crop export structures of Russia and Ukraine in 2021/Q4 and 2023/Q4 in Table 11 and 12 because both countries are significant exporters of crops. It is important to note that the suspension of export commerce between Russia and some NATO nations led to a significant decreas as illustrated in Table 11a,c–e,g,h a significant decrease in the share of Russia's total exports of maize, wheat, and aggregate food to NATO economies following the Russo-Ukrainian conflict. On the other hand, there was a noticeable rise in the share of Russia's

total rice exports to NATO markets, as shown in Table 11b,c. Table 12 illustrates how Ukraine's situation differed from Russia's. It shows an increase in exports of maize, wheat, and aggregate food to NATO economies, which raised the percentage of exports to NATO economies relative to Ukraine's total exports of these commodities.

In general, different economies and crops are affected differently by the conflict between Russia and Ukraine.

Russia and Ukraine are affected by the crisis in different ways. It had a major effect on economic relations and drastically changed Russia's topographical characteristics between the economy of Russia and NATO, especially with relation to wheat. The conflict affected Ukraine as well, albeit less severely than in Russia. The results show that Russia's network properties and trade dynamics were more significantly impacted by the conflict than those of Ukraine.

Discussion:

Concerns about global trade and food security have been raised by the conflict between Russia and Ukraine. Both Russia and Ukraine are major exporters of grain, making up about 40% of the world's total. Notably, in 2021, these economies accounted for over 30% of global wheat exports. As a result, the battle has led to significant rises in global food costs as well as decreases in the world's food supply. In this research, we use crop trade data from the UN Comtrade Database to evaluate structural changes across three international crop trade networks and an aggregate worldwide food trade network. We also examine the changes in crop trade links between NATO economies and both Russia and Ukraine, as well as the topological characteristics of both countries. We hope to offer insightful information on how the conflict has affected the network structures and trade dynamics in the global agrifood industry through this thorough analysis.

First, we show how the number of nodes, edges, and total edges of three international crop trade networks and the global food trade network changed structurally between Q1 2016 and Q4 2023 in terms of weight, density, clustering coefficient, average degree, average strength, efficiency, and natural connection. We discovered that both the overall international food trade network and the structure of the international crop trade networks had been impacted by the conflict between Russia and Ukraine.

Additionally, different crop sectors are affected differently by the conflict between Russia and Ukraine on global crop trading networks. The international wheat trade network is likely to be most severely disrupted by wheat output losses in Ukraine and restrictions on wheat exports.

In contrast to the behavior seen in the individual international crop trade network, all topological measures for the global food trade network show an overall upward trend. In 2022, the average in-strength, the number of nodes, the link weights, and the link reciprocity all showed a steady trend.

However, when the fight started, changes were noted in the number of edges, average in-degree, density, efficiency, and natural connectedness. The fact that these network indicators rose in 2022/Q2 but fell in 2023/Q3 is another noteworthy discovery. This implies that the conflict had a short-term, negligible influence on the global food trade network before having a long-term, detrimental impact. The results of the global wheat trade network, which indicate a decline in connection, are somewhat at odds with this conclusion. The substitution impact between wheat, rice, and maize could be one reason for this discrepancy.

We specifically look at how the crisis between Russia and Ukraine has affected both countries. The quarterly percentage changes in in-/out-degrees, in-/out-strengths, betweenness centrality, and PageRank for both countries are examined in our study. The results show that Russia's crop trade has suffered in the short term as a result of the conflict between Russia and Ukraine. In contrast, the conflict has had comparatively less of an impact on Ukraine.

We also examine the pre- and post-conflict commercial ties between NATO economies and Russia and Ukraine. Compared to Ukraine and NATO economies, it is noted that the crisis has had a greater effect on the agriculture trade links between Russia and NATO economies. The percentage of Russia's overall exports of maize, wheat, and aggregate food to NATO nations has significantly decreased as a result of the termination of export commerce between Russia and some NATO economies.

