The multiple dimensions of resilience in agricultural trade networks

**Abstract**

The resilience of the global food and agricultural trade network has been put to the test historically and also more recently by the COVID-19 pandemic in 2020 and the ongoing war in Ukraine that started in February 2022. Such shocks have the potential to propagate throughout the entire network and affect the food availability and variety of countries in the network. This paper employs network analysis to examine the evolution of multiple dimensions of resilience within the food and agricultural trade network since the World Trade Organization (WTO) Agreement on Agriculture (AoA) in 1995. It explores the evolution of connectivity and structure of the connectivity of the trade network and their implications for resilience in the face of trade shocks. Between 1995 and 2007, there was rapid development and increased connectivity in food and agricultural trade, resulting in countries worldwide becoming more interconnected with global markets. However, progress has been constrained in subsequent years. Analysis of the structure of the trade network reveals that the enhanced connectivity among countries has bolstered their resilience to trade shocks to some extent mainly until 2007, but vulnerabilities persist, and there are indications of slight tendencies towards disintegration and lower resilience in recent years.

**Keywords:** Global food trade, network analysis, network integration, structure of integration, resilience

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# Introduction

The resilience of the global food and agricultural trade network, which refers to its ability to withstand and recover from disturbances and adapt to risks and long-term structural changes while maintaining stable food variety and quantity (Mena, Karatzas and Hansen, 2022), has been tested in various circumstances. The COVID-19 pandemic resulted in widespread restrictions on movement and trade across the globe in 2020 and 2021. Since February 2022, the war in Ukraine has introduced localized shocks to the network, impacting agricultural production and export capabilities of key players in the market. Such shocks have the potential to propagate throughout the entire network through transmission effects and potentially self-propagating trade disruptions. The resilience of the trade network depends on the connectivity of countries within the network, as well as structure and distribution of that connectivity (Acemoglu, Ozdaglar and Tahbaz-Salehi, 2015). Increased connectivity strengthens the buffer capacity of the network but can also transmit negative shocks (Dellink, Dervisholli and Nenci, 2020)

The main objective of this paper is to analyze the changes in the resilience of food and agricultural trade since the inception of the World Trade Organization (WTO) and the Agreement on Agriculture (AoA) in 1995. We analyze changes in connectivity and structure of connectivity of the global trade network. We assess the network's resilience from the importing countries' perspective and in terms of its ability to withstand disruptions in both product variety and quantity, in the short and relatively longer term. To achieve this, we employ a variety of network measures using a balanced panel of 190 countries for the years 1995, 2007, 2013, and 2019.

Fostered by the AoA, the emergence of preferential and regional trade agreements (RTAs) and progress in transportation and communication technology, global food and agricultural trade expanded rapidly during the early 2000s, accompanied by an increasing share of low- and middle-income countries being active in global trade and the evolution of global value chains in the food and agriculture sector (Dellink, Dervisholli and Nenci, 2020; FAO. 2020.). This trend was interrupted by the 2008 financial crisis, followed by a slowdown of the expansion of global trade.

The greater integration of countries into the trade network brings trade-offs for country- and global-level resilience to trade shocks (Karakoc and Konar, 2021).At the country level, individual countries can mitigate domestic food production shocks, such as those caused by extreme weather events, by adjusting trade quantities, thereby ensuring food security. At global level, the exchange of foods among countries can help offset specific shocks in the network, evening out supply fluctuations worldwide and reducing price volatility. However, there are concerns that increased import dependency and greater connectivity through trade may also increase vulnerability to shocks, rather than contributing to resilience. The transmission of shocks and vulnerability can be exacerbated if countries in the network respond to disruptions by imposing trade restrictions, leading to self-propagating trade disruptions and price spikes.

The vulnerability of countries to external trade shocks depends on various factors, including the structure of the trade network. If a small number of dominant players control the network and many other countries are connected to these hubs without direct connections among each other, shocks affecting the dominant players can easily propagate throughout the network, potentially amplified by global value chains. Conversely, a shock to the system is more likely to dissipate when many countries in the network are connected to multiple trade partners, providing a greater degree of resilience (Acemoglu *et al.*, 2012a; Acemoglu, Ozdaglar and Tahbaz-Salehi, 2015; Lucas, 1977; UNCTAD. 2019)

Some argue that there is a trade-off between economic efficiency and resilience in the global network of food trade. While high specialization in line with comparative advantages increases economic efficiency, the dependence on few major exporters for specific goods may also induce vulnerabilities and reduce resilience of the global network (Karakoc and Konar, 2021). “Diverse systems that have many different complementary components from multiple sources are generally more resilient than systems with few components, allowing systems to compensate for the loss or failure of some components with other functionally redundant components” (Kummu *et al.*, 2020). “Well-connected food systems can overcome and recover from disturbances faster by ‘importing’ sources of resilience”, whereas “overly connected systems […] may lead to rapid spread of disturbances and unintended impacts across the entire food system”. Raj, Brinkley and Ulimwengu, (2022) find that global trade in food “has allowed countries to buffer against domestic food production shortfalls and gain access to larger markets, but has also opened economies up to shocks and increased extraction of food resources”. Burkholz and Schweitzer, (2019) emphasize the importance of considering the structure of higher-order trade networks (as opposed to direct connectivity among countries in first-order indicators) to take cascading shocks in the network into account.

The empirical literature often simulates the resilience of trade networks by randomly or targetedly removing countries or trade links in the network, and then analysing how certain measures of network connectivity change in response to these shocks (Karakoc and Konar, 2021). Higher changes in connectivity in response to the introduced shocks indicate lower resilience of the network. These approaches primarily rely on pure connectivity measures to calculate resilience, and the role of the structure of connectivity is implicitly captured through the calculation of network connectivity across years. As (Karakoc and Konar, 2021) aptly describes, these approaches do not explicitly explain the economic aspects of changes in resilience.

