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Article

The multiple dimensions of resilience in agricultural trade networks

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Abstract

The global food and agricultural trade network is crucial for food security. Shocks such as those posed by extreme weather events, conflicts, pandemics, and economic crises can test the resilience of the trade network to the sudden interruption of trade flows. Depending on the level of connectivity in the trade network and its structure, such shocks have the potential to propagate through the entire network and can affect countries' food availability and variety. This paper contributes to the literature on food and agricultural trade networks in two main ways: (1) understanding the global trade network as a complex system that can be affected by and responds to shocks, we define and operationalize its resilience as a multidimensional concept, which is shaped by the interdependencies in the network and their structure; and (2) applying techniques from network analysis to examine the evolution of three dimensions of resilience within the global food and agricultural trade network between 1995 and 2019. The main findings show that, between 1995 and 2007, trade connectivity among countries increased. Overall, this bolstered countries' and the network's resilience to trade shocks. However, vulnerabilities persisted in terms of ensuring sufficient product variety and quantity. Adding to these vulnerabilities, trade integration stalled in the second half of the series, pointing to a slight tendency towards trade disintegration and potentially lower resilience of countries to trade shocks already in 2019.

Keywords: Global food trade, Network analysis, Network integration, Structure of integration, Resilience

JEL codes: Q17, Q18, F14

1. Introduction

The resilience of the global food and agricultural trade network describes the network's ability to withstand and recover from disturbances and adapt to risks and long-term structural changes while maintaining the stable supply of food in both quantity and variety (Mena, Karatzas, and Hansen 2022). Trade disturbances can result from natural disasters such as those posed by extreme weather events, conflicts, pandemics, or economic crises. For example, the COVID-19 pandemic resulted in widespread restrictions on movement and trade around the world in 2020 and 2021. In 2022, the war in Ukraine introduced shocks to the network, impacting agricultural production and export capabilities of key players in the market. Through trade disruptions and transmission effects, such shocks have the potential to propagate through the entire network, affecting food supply in far-away locations.

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; Acemoglu, Akcigit, and Kerr 2016). Depending on the network structure, increased connectivity strengthens the buffer capacity of the network but can also transmit negative shocks (Sartori and Schiavo 2015).

The main objective of this paper is to analyse evolution and changes in the resilience of the food and agricultural trade network since the establishment of the World Trade Organization (WTO) and the Agreement on Agriculture (AoA) in 1995. We identify and discuss linkages between network structure and three main dimensions of resilience related to that structure: (1) country-level resilience versus global-level resilience (layers/levels), (2) dynamic transmission of shocks (dynamics), and (3) effects on diversity and volume of trade (margins). The analysis applies a variety of network measures to a balanced panel of 190 countries. Results are shown for four snapshot years indicating major events or turning points in global markets: 1995 (establishment of the WTO), 2007 (build-up of the 2008 financial crisis), 2013 (levelling off of growth of global food and agricultural trade), and 2019 (determined by data availability).

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 (Jafari, Engemann, and Zimmermann 2023a,b) and the evolution of global value chains in the food and agriculture sector (FAO 2020; Nenci et al. 2022; Tabe-Ojong et al. 2024). This trend was interrupted by the 2008 financial crisis, and later followed by a slowdown of the expansion of global trade. The stalemate of trade negotiations at multilateral level (Beghin and O'Donnell 2021; Kerr 2021) and the proliferation of RTAs have led to concerns about increasing regionalization of agricultural markets including a potential fragmentation of the global food and agricultural trade system into various trading blocs (FAO 2022; Jafari, Engemann, and Zimmermann 2023a,b).

A 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 existence and significance of 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 (Lucas 1977; Acemoglu et al. 2012; Acemoglu, Ozdaglar, and Tahbaz-Salehi 2015; 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 according to 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' (Kummu et al. 2020). 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 connectivity (as opposed to direct connectivity among countries) to take cascading shocks in the network into account.

The empirical literature often simulates the resilience of trade networks by randomly or deliberately 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). More pronounced changes in connectivity in response to the introduced shocks indicate lower resilience of the network. These approaches primarily rely on connectivity measures to describe trade resilience. The role of the structure of connectivity is implicitly captured through the calculation of network connectivity across years. As Karakoc and Konar (2021) discuss, these approaches do not explicitly consider economic aspects of changes in resilience.

This study contributes to the literature in two main ways. Firstly, it introduces an analytical framework to assess the resilience of the food and agricultural trade network. Understanding the global food trade network as a complex system that can be affected by and responds to shocks, we define and operationalize its resilience as a multidimensional concept, which is shaped by interdependencies in the network and their structure. Secondly, we apply techniques from network analysis to examine the evolution of three dimensions of resilience within the global food and agricultural trade network between 1995 and 2019: (1) We distinguish country-level and global-level resilience as two interconnected layers (levels) of resilience in the trade network. Resilience at both levels is defined by trade connectivity (focus on country-level) and the distribution of connectivity (focus on global level). While a higher level of connectivity can increase resilience, a highly skewed distribution of connectivity reduces it. (2) To analyse the dynamics of shock transmission, 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. This is complemented by an examination of the probability and extent of exacerbation of local shocks in network localities. (3) Potential effects of shocks on the margins of trade in terms of product availability, encompassing both variety and quantity, are assessed through trade relationships along the extensive margin (trade per country, and trade per country and product) and the intensive margin (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 methodology and data used in the analysis. In the 'Results and Discussion' section, we examine the evolution of the structure of integration of the food and agricultural trade network, as well as the local and global structure of connectivity formation in the trade network to analyse changes in resilience over time. The concluding section summarizes the findings, provides policy implications, and suggests future directions for research.