While previous studies have broadly examined geopolitical impacts on global food security and trade, our study adds to the body of literature by offering a detailed analysis of the structural changes within international crop trade networks and the overall international food trade network in response to the Russia-Ukraine conflict dynamics Our emphasis on network measures includes density, reciprocity, efficiency, average in-degree, average in-strength, number of nodes, number of edges, link weights, and natural connectivity provides a fresh viewpoint. For example, although address substitution effects among staple crops, our research identifies particular disruptions in the global wheat trade network brought on by export limitations and output losses in Ukraine.

Our results highlight the asymmetrical effects on Russia and Ukraine, exposing unique vulnerabilities and adaptive techniques within both agricultural networks, in contrast to earlier economic models that frequently ignore network subtleties This sophisticated approach, which is consistent with research highlighting resilience and adaptive capability in food supply chains, improves our comprehension of how geopolitical crises can alter the dynamics of global food commerce and market stability.

Our analysis reveals a number of themes and constraints that influence the consequences of our conclusions. First off, longitudinal evaluations are essential for assessing long-term resilience, even though our study sheds light on immediate effects on crop trade networks and flexible tactics in the face of persistent geopolitical unpredictability. Second, depending solely on UN Comtrade statistics makes it more difficult for us to identify regional variations in agricultural trade dynamics and informal trade channels. To strengthen the validity of our findings, future studies should use more detailed data sources and qualitative evaluations. Thirdly, vulnerabilities in global food supply chains are highlighted by the noted drop in trade volumes and connectivity within the worldwide wheat trade network. Policy interventions that support diversified sourcing techniques and fortify regional frameworks for food security are necessary to address these vulnerabilities. Finally, our analysis emphasizes the consequences for accomplishing the Sustainable Development Goals (SDGs), especially SDG 17 (Partnerships for the Goals) and SDG 2 (Zero Hunger). In order to guarantee food security and lessen the socioeconomic effects on vulnerable populations, the conflict's interruption highlights the necessity of international cooperation and adaptable governance institutions.

Table 9. Summary of principal findings

Research Question	Main Finding
Impact on Wheat Trade	Most severely affected
Impact on Rice Trade	Moderate
Impact on Maize Trade	Moderate
Impact on Food Trade Network	Initially resilient
Impact on Russia	Significant negative effect
Impact on Ukraine	Less severe impact
Impact on NATO Trade Relations	Shift away from Russia
Food Security Implications	Increased vulnerability
Network Resilience	Reduced efficiency
Long-Term Outlook	Trade diversification increasing

Conclusions:

International trade networks have been greatly damaged by the conflict between Russia and Ukraine, especially in the global agrifood industry. Our thorough investigation shows that the structural integrity of global grain trade networks has been compromised by conflict, with wheat trade being particularly affected. Network indicators, such as the number of edges and average in-degree, initially increased in early 2022 but eventually decreased, indicating the conflict's wider effects on trade efficiency and connectivity.

It's interesting to note that the overall international food commerce network showed a more robust structure, despite significant disruptions to the wheat trading network.

This resilience, which enables the global food supply chain to adjust in spite of the difficulties presented by the conflict, is probably caused by the substitution effect among staple crops like wheat, rice, and maize. Our research also emphasizes the differing effects on economic interactions between the economies of NATO and Russia and Ukraine. Following the battle, trade ties between Russia and NATO economies drastically decreased, especially for wheat and other food, while Ukraine was able to strengthen its ties with NATO economies. The different geopolitical and economic variables at work are highlighted by this disparity. The observed shifts in trade patterns highlight the intricate relationship between international food security and geopolitical developments. In addition to having an impact on economic arrangements, the conflict has caused strategic changes in crop export connections, especially between NATO economies and the warring countries. These results highlight the necessity of strong and varied trade tactics to lessen such disruptions and offer insightful information on the adaptive responses within global trade networks during times of geopolitical instability.

In conclusion, worldwide crop trade networks have been significantly impacted in the short and maybe long term by the Russia-Ukraine conflict. To comprehend the changing dynamics and create plans that strengthen the resilience of international food commerce systems against geopolitical disturbances, ongoing observation and study are crucial. In light of the Russia-Ukraine crisis, our analysis provides important insights into the structural dynamics of global crop trading networks. However, interdisciplinary research is essential to comprehensively address the complex challenges facing global food security in the 21st century.

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