This study contributes to the literature in four main ways. Firstly, it introduces an analytical framework to analyze the resilience of the agricultural and food trade system by identifying two major dimensions of resilience: connectivity and the distribution of connectivity. While connectivity can increase resilience, the heterogeneous distribution of connectivity reduces it. Secondly, the study relies on direct and indirect connectivity measures, including different orders of these measures, and their distribution to understand the immediate and long-term impacts of shocks in the network. The direct measures of connectivity of countries and their distribution may inform the short-term probability of shock propagation, and indirect measures of connectivity and their distribution may help to understand the resilience of the trade network in a relatively longer term. Thirdly, this analysis is complemented by an examination of the probability of the exacerbation of local shocks in network localities, and the geographical extent that the shocks may move from that locality. Fourthly, the study analyzes the resilience of the trade network in terms of product availability, encompassing both variety and quantity. The former relates to assessing the resilience of trade relationships along the extensive margin (trade per country, and trade per country and product), while the latter relates to examining the resilience of the network in terms of the intensive margin of trade (trade value per country link).

The following section presents an initial examination of significant changes in global food and agricultural trade. This is followed by a definition of the concept of resilience and an exploration of its multidimensionality. Next, we describe the network methodology and data utilized for the analysis. In the results section, we examine the evolution of the integration structure of the agricultural and food trade system, as well as the local, regional, and global structure of connectivity formation in the trade network to analyze changes in resilience over time and its current status. The concluding section summarizes the findings, provides policy implications, and suggests future directions for research.

# Evolution of food and agricultural trade

Agri-food trade accounted for approximately 35% of its production value in 2019 (based on FAOSTAT). Since 1995, the trade value has fluctuated around a positive trend, while the number of commodity-specific trade links has steadily increased (Figure 1). These positive trends are driven by technological progress, the reduction of trade barriers, transportation, and communication costs, and demand shifts associated with global economic growth (Beckman *et al.*, 2018; FAO. 2020., Hendrik and Lewer, 2015).

Between 1995 and 2019, the trade volume more than doubled and increased by a factor of around 3.5 in nominal terms. The stable growth observed since 1995 was interrupted by the global recession in 2008-2009. It recovered during 2010-2011, mainly driven by continuing growth in emerging economies, but has since been levelling off. Trade tensions between China and the USA during 2018-2019 are reflected in a drop in terms of trade links and value in 2019 (Figure 1). In comparison to trade values, the number of established bilateral trade links at the country level has steadily increased since 1995 with fewer fluctuations. The most significant increases were observed from 1995 to 2002, followed by a slower growth until 2015, and a subsequent levelling off. Both the positive trend and the fluctuations in agri-food trade may be linked to changes in the structure of the global trade system (Korniyenko, Pinat and Dew, 2017)

Figure 1: Evolution of agri-food trade (1995-2019)

# Framing the multidimensionality of resilience

Shocks in the trade network affect both exporters and importers. Exporters lose export revenue and importers experience disruptions to their supply of final and intermediate products. Risks to food security from disruptions in food trade are usually assumed to be higher for importers, we therefore characterize the resilience of the trade network from the importer perspective. Effects on the exporter side are analogue to those on the importer side and could be further explored in follow up studies. A shock to trade can be caused internally or externally. From an importer's perspective, an internal shock occurs when demand is disturbed, such as a significant reduction in income in the importing countries. External shocks happen when exporting countries face disruptions, including disturbances in the exporter's production system, for example, caused by extreme weather conditions, conflicts or pests. Some shocks are bilateral, affecting both exporters and importers. Sudden trade barriers are an example of bilateral shocks, disrupting both parties involved. The network of food and agricultural trade is susceptible to various risks, and when a shock occurs in one country or region, it can have ripple effects on third countries/regions. We speak of direct effects if trade partners are affected directly, indirect effects occur in third countries/regions and are transmitted through global value chains or other mechanisms.

## Country-level resilience vs global (network)-level resilience

Shocks may affect individual countries directly or indirectly, and the ability of an individual country to withstand, adapt to and recover from such disruptions, known as country-level resilience, depends on their connectivity within the trade network. Country-level resilience entails countries’ capacity to maintain food supply stability and functionality by importing products in varying volumes and varieties from different sources. The individual capacity of countries to absorb shocks determines the global (network) level resilience, which refers to the ability of the network to collectively absorb, adapt, and recover from disturbances. The concept of global level resilience takes into account the interdependencies and interactions between countries, examining how shocks or disruptions in one country can propagate and affect others within the network.

Resilience in food and agricultural trade can be characterized based on two dimensions: (i) connectivity at country-level and (ii) distribution of connectivity across countries. For an individual country, if connectivity is high, the country should be able to adapt to trade disruptions more easily than a country with low connectivity. Trade network resilience can be defined by considering two dimensions: the average level of connectivity across countries and the distribution of connectivity across countries. Based on these two dimensions, four potential pathways/states of resilience can be distinguished: (I) High overall (average) connectivity and a relatively normal distribution of connectivity across countries; (II) High overall (average) connectivity, but a more heterogeneous distribution of connectivity across countries; (III) Low overall connectivity and a relatively even distribution of connectivity across countries; (IV) Low overall connectivity and a relatively heterogeneous distribution of connectivity across countries (Arriola *et al.*, 2020; Korniyenko, Pinat and Dew, 2017). The first pathway/state is the most favorable for the resilience of the network, while the fourth pathway/state represents a state of low network resilience. The two intermediate pathways/states involve trade-offs between the average level of connectivity and the distribution of connectivity.