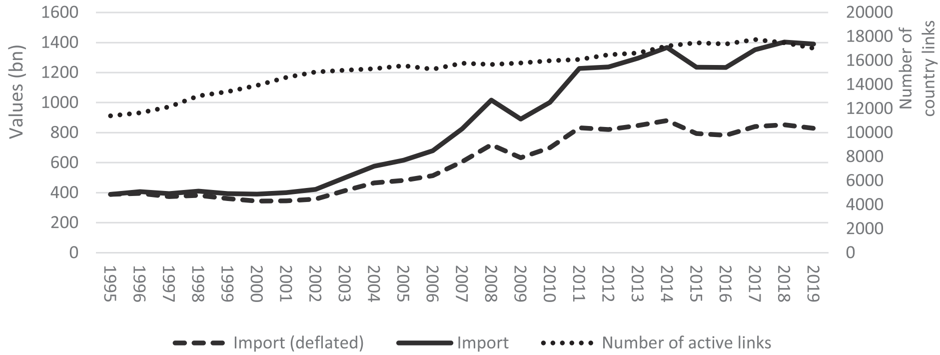

Figure 1. Evolution of agri-food trade (1995–2019). *Source:* Based on FAOSTAT (n.d.).

2. Evolution of food and agricultural trade

The exchange of food across borders enables countries to buffer imbalances in their domestic markets, smoothening availability, increasing diversity, reducing prices, and hedging against domestic production shortfalls.

Since the establishment of the WTO and the explicit inclusion of agriculture in the multilateral rulebook through the AoA in 1995, agricultural markets have liberalized significantly. The liberalization process at multilateral level has been reinforced by the conclusion of an increasing number of RTAs (Jafari, Engemann, and Zimmermann 2023b). Driven by the reduction of trade barriers, technological progress in transportation and communication, and shifts in demand associated with global economic growth (Beckman et al. 2018; Van den Berg and Lewer 2015; FAO 2020), since 1995 and until the early 2010s, the value of trade fluctuated following a positive trend, while the number of trade links among countries increased steadily (Fig. 1).

The continuing growth of the trade value observed since 1995 was interrupted by a plunge in prices related to the 2008 global financial crisis. The trade value recovered during 2010–2011, mainly driven by continuing growth in emerging economies, but has since levelled off. In 2015, a drop in food prices, which was related to ample supplies at a time of weak world demand, also led to a reduction in trade value, followed by a recovery in 2017. Since 2014, also the increasing connectivity in terms of numbers of trade links has levelled off.

Slow progress in the multilateral negotiation process together with a continuing proliferation and deepening of RTAs and recent geopolitical tensions are thought to have contributed to a slower expansion of global food and agricultural trade, increasingly regionalized trade structures, and a potential development towards more fragmented trading blocs (Beghin and O'Donnell 2021; Kerr 2021; Jafari, Engemann, and Zimmermann 2023a,b). In fact, trade tensions between China and the USA during 2018–2019 may be reflected in a drop in trade value and number of trade links in 2019 (Fig. 1). Both trends and fluctuations in food and agricultural trade are shaped by structural changes in the global trade network and, at the same time, affect the structure of the network (Korniyenko, Pinat, and Dew 2017).

3. Framing the multidimensionality of resilience

Resilience as a concept is used in many disciplines. It is a major research area in ecology and psychology, but has received relatively little attention in economics, and even less in international trade (Mena, Karatzas, and Hansen 2022). The concept of multiple dimensions of resilience is well-developed in ecosystem research. Properties defining resilience in socioecological systems have been described as (1) resistance, the ability to withstand disturbance; (2) recovery, the ability to return to the original state; (3) stability, the ability to retain the same function and structure; (4) vulnerability, inability to withstand disturbance; and (5) adaptive capacity, the ability to deal with change (Walker, Keane, and Burke 2010; Yi and Jackson 2021).

Similar, albeit less developed, models can be found in the economic literature. In defining economic resilience to disasters, Rose (2004) distinguishes between static economic resilience, referring to the ability or capacity of a system to absorb or cushion against damage or loss, and a more general definition incorporating dynamic concepts such as stability as the ability of a system to recover from a severe shock. Hynes et al. (2022) understand economics in a complex system way and link economic resilience with comparable notions from physics. To operationalize resilience from an implementation point of view, they distinguish resilience by design—promoting endogenous reorganization in the economy, and by intervention—including exogenous measures such as bailouts, stockpiles, and building buffers. They argue that a more nuanced understanding of the underlying structure of the economic system is needed to inform policy decisions that promote resilience and result in better outcomes in the long run.

All of these approaches build on some common features. Resilience refers to a static ability or dynamic response of a complex system to disturbances or shocks. Resilience is a multidimensional approach and in determining the resilience of a system, the structure of the system with all its interdependencies plays a prominent role.

Bringing the concept of resilience to trade, we understand the global food trade network as a complex system that can be affected by shocks such as those arising from extreme weather events, conflicts, pandemics, and the wider economy. We define resilience as a multidimensional concept. The resilience of the food and agricultural trade network is shaped by the interdependencies in the network and their structure. Shocks can affect different actors in different ways (e.g. exporters and importers); there are multiple layers (e.g. countries, regions, and world), which can be affected differently; actors respond to shocks and, depending on the magnitude of shock and impact, the interaction of the responses of different actors can lead to an aggregate response/adaptation of the whole network. Actors and layers can be affected directly (immediately) or indirectly (dynamically). Finally, we consider effects on the diversity of traded products (extensive margin) and volume of trade (intensive margin).

In this paper, we focus on three main dimensions of resilience of the food and agricultural trade network: (1) country-level resilience versus global-level resilience (layers/levels), (2) dynamic transmission of shocks (dynamics), and (3) effects on diversity and volume of trade (margins). Effects in all three dimensions depend on system interdependencies and the structure of these dependencies and are discussed through this lens in the following subsections.

The main actors in the trade system are exporting and importing countries, referred to as exporters and importers in this paper. 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. There are also systematic shocks such as the COVID-19 pandemic that simultaneously affect supply, demand, and bilateral trade links of countries in the trade network.