## Transmission/propagation of shocks

A shock to an importer, whether bilateral, external, or internal, can directly disrupt the availability and variety of food and agricultural products in that country. The indirect impact of such a shock can be far-reaching due to two main reasons. Firstly, production processes are often fragmented and involve multiple countries (global value chains). The fragmented production process means that the unavailability of a specific product or variety in an importing country can have implications for the direct partners of that country. These partners may utilize the imported products as intermediate inputs for further processing and exporting to other countries. Consequently, the availability and variety of products in other countries that depend on processed goods from the initial importers are also affected. The extent and magnitude of this spillover effect depends on the level of fragmentation in the production process. Secondly, due to substitution and price effects shocks can even be transmitted to the trade of products that are not directly traded in global value chains. Thus, shocks can cascade through the trade network and affect multiple countries that are only indirectly connected to the specific importer.

### Short-run versus long-run transmission of shocks

Examining countries' direct connectivity can reveal immediate spillover effects, impacting trading partners directly. Higher-order connectivity offers insights into longer-term impacts on a broader range of countries. If countries are connected to others through indirect/higher-order trade relationships, shocks from network cores can propagate more easily, particularly if global value chains are disrupted across multiple countries. The spread of these shocks across the network takes longer to manifest compared to the immediate effects experienced by direct trading partners. Nevertheless, higher levels of direct and indirect connectivity mean that alternative suppliers can more readily substitute for disrupted imports, especially if only specific countries are affected. Existing trade relationships can be leveraged in such circumstances.

### Mode and magnitude of shocks propagation

Beyond the large-scale distribution of direct and indirect connectivity, the mode and density of connectivity among smaller agglomerations of countries is important as they can accelerate or decelerate shock transmission. For example, the mode of connectivity in formations of bilateral and triadic trade relationships may affect shock propagation. In a one-way direct trade relationship (asymmetric bilateral trade relationships), as opposed to a two-way direct trade relationship (mutual trade relationship), a local shock would transmit from the exporter to the importer but without repercussions back to the exporter as could be implied in a two-way direct trade relationship. In triadic trade relationships, the magnitude of propagation depends on the different types of trade relationships between the three parties. The more transitive (interconnected) the trade relationships are, the higher the (self-)propagation of the shock within that specific network locality, probably resulting in a stronger impact on the rest of the network.

In a pronounced core-periphery structure of the network, shocks from major hubs can transmit to the periphery and identifying the major hubs within it, we can gain insights into the potential impact of shocks originating from specific regions or countries (This is already repeated in the result section).

## Diversity and intensity of trade (extensive versus intensive margin)

The concept of the extensive margin of trade refers to the diversity of trade in terms of the number of trading partners and the range of products exchanged. A higher level of diversity on the extensive margin indicates that a country has numerous trading partners and engages in trade of a wide array of products, thereby expanding its trade network. The intensive margin of trade focuses on the volume/value of goods exchanged between trading partners. An increase in the intensive margin signifies a larger volume/value of goods being traded between countries, reflecting a deeper level of trade integration. In general, a greater diversity of trade partners and products traded would avoid dependencies on trade with few partners of few products but at a high intensity. However, there will be trade-offs between efficiency gains based on specialization and resilience based on diversification (Karakoc and Konar, 2021).

# Materials and methods

Our approach to address the multidimensional aspects of resilience primarily involves analyzing the connectivity and structural facets of trade networks. This analysis relies on various measures derived from network theory, considering both direct and indirect (2nd and higher) orders of interdependencies among countries, as well as the structure of these connections.

We evaluate both direct connectivity between countries and their indirect connectivity. Indirect connectivity is assessed through second-order and eigenvector measures. Direct connectivity pertains to a country's connections with its immediate trading partners. Second-order connectivity relates to a country's connections with the trading partners of their direct partners (the connections of their partners' partners). Meanwhile, eigenvector connectivity represents a country's connections to the entire network, serving as a measure of its influence within the network. The average of country-level connectivity measures, while maintaining a constant network size, provides a global connectivity measure.[[1]](#footnote-2)

To gather information on the distribution of connectivity across countries worldwide, we employ various measures to assess the distribution's characteristics. One frequently used measure of distribution heterogeneity, showing the thickness or heaviness of the tail of the distribution, is the percentage of out-of-interval observations (Sartori and Schiavo, 2015) calculated around the mean ± double standard deviation. Moreover, skewness and kurtosis statistics offer insights into the shape of the distribution. Skewness reflects the distribution's asymmetry concerning the symmetric bell-shaped Gaussian (normal) distribution. In a normal distribution, skewness holds a value of zero. Positive (negative) skewness indicates right (left) fat tails. A larger absolute value denotes higher skewness. Kurtosis measures how the data clusters around the tails or the peak compared to a normal distribution. A kurtosis lower than the reference level for a Gaussian distribution (which is 3) suggests the presence of a thin tail. The obesity index, proposed by (Cooke, Nieboer and Misiewicz, 2014) provides additional insights into the tail behavior of the distribution. It operates on the heuristic that in heavy-tailed distributions, larger observations are farther apart than smaller ones. Considering individual centrality measures as independent and identically distributed values sampled randomly from the data, the Obesity index is the probability that the sum of the largest and smallest of the four observations is greater than the sum of the other two observations.[[2]](#footnote-3)

|  |  |  |  |
| --- | --- | --- | --- |
| **Connectvity measures** | **Level of aggregation** | **Structure used to analyse global resilience** | **Temporal dimention of resileince** |
| Direct connectivity | Country and Global level | Distribution of country level | Short term spillover impacts |
| Indirect Connectvity |  |  |  |
| Second order Connectvity | Country and global level | Distribution of country level | Midterm spillover impacts |
| Eigenvector Connectvity | Country and global level | Distribution of country level | Longer term spillover impacts |
|  |  |  |  |
|  |  |  |  |
| Bilateral trade relatinships |  | Density and mode of bilateral trade (dyad)formation |  |
| Triad trade relatinships |  | Density and mode of triad formation |  |

Different orders of connectivity offer insights into the temporal dimension of resilience. The evolution of first-order connectivity, observed through both its mean and distribution, uncovers the immediate (short-term) spillover impact of shocks. Conversely, second-order and eigenvector connectivity measures provide information on the longer-term resilience to shocks. These shocks could originate from countries not directly connected, affecting a given country, or from directly connected countries but spilling over to a country through indirect linkages.

The manner in which connectivity occurs in the formation of bilateral and triadic trade relationships can significantly impact shock propagation. In examining the mode of connectivity within bilateral trade relationships, we analyze changes over time in the density of unilateral/asymmetric and bilateral trade relationships concerning total relationships. Density is calculated as the number of bilateral or trilateral trade relationships over the total possible number of relationships. It's important to note that the count of trade relationships is irrespective of the type of trade link; both bilateral (two trade links) and unilateral trade (one trade link) relationships are considered as a single trade relationship. In terms of triadic trade relationships, i.e., those involving three countries, there exist 13 distinct types that depict various connections among the three countries (See Figure A1).

We also identify which countries wield the greatest influence on the network using betweenness connectivity. The betweenness connectivity of each country in the network illustrates how often a particular country acts as an intermediary, connecting two other countries that aren't directly linked (Freeman, 1978).This measure signifies the overall reliance of the trade network on that country. A higher value of this measure designates a more prominent role for the country as a hub, while countries with low betweenness are considered more peripheral within the network.[[3]](#footnote-4) Both betweenness and eigenvector centrality reflect a node's importance within a network but from different perspectives— one emphasizing its position in controlling the network's communication or interaction pathways, and the other considering influence through well-connected neighbors.

We apply the measures mentioned above to a trade network from three different perspectives: a binary trade network indicating whether countries have any trade transactions with each other (network of country trade links), a weighted trade network that quantifies the number of trade commodities exchanged between each pair of countries (the network of country product trade links), and a weighted trade network that represents the value of trade between any two countries in the network (trade intensity matrix). The first two types of networks (network of country trade links and the network of country product trade links) are employed to analyze the trade network along the extensive margin of trade, while the third type of network (trade intensity matrix) is used to analyze trade from the intensive margin.

Each of these networks can be directed or undirected, depending on whether the direction of trade flows is considered in the analysis. In our calculations of the trade network, we use the directed trade network unless indicated otherwise. Table 2 provides a description of the network indicators we used and their corresponding mathematical formulas.

Table Description of network indicators used in the analysis

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Network measure** | **Description** | **Level of aggregation** | **Direction and weight** | **Mathematical formula** |
|  | Connectivity/centrality measures | | | |
| Network density | Shows the proportion of actual connections (links) over potential connections (links) and thus the probability of the presence of a link between any two countries. In a fully connected network, the density is equal to one indicating that each country is linked to (trades with) all other countries. | Global | Undirected, unweighted | Number of links (*m*) over total number of possible links :., In the undirected network, the total number of possible links is , where *n* is the number of nodes (countries). |
| Node degree (first-order and second-order) | First-order: The degree connectivity indicates the total number of trade links of a country and is identified based on binary network analysis. Outdegree refers to export flows, indegree refers to import flows. In this analysis, the in-/out-degree of a country is normalized by the total number of theoretically possible degrees. In the directed network, the total possible number of degrees (links) for each node (country) is: (n – 1)\*2.  Second-order: Second-order degree is defined as the sum of the first-order degree of all direct trade partners. The second-order degree is normalized by its maximum across years. | Local and global average | Directed, unweighted | First-order: The degree connectivity is the degree of the network (*d*) over the maximum possible degree : .  Second-order: Second-order degrees are calculated by multiplying the binary trade matrix with itself (following (Acemoglu *et al.*, 2012b; Sartori and Schiavo, 2015). |
| Node strength (first-order and second-order) | First-order: Strength indicates the total number of traded products or the trade value associated with each aggregate trade flow. It is derived from weighted network analysis. Outstrength refers to export flows, instrength refers to import flows. The in-/out-strength of a country is normalized by dividing by the highest observed in-/out-strength across years.  Second-order: Second-order strength is defined as the sum of the first-order strength of all direct trade partners. The second-order strength is normalized by its maximum across years. | Local and global average | Directed, weighted | First-order: Sum of columns (exporter country) for each row (importer country) of the trade matrix for each year. The sum is normalised by dividing by the highest observed in-/out-strength across countries and years.  Second-order: Product- and trade value-weighted trade matrices are multiplied with the transpose of the normalized first-order strength matrix. |
| Eigenvector centrality | Connectivity of a node based on the connectivity of its neighbours, the neighbours of the neighbours and so on, i.e. the connectivity of a node proportional to the sum of connectivity indices of its neighbours. The more important the neighbours in the network, the higher the connectivity of a given node.  The eigenvector centrality has a similar interpretation as the first- and second-order degree connectivity measures, but also considers all higher-order degrees. | Local and global average | Directed, unweighted/weighted | Mathematically, the eigenvector centrality of each node is calculated as    where is a proportionality constant. implies that node receives the contribution to the connectivity from its neighbours through incoming links. The above formula in matrix form is  which means the vector of connectivities is an eigenvector of with eigenvalue .  The weighted eigenvector centrality measure is straightforward, in this case refers to the weights (e.g. trade values). |
| Betweenness coonectvity | This measure shows the overall dependence of the trade network on that country. | Local and Global | Directed/ weighted and unweighted | In statistical terms, the betweenness index is a measure of a median. In country trade link network, the betweenness connectivity for each country is the total number of the shortest path in the network that goes through a given country over the total possible shortest path. In the weighted trade networks, a weight is assigned to each shortest path, whereas the weight is either the number of commodities or the value of trade that occurs on that shortest path |

Source: Adapted from (Geyik *et al.*, 2021) and (Jafari, Engemann and Zimmermann, 2023).