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, whereas indirect effects occur in third countries/regions and are transmitted through global value chains or other mechanisms.

3.1 Country-level resilience versus 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 domestic market and their interdependencies (operationalized as trade connectivity) within the trade network. Country-level resilience entails countries' capacity to maintain food supply stability and functionality to shocks by adjustments in the domestic market and/or by importing products in varying volumes and varieties from different sources. The individual capacity of countries to absorb shocks and country-level responses determine the global (network)-level resilience, which refers to the ability of the network (system) 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.

Interdependencies of layers of resilience in food and agricultural trade can be operationalized based on (1) connectivity at country-level and (2) distribution of connectivity across countries. For an *individual country*, if connectivity is high and well-diversified, the country should be able to adapt to trade disruptions more easily than a country with low and less diversified 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: (1) high overall (average) connectivity and a relatively lightly tailed (skewed) distribution of connectivity across countries; (2) high overall (average) connectivity, but a heavier tailed (skewed) distribution of connectivity across countries; (3) low overall connectivity and a relatively lightly tailed (skewed) distribution of connectivity across countries; and (4) low overall connectivity and a relatively heavily tailed (skewed) distribution of connectivity across countries (Korniyenko, Pinat, and Dew 2017; Arriola et al. 2020). The first pathway/state is the most favourable 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.

The resilience of a country against shocks is affected by several factors at different scales including the countries' domestic supply and demand conditions. While the resilience of the trade network may itself be influenced by the characteristics of individual countries, this paper focuses on trade and its structural characteristics in the global market. It does not explicitly assess countries' domestic capacity to adjust to shocks nor the interlinkages between the resilience of the trade network with countries' domestic conditions. Inferences are drawn from and refer to observed trade patterns.

The conceptual framework of the layers of trade network resilience emerges from the literature on financial networks. This body of literature analyses (see, for example, Elliott, Golub, and Jackson 2014; Glasserman and Young 2016) or reviews (see Hasman 2013; Bougheas and Kirman 2015) the role of connectivity (each organization becoming interdependent with its counterparts) and diversification (the number of counterparts of each organization) in explaining the resilience of financial networks in the face of failures in the network (e.g. bankruptcies, defaults, and other insolvencies).

3.2 Transmission/propagation of shocks

A shock to an importer, whether bilateral, external, internal, or systematic, 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 three main reasons. Firstly, production processes are often fragmented and involve multiple countries (global value chains)—about a third of all agrifood exports take place through global agricultural value chains (FAO 2020). The fragmented production process implies 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 depend on 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, re-exports (without altering the original products or with simple processing) can occur across countries for several reasons including incentives to reduce information costs, taking advantage of the international shipping industry, and evading taxes and trade barriers (Feenstra and Hanson 2004). Information costs can create incentives for buyers and sellers to trade through middlemen located in a third country. If buyers have incomplete information about the quality of sellers' products and find it costly to find sellers that may comply with their standards, and if sellers have incomplete information about the preferences of buyers, specialized traders may offer a way of solving this two-sided information problem. Taking advantage of hubbing in international shipping, particularly when products are shipped through experienced hub countries such as the Netherlands, Hong Kong, and Singapore, is common in the trade of food and agricultural products. For example, as of 2023, one-third of the Netherlands' exports of unprocessed and processed agricultural products actually were re-exports (Wageningen Economic Research 2024). Also, to avoid corporate taxes in origin countries, firms may choose to first export to a country with low corporate taxes at relatively low export prices. From there they would re-export at higher prices to the final destination. Through re-exports, firms may also take advantage of differences in trade barriers such as tariffs and quotas across countries to minimize trade costs.

Thirdly, due to substitution, price, and income effects, shocks can also be transmitted to the trade of products that are not directly affected by the shocks. An importing country may substitute across products and exporters. Moreover, income effects mean that a reduction in imports from a given exporter may reduce the earnings of this exporter, in turn, reducing the exporter's imports.

Thus, shocks can cascade through the trade network and affect multiple countries that are directly or indirectly connected to the specific importer.

3.2.1 Short-run versus long-run transmission of shocks

Examining countries' direct connectivity can reveal spillover effects, immediately impacting direct trading partners. 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, trade flows to or from re-exporting countries are affected, or the price, substitution, and income effects are strong. 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. We note that different shocks may have different diffusion processes, some diffuse immediately, some diffuse slowly, or even on the basis of expectations. Therefore, the temporal interpretation of the shock diffusion may be interpreted on a shock-by-shock basis and not across shocks.

3.2.2 Mode and magnitude of shock propagation

Beyond the large-scale distribution of direct and indirect connectivity, the mode (the way trade relationships are formed) and density of connectivity among smaller agglomerations of countries are important as they can accelerate or decelerate shock transmission. For example, the mode of connectivity in formations of bilateral and triadic trade relationships (trade relationships involving two and three countries, respectively) 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. Nonetheless, both asymmetric bilateral trade relationships and transitive triad relationships can contribute to resilience, provided that partners within the locality of the shock can absorb part of the shock. The ultimate impacts of bilateral and triad relationships on shocks propagation (either dissipating it or amplifying it) depend on the magnitude of the shock, the trade partners' characteristics such as size, and their ability to redirect the shocks. As the impact of micro-level formations on shock propagation is multifaceted and context specific, we will focus on analysing and describing the evolution of such relationships and refrain from making strong assumptions on their impact on resilience.

In a network with a pronounced core–periphery structure, shocks from major hubs, defined as countries significantly influencing import/export activities within the overall network, hold considerable sway. Hub countries can be dominant in a network when a large number of countries are connected to the wider network only through the hub and the hub country accounts for a significant amount of trade. Shocks affecting such hub countries can propagate to all their direct trade partners and throughout the wider network. Each country in the network can exert a certain degree of influence on others' trade, while the significance of shocks originating from a specific country to the total trade network varies depending on its position in the network. Identification of the network structure and its major hubs can yield crucial insights into the potential impact of shocks originating from specific regions or countries.