## Data and construction of the world trade matrix

To calculate the network measures, we utilize data from the FAOSTAT database on international bilateral trade of food and agricultural products[[4]](#footnote-5). Our analysis covers snapshots of world trade involving 190 countries for the years 1995, 2007, 2013, and 2019. The selection of these specific years is based on their significance in relation to global trade dynamics (See figure 1). We choose 1995 as the year of the establishment of the WTO, 2007 as the onset of the global food price crisis before the financial crisis, 2013 as a year when growth in global food and agricultural trade had already leveled off, and 2019 as the most recent year for which data was available at the time of analysis.

The trade matrix is constructed using bilateral import flows, which are often deemed more reliable than export data (Cadot, Carrère and Strauss-Kahn, 2011)Generally, import and export links and values are highly correlated, allowing for generalizations about overall trade patterns. In situations where import values were not available but corresponding export values were reported by partner countries, we reflect export values to represent import values. Trade values are expressed in USD and deflated using the 1995 United States of America Consumer Price Index (e.g., (Rose, 2004))

# Results and discussion

## Perspective: Country-level vs global-level resilience

### Level of connectivity

The direct connectivity of all countries increased between 1995 and 2019 (Figure 1) along both extensive and intensive margins. Especially the increased connectivity along the extensive margins indicates improved resilience of individual countries against trade shocks originating from one or few trade partners through a greater diversity of trade partners and imported products. Greater connectivity at the intensive margin implies that countries also increased the overall value of their imports between 1995 and 2019. In 1995, countries in North America, East Asia, Oceania, the European Union, and partially South Africa and countries in Northern Africa were already well-connected. By 2019, the connectivity of most countries had increased, particularly in countries of the former Soviet Union. However, the connectivity of many African countries, Small Island Developing States and land-locked countries remained low along both extensive and intensive margins, and, in general, countries in these groups are the least connected in the world. The overall density of the trade network increased from 32% to 47%, indicating a higher number of countries engaging in trade with one another. The general increase in the connectivity measures of first order, both in terms of trade links and the intensity of trade, indicates changes in the intermediate and global connectivity of the trade network encompassing all countries, on average.

Figure Country-level connectivity to the global food and agricultural trade network, by country, 1995 and 2019



Source: (Jafari, Engemann and Zimmermann, 2023)

### Distribution of connectivity

While direct connectivity of all countries increased, connectivity is still unevenly distributed. At both extensive margins and the intensive margin (Figure 2), the distribution of direct connectivity across countries was strongly right-skewed in 1995 indicating a high concentration of trade among few countries. Between 1995 and 2007, especially the distribution of connectivity by trade partner shifted to the right and became more bell-shaped (Panel A) indicating a more balanced trade system with overall lower vulnerability to trade shocks as shocks to trade links with one or few countries in the network can be substituted with links with other countries. The distributions of trade intensity and trade links by country and product became flatter and less concentrated between 1995 and 2007 as well. Nonetheless, connectivity along these dimensions remained much more concentrated than the connectivity by trade partner. Only few countries possess a comparative advantage and are main exporters, suggesting a high dependency of other countries in the network on these key exporters (Bren d’Amour *et al.*, 2017; Geyik *et al.*, 2021; Gutiérrez-Moya, Adenso-Díaz and Lozano, 2021; Puma *et al.*, 2015; Soffiantini, 2020).This underlines economic efficiency of the network but may imply low resilience to trade shocks in specific commodities and for the bulk of countries’ import value (Karakoc and Konar, 2021). Overall, the development of the patterns of direct connectivity between 1995 and 2007 appeared to follow Pathway I, indicating higher connectivity and a more equitable contribution of countries to the overall connectivity. These findings are consistent with (Sartori and Schiavo, 2015)and (Konar *et al.*, 2011), who also observed a rightward shift of the distribution of first-order degree connectivity and a thinning of the distribution's tails over time.

Average connectivity continued to rise between 2007 and 2019, albeit at a slower pace. However, the distributions displayed an increasing trend of tail-heaviness during the period 2013-2019. Kurtosis and skewness both decreased between 1995 and 2007 but increased thereafter (Appendix, Table 4), suggesting a development along Pathway II: higher connectivity, yet an uneven distribution of connectivity across countries. The resilience of the food and agricultural trade network improved between 1995 and 2007 but has made limited progress ever since.[[5]](#footnote-6)

Figure . Distribution of connectivity (first-order indegree/instrength)

|  |  |  |
| --- | --- | --- |
| Panel A: Direct trade links by country (extensive margin, unweighted) | Panel B: Direct trade links by country and product (extensive margin, weighted with number of products traded) | Panel C: Direct trade intensity (intensive margin, weighted with trade value) |
| Chart  Description automatically generated |  |  |

## Shocks transmission/propagation

### Transmission of shocks in short- and long-run

While the distribution of countries' direct connectivity reveals the immediate impact of shocks, higher order connectivity measures offer insights into the longer-term effects and their reach across a wider range of countries. Similar patterns to direct connectivity are observed for indirect connectivity. As the number of trade links between countries continues to increase, the indirect connectivity of countries, as indicated by second-order and eigenvector connectivity, also experiences growth. The distributions of indirect connectivity (Figure 3) generally shifted rightwards, indicating an overall increase in average connectivity, particularly between 1995 and 2007. Since 2007, the distribution of trade links by country at second and higher orders of connectivity has tended to exhibit left-skewness. This could indicate a transition from a state where a small fraction of highly connected countries coexisted alongside a large number of countries with few connections to a state where only a small fraction of countries has a low level of indirect connectivity. However, this also implies that some countries still lag behind in terms of indirect connectivity.