3.3 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 value of goods exchanged between trading partners. An increase in the intensive margin signifies a larger 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).

4 Materials and methods

We apply several types of network measures to the food and agricultural 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 commodities exchanged between each pair of countries (network of country–product trade links), and a weighted trade network that represents the value of trade between any two countries in the network (network of trade intensity). The first two types of networks (network of country trade links and network of country–product trade links) are employed to analyse the trade network along the extensive margin of trade, while the third type of network (trade intensity network) is used to analyse the trade network from the intensive margin. In network terminology, measures applied to the network of country trade links refer to degree connectivity and measures applied to the other two types of networks refer to strength connectivity. Each of these networks can be directed or undirected, depending on whether the direction of trade flows is considered in the analysis. We use the directed trade network, focusing on import links, which leads us to consider in-degree and in-strength connectivity measures. In the following, we skip the prefix 'in-'.

4.1 Measures of connectivity and network structure

Our approach to address the multidimensional aspects of resilience primarily involves analysing the connectivity and structural facets of trade networks. This analysis relies on various measures derived from network theory, considering both direct (first) and indirect (second and higher) orders of interdependencies among countries, as well as the structure of these connections. We measure connectivity at the country and global level. Table 1 provides an overview of the network indicators applied in this study[1] and their relevance for the analysis of the resilience of trade networks.

At country level, we assess both direct connectivity between countries and their indirect connectivity. Direct connectivity pertains to a country's connections with its immediate trading partners and is assessed through the first-order degree/strength connectivity. The first-order degree connectivity of each country is the total number of import trade links per country. The first-order strength connectivity is the total number of product country trade links or values of import flows associated with that country. Indirect connectivity is assessed through second-order and eigenvector measures. Second-order connectivity relates to a country's connections with the trading partners of their direct partners (the connections of their partners' partners). The second-order degree/strength is the sum of the first-order degree/strength of all direct trade partners. Eigenvector connectivity represents a country's connections to the entire network, serving as a measure of its influence within the global network. The eigenvector connectivity has a similar interpretation as the first- and second-order degree connectivity measures, but it considers the first-order, second-order, and all higher-order degrees (see Supplementary material details). That is, the connectivity of a country based on the connectivity of its neighbours, the neighbours of the neighbours, and so on. It is defined as the connectivity of a country proportional to the sum of connectivity indices of its neighbours. The average of country-level connectivity measures, while maintaining a constant network size, provides a global connectivity measure.[2]

To assess the structure of connectivity, we analyse the distribution of connectivity across countries worldwide. We focus on visual analysis of the distribution of various connectivity measures and calculate moments and other distributional measures. Skewness and kurtosis offer insights into the shape of the distribution. Skewness reflects the distribution's asymmetry concerning the symmetric bell-shaped Gaussian (normal) distribution that has similar densities on both the left and right tails of the distribution. In a normal distribution, skewness holds a value of zero. Positive (negative) skewness indicates that right (left) tails are heavier than left (right) tails. A larger absolute value denotes higher skewness. Kurtosis

Table 1. Overview of network measures and their relevance for the analysis of the resilience of trade networks.

Connectivity measures	Direction and weight	Level of aggregation	Structure used to analyse global resilience	Relevance for the temporal dimension of resilience
Direct connectivity				
First-order degree/strength connectivity	Directed, un/weighted	Country and global	Mean and distribution of country-level connectivity	Immediate spillover effects
Indirect connectivity				
Second-order degree/strength connectivity	Directed, un/weighted	Country and global	Mean and distribution of country-level second-order connectivity	Mid-term spillover effects
Eigenvector degree/strength connectivity	Directed, un/weighted	Country and global	Mean and distribution of country-level eigenvector connectivity	Longer-term spillover effects
Micro-level formation of connectivity				
Bilateral trade relationships	Directed, unweighted	Global	Density and mode of bilateral trade formation	Immediate spillover effects
Triad trade relationships	Directed, unweighted	Global	Density and mode of triad formation	Immediate spillover effects
Network structure				
Intermediary (betweenness) degree/strength connectivity	Directed, un/weighted	Country and global	Distribution of countries' overall influence on the network and identification of trade hubs	Longer-term spillover effects

Source: Based on Jafari, Engemann, and Zimmermann (2023b).

measures how the data clusters around the tails or the peak compared to a normal distribution. A kurtosis higher than the reference level for a Gaussian distribution (which is three) suggests the presence of a heavier or thick/tailed distribution.

Another 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. The obesity index, proposed by Cooke, Nieboer, and Misiewicz (2014), provides additional insights into the tail behaviour of the distribution. It operates on the heuristic that in heavy-tailed distributions, larger observations are further apart than smaller ones. Considering individual centrality measures $\{X_1, X_2, X_3, X_4\}$ as independently and identically distributed values, sampled randomly from the total observations across countries for specific network measures, 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. Our calculation of the obesity index is based on 10,000 random samples of four observations drawn from all observations. It is computed as $OB(X) = P(\mathrm{X1} + \mathrm{X4} \ > \mathrm{X2} + \ \mathrm{X3}|X1 \leq X2 \leq X3 \leq x4)$.

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 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 way of connectivity formation in bilateral and triadic trade relationships can significantly impact shock propagation. In examining the mode of connectivity within bilateral trade relationships, we analyse changes over time in the density of unilateral/asymmetric and bilateral trade relationships. Density is calculated as the number of bilateral or trilateral trade relationships over the total possible number of relationships. It is 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 thirteen distinct types that depict various possible modes of connectivity among three countries (see Fig. S1).