The increased higher-order connectivity signifies an overall stronger integration of countries in the network in the sense that trade shocks originating in a country A and affecting its direct trade partner country B may more easily transmit to countries connected to country B but that have no direct connection to country A. Shocks may transmit to third countries if reduced exports by country A imply reduced exports of country B to its trading partners. In theory, there are three pathways: (i) exports of like products or re-exports: reduced imports of product X by country B lead to reduced exports of product X of country B; (ii) global value chains: reduced imports of product X by country B imply that country B cannot produce and export value added product X (X+); (iii) reduced imports of product X by country B lead to reduced exports of substitutes of product X from country B (Xsubst).

The distributions of second-order indegree and eigenvector connectivity of trade links by country and product, as well as trade intensity (Figure 3), demonstrate less skewness compared with their first-order connectivity. Although greater higher-order connectivity may increase countries’ vulnerability to transmission of shocks through the network, the more balanced distributions of higher-order connectivity could suggest that the high indirect connectivity (especially of less integrated countries) may also contribute to reducing their vulnerability to shocks in the system as shocks could be buffered by substituting lost trade links with alternative higher-order suppliers/products. As in the case of direct connectivity, the measures of tail-heaviness for second-order connectivity (Appendix, Table 4) suggest a slight reversal of the trend towards a more evenly distributed connectivity between 2013 and 2019.

Figure . Distribution of indirect connectivity (second-order indegree/instrength and eigenvector indegree/instrength)

|  |  |  |
| --- | --- | --- |
| Panel A: Indirect trade links by country (second-order indegree) | Panel B: Indirect trade links by country and product (second-order indegree) | Panel C: Indirect trade intensity (second-order instrength, intensive margin, weighted with trade value) |
| Chart  Description automatically generated with medium confidence |  |  |
| Panel D: Indirect trade links by country (eigenvector indegree) | Panel E: Indirect trade links by country and product (eigenvector indegree) | Panel F: Indirect trade intensity (eigenvector instrength, intensive margin, weighted with trade value) |
|  |  |  |

### Mode and magnitude of shocks propagation

Between 1995 and 2019, the total number of trade relationships between countries, encompassing both one-way trade links (asymmetric) and two-way trade relations (mutual), saw a notable increase, from 7,084 active trade relationships in 1995 to 10,454 in 2019. The most substantial change took place during the period from 1995 to 2007 (Table 5). The proportion of actual trade relationships compared to the total possible trade relationships grew from 39 percent in 1995 to 58 percent in 2019. The majority of trade relationships during this time period remained mutual, accounting for approximately 60 percent to 63 percent of all trade relationships across the years. Mutual trade relationships, as opposed to one-way trade, signify a high density of connectivity between countries. This density may contribute to greater exchange of goods in terms of both quantity/value and diversity. However, it also raises the likelihood of shock propagation through a multiplier mechanism: a shock originating in one country can affect its bilateral trading partner, and due to the bilateral trade linkages, the shock may amplify beyond its initial impact on the country where it originated.

The number of trilateral trade relationships (triads) experienced significant growth. The proportion of active triads over all possible triads, known as the intensity of triads, increased from 40 percent in 1995 to 56 percent in 2007. Subsequently, it remained stable at around 60 percent in 2013 and 2019 (Table 2). Theoretically, there are 16 different types of triads that can be formed by three countries, with 13 of them involving all three countries (see Figure A1 in Appendix A). In 1995 and 2007, the most common types of triads in the global food and agricultural trade network were intransitive triads (labelled as 201 and 111D in Figure A1, respectively), where countries interacted through intermediaries. However, in 2013 and 2019, the most frequent type of triad (labelled as 300 in Figure A1) was transitive, with reciprocal trade occurring between all three countries. In general, the share of transitive (multi-way) trade relationships increased from 19 percent in 1995 to 30 percent in 2019, while the share of intransitive trade relations decreased. This indicates stronger trade relationships between countries and larger groups of countries in 2019 compared to 1995, signifying increased connectivity. This connectivity may strengthen the ability of countries to provide mutual support in the face of shocks. However, it also renders them more vulnerable due to the multiplier mechanism and the subsequent cascading effects of shocks.