We also identify which countries wield the greatest influence on the network (the hub countries) using intermediary/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 are not directly linked (Freeman 1978). Technically, the betweenness connectivity for each country is the total number of shortest paths in the network that goes through a given country over the total possible shortest paths. In our analysis, a weight is assigned to each trade link to identify the shortest path, whereas the weight is the reciprocal of the import value or the number of commodities traded on that link. The higher the value of the measure is, the more important is the country as a hub. Countries with low betweenness are peripheral countries. 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. Both betweenness and eigenvector centrality reflect a country's importance within a network but from different perspectives—the former emphasizing its position in controlling the network's communication or interaction pathways, and the latter considering influence through well-connected neighbours.

4.2 Data and construction of the world trade matrix

To calculate the network measures, data from FAOSTAT (n.d.) on international bilateral trade of food and agricultural products are used.[3] Our analysis covers snapshots of global bilateral trade flows of 190 countries in the years 1995, 2007, 2013, and 2019, and includes 425 agriculture and food items. The selection of these specific years is based on their significance in relation to global trade dynamics (see Fig. 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 levelled off, and 2019 as the most recent year for which data were 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 some generalization of overall trade patterns. Where import values were not available but corresponding export values were reported by partner countries, export values are used to represent import values. When both export and import are zero, we consider zero trade values (see De Benedictis and Tajoli 2011). Trade values are expressed in US dollars and deflated using the 1995 United States of America Consumer Price Index (e.g. Rose 2004).

Table 2 provides a summary of the data related to the constructed trade matrices. The number of trade links and the average links per country (per country and product) increased significantly by a factor of 0.4 (1.3) until 2007. Since then, the number has grown more slowly. Import values tripled from $389 billion in 1995 to $828 billion in 2019, with a significant increase occurring between 1995 and 2007. Comparing trade links and values across countries suggests a heterogeneous contribution of individual countries to the overall integration of the trade network. This is evident when comparing the 10th, 50th, and 90th percentiles of the trade matrices from different perspectives, including trade links by country, trade links per country and product, and trade intensity. The increase in the mean and various percentiles of the trade matrix observations indicates higher integration into the trade network and a more balanced integration of countries, particularly until 2007.

5 Results and discussion

5.1 Perspective: Country-level versus global-level resilience

5.1.1 Level of connectivity

The direct (first-order degree and strength) connectivity of the majority of countries increased between 1995 and 2019 (see Fig. 2) 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 and BRICS countries. However, the connectivity of many African countries, small island developing states, and landlocked developing countries remained low along both extensive and intensive margins, and, in general, countries in these groups are the least connected in the world. Table 3 shows the degree of integration in the network from different perspectives for specific country groups in the snapshot years. Across country groups, connectivity increased mainly between 1995 and 2007, with slight improvements ever since.[4] Table S1 ranks the ten top and least countries in terms of their first-order degree/strength integration to the global trade network in the years 1995 and 2019. The topmost integrated countries are mainly the developed countries plus China whereas the least ten countries are generally the small island developing states.

Table 2. Summary statistics of integration into the agri-food trade network from different perspectives.

	Trade links per country				Trade links per country and products				Trade intensity			
Descriptive statists	**1995**	**2007**	**2013**	**2019**	**1995**	**2007**	**2013**	**2019**	**1995**	**2007**	**2013**	**2019**
Number of trade links or import values	11,395	15,768	16,635	17,016	212,602	363,873	415,306	481,282	389,336,822	606,763,568	847,683,319	828,389,748
Average number of trade links or import value per country	60	83	88	90	1,119	1,915	2,186	2,533	2,049,141	3,193,492	4,461,491	4,359,946
10th percentile of links or import values	19	32	38	36	141	320	318	535	13,485	36,017	39,130	61,888
Median links or value	48	80	83	86	582	1,488	1,573	1,762	197,498	492,920	849,640	963,856
90th percentile of links or import values	122	136	147	148	2,771	4,107	4,910	5,602	3,891,200	6,672,712	10,272,846	10,430,339

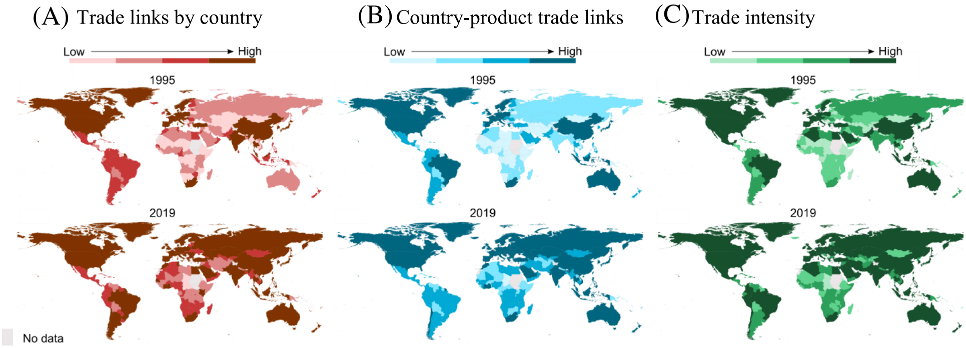

Figure 2. Country-level connectivity to the global food and agricultural trade network, by country, 1995 and 2019. *Note:* Panel A is based on first-order degree connectivity, while Panels B and C are based on first-order strength connectivity.

The overall density of the trade network increased from 32 to 47 per cent (Table S2), indicating a higher number of countries engaging in trade with one another. The general increase in the connectivity measures of first and higher order, both in terms of trade links and the intensity of trade (Table S2), indicates changes in the intermediate and global connectivity of the trade network encompassing all countries, on average.

5.1.2 Distribution of connectivity

While direct connectivity of all countries increased, it is still unevenly distributed. At both the extensive and intensive margins (Fig. 3), 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 by links with other countries.

The distributions of trade intensity and country–product trade links 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 (Puma et al. 2015; Bren d'Amour et al. 2017; Soffiantini 2020; Geyik et al. 2021; Gutiérrez-Moya, Adenso-Díaz, and Lozano 2021). 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).

In particular, the dependence on few major exporters of specific commodities can lead to market vulnerabilities. High market concentration has been found in the trade network of cereals, which is dominated by a few exporters with global significance, including countries in Northern America and Western and Eastern Europe (Puma et al. 2015; Karakoc and Konar 2021). Vulnerability in global cereal trade was demonstrated during the food price spikes in 2007–2008 and 2010–2011, when imbalances in supply and demand were met with and aggravated by export restrictions of several major producer countries.[5] Highly import-dependent countries, such as those in the Middle East and Northern Africa, are most vulnerable to (relative) shortages in global cereal supply and the price spikes in 2007/08 and 2010/11 are thought to have contributed to social unrest in the region at that time (Bren d'Amour et al. 2016; Soffiantini 2020; Gutiérrez-Moya, Adenso-Díaz, and Lozano 2021; Karakoc and Konar 2021).

Table 3. Global integration across group of countries (first-order degree/strength).

	Trade links per country					Trade links per country and products					Trade intensity				
	1995	2007	2013	2019	Diff. 2019 and 1995	1995	2007	2013	2019	Diff. 2019 and 1995	1995	2007	2013	2019	Diff. 2019 and 1995
Global	0.33	0.46	0.49	0.50	0.17	0.67	0.75	0.76	0.79	0.12	0.67	0.72	0.74	0.75	0.08
Developed economies	0.57	0.70	0.73	0.75	0.18	0.79	0.85	0.87	0.89	0.1	0.77	0.82	0.83	0.83	0.06
Developing countries	0.28	0.42	0.45	0.46	0.18	0.63	0.72	0.73	0.76	0.13	0.65	0.69	0.72	0.73	0.08
Landlocked countries	0.19	0.34	0.39	0.41	0.22	0.57	0.66	0.70	0.73	0.16	0.59	0.65	0.68	0.69	0.1
Small island developing countries	0.18	0.31	0.32	0.32	0.14	0.58	0.68	0.67	0.71	0.13	0.55	0.61	0.61	0.63	0.08
Sub-Saharan Africa	0.23	0.38	0.42	0.44	0.21	0.60	0.69	0.71	0.74	0.14	0.61	0.66	0.69	0.69	0.08
South East Asia	0.36	0.45	0.54	0.61	0.25	0.67	0.75	0.80	0.82	0.15	0.70	0.75	0.79	0.81	0.11

Note: The results are based on the first-order degree/strength connectivity.

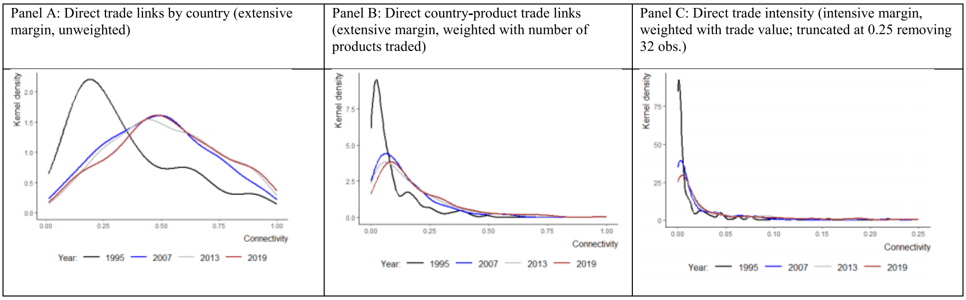

Figure 3. Distribution of connectivity (first-order in-degree/in-strength).

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 direct 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 (Table S3), 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.[6]

5.2 Shock transmission/propagation

5.2.1 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 (Fig. 4) 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-order and eigenvector 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 have 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 country A and affecting its direct trade partner country B may more easily transmit to countries connected to country B but without a 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 channels: (1) 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; (2) global value chains: reduced imports of product X by country B imply that country B

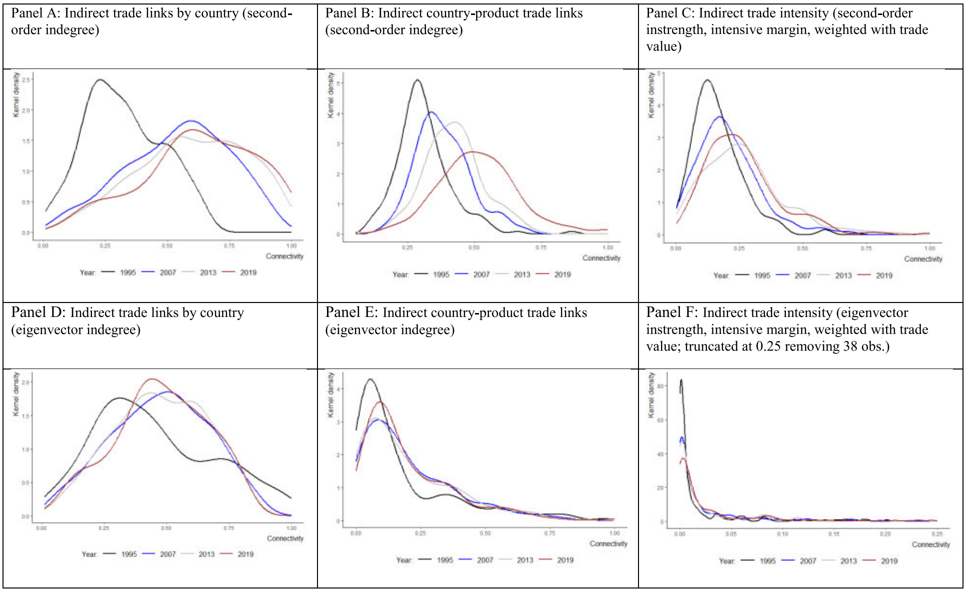

Figure 4. Distribution of indirect connectivity (second-order in-degree/in-strength and eigenvector in-degree/in-strength).

cannot produce and export value-added product (X+); (3) 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 degree and eigenvector connectivity of country–product trade links, as well as trade intensity (Fig. 4), 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 (Table S3) suggest a slight reversal of the trend towards a more evenly distributed connectivity between 2013 and 2019.