Table 2. Structure of bilateral and trilateral trade relationships



### Extent of shocks propagation

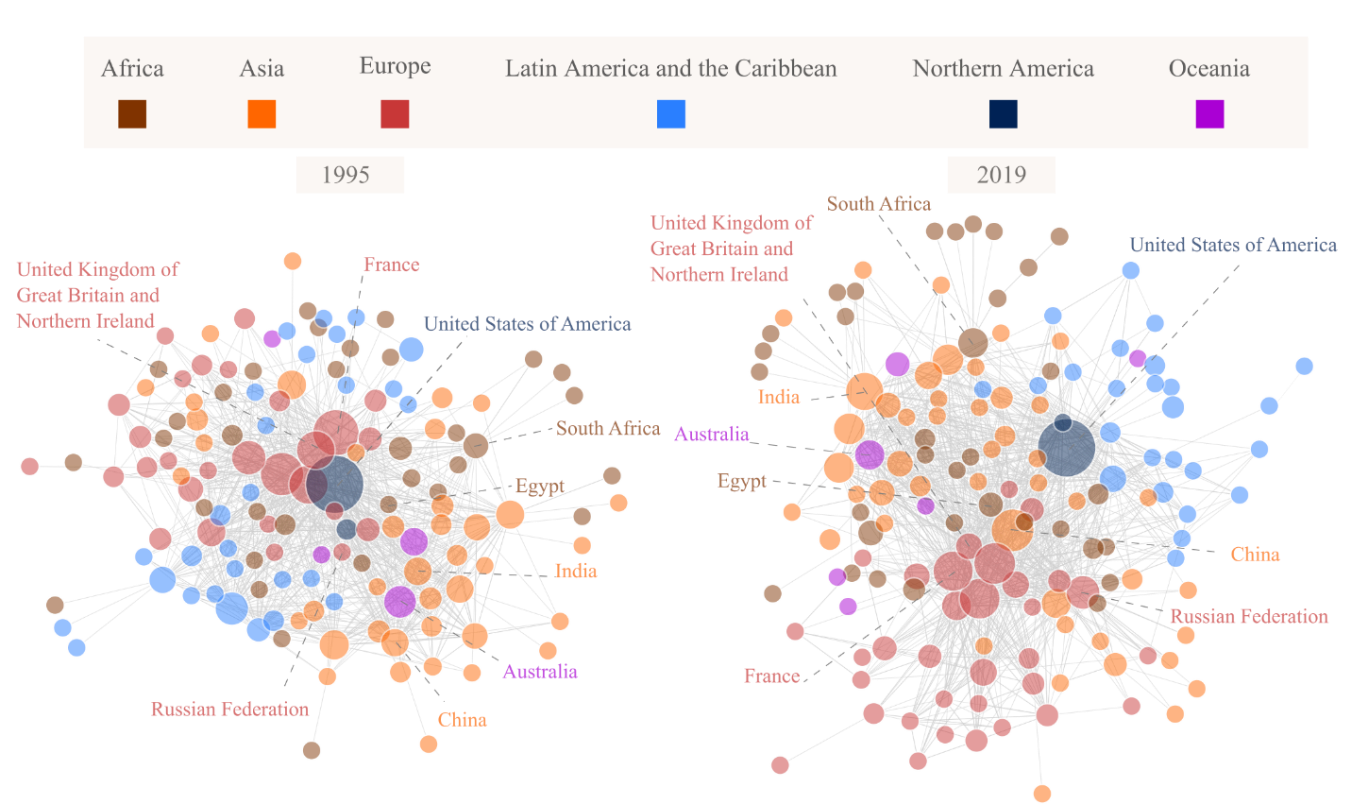
By examining the core-periphery structure of the network and identifying the major hubs within it, we can gain insights into the potential impact of shocks originating from specific regions or countries. This analysis allows us to assess the vulnerability and interconnectedness of different parts of the network, enabling a better understanding of how disruptions in certain regions or countries may ripple through the global food and agricultural trade system. When examining betweenness, we observe a distribution that is heavily right-skewed for both trade links and trade values (trade intensity) (see Figure 6). This indicates that a few countries play a crucial role in the connectivity of the network. These countries act as trade hubs, connecting with numerous partners, and indirectly linking smaller partners to the global network.

Which countries are hub and which are peripheries? In this respect, the structure of the trade network has undergone significant changes due to increased connectivity, the expansion of food and agricultural trade, and the emergence of new players in global markets. Over time, there has been an increase in the number of trade hubs, and in 2019, the network relies on a greater but less dominant set of hubs compared to 1995. This suggests a diversification of hub countries and declining dependency on a small number of dominant hubs.

As illustrated in Figure 7 using betweenness indices and in terms of trade intensity, the United States of America held the position of the most significant hub in 1995, which remained unchanged in 2019. However, China experienced substantial growth and transitioned from a relatively minor hub in 1995 to the second-largest hub by 2019. This shift can be attributed to China's accession to the WTO in 2001 and its subsequent rapid economic expansion, propelling it from the network's periphery to a central player (Tombe and Zhu, 2019)

Several Northern and Western European countries that occupied top positions as hubs in 1995 saw a decline in relative importance, making way for emerging economies such as India, the Russian Federation, and South Africa (Figure 7). These emerging economies not only increased their global integration but also evolved as significant regional hubs, connecting smaller countries within their respective regions to the global market (Chen and De Lombaerde, 2014; Iapadre and Tajoli, 2014). In 1995, the trade network exhibited a distinct core-periphery structure, characterized by a limited number of traders in the core and numerous less-connected countries in the periphery. However, with the emergence of additional trade hubs, the structure shifted towards a more balanced arrangement, featuring smaller core-periphery sub-networks (Figure 7). Similar structural changes and a trend towards decentralization have also been identified by (Sartori and Schiavo, 2015) for food trade and by Vidya, Prabheesh and Sirowa, ( 2020) for all merchandise trade.

Figure . The food and agricultural trade network and trade hubs, 1995 and 2019

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Note: Based on trade intensity.

Figure . Distribution of betweenness across countries

|  |  |  |
| --- | --- | --- |
| Panel A: Betweenness by trade links by country and product | Panel B: Betweenness by trade links by country and product | Panel C: Betweenness by trade intensity |
|  |  |  |

# Concluding remarks

Based on network analysis, this paper studied the evolution of multiple dimensions of resilience in the agricultural and food trade network. During the period 1995-2007, food and agricultural trade experienced rapid development in terms of establishment of direct trade links by country, by country and product and trade intensity, leading to improved connectivity of countries to the global market. However, together with a slowdown in overall economic growth, progress in food and agricultural trade connectivity has been relatively limited since 2007. The distribution of connectivity among trade partners even indicates a reversal of the trend towards a more balanced trade network between 2013 and 2019, which could potentially compromise resilience if this trend persists. Overall, the resilience of the trade network in terms of short-term response to the shocks appears to have increased between 1995 and 2007, with limited progress ever since.

Similar patterns to those observed for direct connectivity are found for indirect connectivity, measured as second-order and eigenvector connectivity, and thus for the longer-term resilience of the trade network. Moreover, the distributions of indirect connectivity measures by trade links by country, country and product, and trade intensity are less skewed than their counterparts for direct connectivity suggesting that the indirect connectivity of marginal countries could help reduce their vulnerability to shocks in the system.

Between 1995 and 2007, countries also developed closer ties at both the micro and intermediate levels. The share of two-way bilateral trade relationships increased compared to one-way trade relationships. Furthermore, trade between countries forming triads became more interconnected. These findings suggest that initial shocks to the trade system have a higher potential for propagation within localized areas due to increased interconnectedness.