5.2.2 Mode and magnitude of shock 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), increased notably, 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 4). The proportion of actual trade relationships in all possible trade relationships grew from 39 per cent in 1995 to 58 per cent in 2019. The majority of trade relationships during this period remained mutual, accounting for approximately 60–63 per cent of all trade relationships across the years. Mutual trade relationships, as opposed to one-way trade, signify a higher density of trade, closer connectivity, and increased interdependency between countries. Mutual trade relationships may contribute to greater exchange of goods in terms of both quantity/value and diversity but also a higher dependency of the trade partners from each other. They may be associated with a higher likelihood of shock propagation through a multiplier mechanism: a shock originating in one country can affect its bilateral trading

Table 4. Structure of bilateral and trilateral trade relationships.

	1995	2007	2013	2019
Structure of bilateral trade relationships				
Active trade relationships	7,084	9,877	10,383	10,454
Share of active trade relationships over total possible ones (%)	39	55	58	58
Share of mutual relationships (%)	61	60	60	63
Share of asymmetric relationships (%)	39	40	40	37
Structure of trilateral trade relationships				
Actual number of triads	446,310	633,492	675,494	680,616
Share of actual triads over total possible ones (%)	40	56	60	60
Most frequent type	201 (24.28%)	111D (17.70%)	300 (18.59%)	300 (20.48%)
Share of transitive (%)	19	27	29	30
Share of intransitive (%)	58	45	43	43
Share of mixed (%)	15	20	20	20
Other (021D,021U) (%)	8	8	8	7

Source: Jafari, Engemann, and Zimmermann (2023a).

partner, and due to the bilateral trade linkages, have repercussions on the originating country—the shock may thus amplify beyond its initial impact.

The number of trilateral trade relationships (triads) increased significantly. The proportion of active triads over all possible triads (the intensity of triads) increased from 40 per cent in 1995 to 56 per cent in 2007. It remained stable at around 60 per cent in 2013 and 2019 (Table 4). Theoretically, there are sixteen different types of triads that can be formed by three countries, with thirteen of them involving all three countries (see Fig. S1). 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 Fig. S1, respectively), in which countries interacted through intermediaries. However, in 2013 and 2019, the most frequent type of triad (labelled as 300 in Fig. S1) was transitive, with reciprocal trade occurring between all three countries. In general, the share of transitive (multiway) trade relationships increased from 19 per cent in 1995 to 30 per cent 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 with 1995, signifying increased mutual connectivity. This may strengthen the ability of countries to provide mutual support in the face of shocks. However, it may also render them more vulnerable due to multiplier effects.

5.3 Extent of shock 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 Fig. 5). 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 trade 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

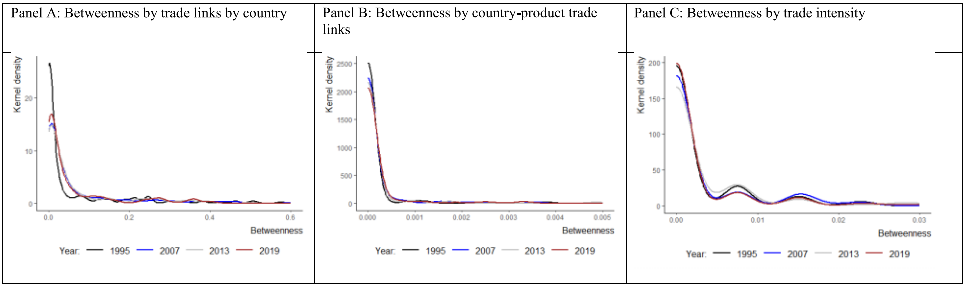

Figure 5. Distribution of betweenness across countries. *Note:* Distributions are truncated on the right-hand tail for the visualization purpose.

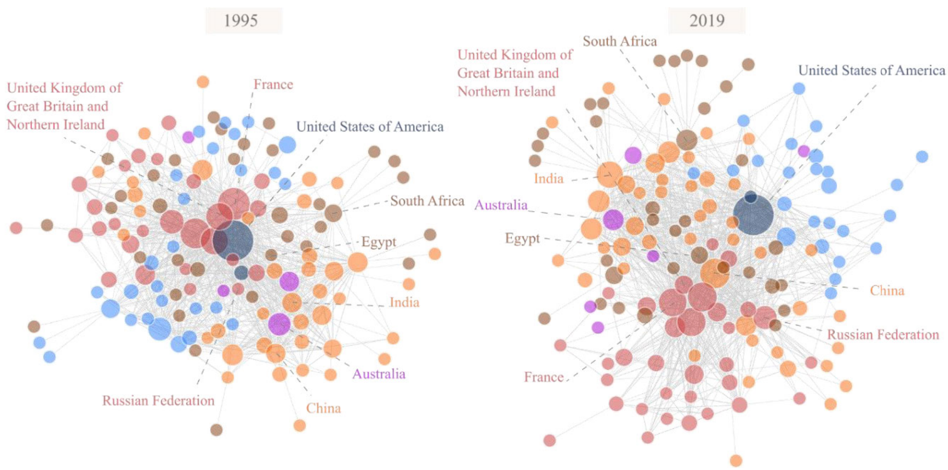

Figure 6. The food and agricultural trade network and trade hubs, 1995 and 2019. *Source:* Jafari, Engemann and Zimmermann (2023a). Notes: Based on trade intensity. Colours denote continents as follows: Brown - Africa, orange - Asia, red - Europe, light blue - Latin America and the Caribbean, dark blue - Northern America, purple Oceania.

expansion of food and agricultural trade, and the emergence of new players in global markets. Over time, the number of trade hubs increased, and in 2019, the network relied 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 Fig. 6 using betweenness indices and in terms of trade intensity, the USA 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 in 2019. This shift can be attributed to China's accession to the WTO in 2001 and its 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 (Fig. 6). 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 subnetworks (Fig. 6 and Table S6). 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.