With more, though less dominant, trade hubs, there was a change to a more balanced structure, characterized by smaller core-periphery sub-networks. Emerging economies played a significant role in linking smaller and less-connected countries to the global market. Despite the emergence of new players and a more equitable distribution of connectivity worldwide, a small number of countries still accounted for a significant share of trade links and values pointing that vulnerabilities and dependencies persisted, particularly concerning specific products.

Diversifying trade partners and imported products should be pursued to enhance resilience against shocks in domestic production and international trade. While pursuing regional trade integration, countries should proactively engage in multilateral negotiations to address the global dimensions and issues of food and agricultural trade. Recent developments raise concerns about the fragmentation of global food and agricultural trade and reduced network resilience to shocks, posing risks to countries' food security and dietary diversity. Fragmentation into regional trading blocs may hinder countries from fully benefiting from trade gains and lead to less efficient outcomes in terms of production allocation and resource utilization. While regional trade agreements contribute to economic growth and regional value chains, deeper provisions in these agreements can address specific trade-offs between economic, environmental, and social interests. However, they cannot replace multilateral negotiations and approaches. Strengthening multilateralism is crucial to counteract emerging vulnerabilities in the food and agricultural trade network and ensure fairness and inclusivity in the global trading system. Deeper multilateral cooperation is also necessary to tackle global environmental externalities like greenhouse gas emissions.

Further research could delve into the role of regional trade agreements and regional trade integration in multilateral processes. This could involve exploring the characteristics of regional trade clusters and modeling their interactions within the multi-layered system. Such analysis would provide insights into the impact of geopolitical shifts on the global food and agricultural trade network and elucidate the effects of comprehensive trade agreements on global trade integration, particularly the risks associated with excluding countries from the integration process.

The multidimensionality of resilience also implies that there are trade-offs regarding the connectivity of countries to the trade network, and this trade-off depends on both the level of connectivity and the structure of connectivity. Analyzing the resilience of the food network analytically without a comprehensive resilience index is not straightforward. Future studies should consider the development of a resilience index that simultaneously takes into account both connectivity and the structure of connectivity. Relying on scale-free measures that summarize the distribution of connectivity among countries in the trade network may be a promising approach.

(Vidya, Prabheesh and Sirowa, 2020)

# Appendix

Table 3. Global connectivity measures from different perspectives of the food and agricultural trade network



Note: Global connectivity measures are the arithmetic average of the country indicators.



Figure A 1. Triad isomorphism classes (following James Moody)

Diagram

Description automatically generated

Note: In a triad, countries can be related in sixteen different types. Thirteen types of triads indicate some form of connection among the three actors, which means 13 different motifs are observed. Each type is labelled according to the three digits MAN scheme. The first digit shows the number of observed mutual (M) trade relationships, the second digit shows the number of observed symmetric (A) trade relationships and the third one shows the number of null (N) trade relationships. If two triad types have an equivalent number of dyads, the fourth digit is used to distinguish the triads further based on edge directions (U: up and D: down), cyclicity (C: cyclic), and transitivity (T: transitive).[[6]](#footnote-7)

Source: Moody, J. Introduction to networks: Methods and measures. Duke Network Analysis Center, Department of Sociology.

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1. Maintaining a constant network size eliminates the necessity to normalize individual country-level measures based on the star network. This is because the connectivity of the star network would remain consistent across years for each connectivity measure. [↑](#footnote-ref-2)
2. Our calculation of Obesity index is based on 10,000 random samples of four observations draw from the all observations. Our index is based on 10,000 random samples of four observations. The obesity index is computed as [↑](#footnote-ref-3)
3. In a trade network, betweenness holds significance concerning the direct importance of countries for the exchange of commodities and intermediate inputs. However, it's essential to note that this index doesn't exclusively indicate the importance of commodity transactions. In scenarios where there are no commodity transactions, a high betweenness measure implies that countries with significant betweenness are central in financial flows among countries. Therefore, a shock in these countries can significantly impact the rest of the network. [↑](#footnote-ref-4)
4. FAOSTAT is source of official statistics pertaining to global food and agriculture, encompassing bilateral trade matrices. While not utilized for comparison in this particular context, FAOSTAT trade data elements align with other FAOSTAT domains and are easily accessible. Consequently, FAOSTAT trade data holds significant appeal as a preferred resource for examining worldwide agricultural trade. Recent examples using FAOSTAT trade data for network analysis include (Burkholz and Schweitzer, 2019; Chung *et al.*, 2020; Dupas, Halloy and Chatzimpiros, 2019; Fair, Bauch and Anand, 2017; Grassia *et al.*, 2022; Gutiérrez-Moya, Adenso-Díaz and Lozano, 2021; Gutiérrez-Moya, Lozano and Adenso-Díaz, 2020; Konar *et al.*, 2011; Puma *et al.*, 2015; Sartori and Schiavo, 2015; Shutters and Muneepeerakul, 2012; Torreggiani *et al.*, 2018) [↑](#footnote-ref-5)
5. Statistical tests were conducted to assess the significance of mean differences of the different connectivity measures over the years (using the Kruskal-Wallis test) and differences in mean connectivity between each consecutive year (utilizing the Kolmogorov-Smirnov and the Wilcoxon-rank tests). These tests provide further support to the aforementioned results. Additionally, the statistical tests also reject the hypothesis of stochastic equality of distributions across the years (using the Friedman test) and between each consecutive year (using the Kolmogorov-Smirnov test). Tables A5- A7 provide the detailed results of these statistical tests. [↑](#footnote-ref-6)
6. A triple of nodes *i* is cyclic if , , ; it is transitive if and implies ; and intransitive if and but . [↑](#footnote-ref-7)