6 Concluding remarks

This paper presents an analytical framework that defines the resilience of the global food and agricultural trade network as an open multidimensional concept. Based on network analysis, we assess the evolution of three specific dimensions of resilience in the food and agricultural trade network. During the period 1995–2007, food and agricultural trade evolved rapidly in terms of the establishment of direct trade links by country, 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 and multilateral trade negotiations, progress in food and agricultural trade connectivity has been relatively limited since 2007. Lending support to hypotheses of increasingly regionalizing agricultural markets and a potential fragmentation into various trading blocs, 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 of countries to shocks 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 buffer capacity of the trade network. Moreover, the distributions of indirect connectivity measured 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 can propagate or dissipate within localized areas, contingent upon the magnitude of these shocks and the specific characteristics of countries involved in the relationship.

With more, though less dominant, trade hubs, there was a change to a more balanced structure, characterized by smaller core–periphery subnetworks. 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.

These findings suggest a number of important policy implications. Remaining open to trade and actively diversifying trade partners and the range of imported products could enhance the resilience against shocks in domestic production and international trade. Vulnerability to shocks in international markets can be reduced by sourcing foods from a wide range of countries from all regions. Indeed, recent developments raise concerns about the fragmentation of global food and agricultural trade and a potentially reduced 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, lead to less efficient outcomes in terms of production allocation and resource utilization, and reduces their resilience to shocks in domestic and foreign markets. While pursuing regional trade integration, the proactive engagement of countries in multilateral negotiations can help address the global dimension and global issues of food and agricultural trade.

The results from this study should be interpreted with caution. While resilience is a multidimensional concept, this study focuses on three important dimensions of resilience, namely layers of resilience in the food and agricultural network, dynamics of resilience, and effects on extensive and intensive margins of trade. Interdependencies and the structure of interdependencies are measures based on various connectivity measures and their distributions. Both connectivity measures and distributions are endogenous to several factors affecting international trade patterns. Considered factors span across different scales (firm, country, country groups, and global level). Future studies may link the resilience concept to these characteristics and/or rely on more disaggregated databases that have firms as main trade actors and consider the environment in which firms operate. Understanding these characteristics and analysing them along the patterns of trade across different scales may offer additional insights on the processes affecting the diffusion of shocks in trade networks.

Connectivity and diversification themselves are interrelated and each may have a nonlinear relationship with resilience (Eliott et al. 2014). It is therefore not straightforward to rank countries in terms of resilience or determine the exact state of resilience of the global trade network. However, changes in connectivity and distribution of connectivity can give an indication of the direction of movements along the different pathways. Judgements about whether the network is resilient or not and identification of inflection points of the network's sensitivity to shocks are beyond the scope of this paper. These would require modelling of the explicit linkages of domestic markets with the global trade network, information, or assumptions on specific shocks and how their diffusion processes unfold, information on the characteristics of countries and country groups involved in the trade network, and types of trade flows. This paper focuses on trade, the connectivity of countries through trade, and structural characteristics of the global trade network. By focusing on a few specific structural dimensions, the paper provides a first attempt to conceptualize and analyse the complexity of resilience related to the food and agricultural trade network. This conceptual framework and descriptive analysis may feed into more advanced conceptual and analytical approaches with a focus on trade or as one component in broader economic studies.

Further research could also delve into the interplay of RTAs and regional trade integration with multilateral processes and the global food and agricultural network. This could involve exploring the characteristics of regional trade clusters and modelling their interactions within the multilayered 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 these trade-offs depend on both the level of connectivity and the structure of connectivity. Analysing and identifying changes in the resilience of the food network to shocks without a comprehensive measure or set of measures is not straightforward. Future studies could consider the development of more advanced measures that simultaneously take 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.

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Supplementary material

Supplementary material are available at *Q Open* online.

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Conflict of interest

There are no conflicts of interest to declare.

Data availability

The data were sourced from FAOSTAT and are accessible online through the official webpage of the Food and Agriculture Organization of the United Nations. The corresponding author will provide the raw and processed data, as well as the R code used for the analysis, upon request.

End Notes

1. In the following, we present the measures, with Supplementary material providing technical definitions of the network and associated measures.
2. 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.
3. FAOSTAT is FAO's global statistical database. It is a main source of official statistics pertaining to global food and agriculture covering 425 individual products for over 245 countries and territories. Among a multitude of economic and environmental indicators related to agricultural production, food security, and nutrition, FAOSTAT also encompasses yearly bilateral trade matrices, compiled from national statistical offices. 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 hold significant appeal as a preferred resource for examining worldwide agricultural trade. Recent examples using FAOSTAT trade data for network analysis include Jafari, Engemann and Zimmermann (2023b), Grassia et al. (2022), Gutiérrez-Moya, Adenso-Díaz, and Lozano (2021), Chung et al. (2020), Burkholz and Schweitzer (2019), Dupas, Halloy, and Chatzimpiros (2019), Torreggiani et al. (2018), Fair, Bauch, and Anand (2017), Sartori and Schiavo (2015), Puma et al. (2015), Shutters and Muneepeerakul (2012), Gutiérrez-Moya, Lozano, and Adenso-Díaz (2020), and Konar et al. (2011).
4. The countries with the highest (least) growth in the number of trade partners are Bosnia and Herzegovina and Armenia (Poland and Venezuela). Countries with the highest (lowest) increase in the number of trade links are the Netherlands and the United Arab Emirates (Venezuela and Mexico). Countries with the highest (lowest) increase in strength are Russia and China (Venezuela and Japan).

5. The 2007/08 food price crisis was caused by the interplay of a multitude of macroeconomic and sector-specific factors and was exacerbated by export restrictions imposed by many countries including major players in the markets (Tadesse et al. 2014; Wright 2014; Rude and An 2015).
6. 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 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 S4 and S5 provide the detailed results of these statistical tests.

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