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Core-periphery structures in global agricultural gross and value added trade networks

Dominika Brózda-Wilamek, Aleksandra Nacewska-Twardowska

ABSTRACT

Objective: This study aimed to identify and explain the structural differences of global agricultural trade networks, depending on the trade metric applied *i.e.*, gross exports (EXGR) versus domestic value-added embedded in foreign final demand (FFD_DVA). By applying the core-periphery framework, we evaluated the degree of hierarchy, structural coherence, and temporal stability of core-periphery patterns within trade relationships between countries from 2011 to 2020.

Research Design & Methods: The analysis employed social network analysis (SNA) techniques, incorporating both the discrete and continuous versions of the core-periphery model, to identify structural roles within agricultural trade networks. The study relied on OECD TiVA data for value-added trade flows and constructs directed, weighted trade networks for EXGR and FFD_DVA separately. We calculated key SNA metrics, such as the final fitness index, coreness scores, the Gini coefficient, and heterogeneity.

Findings: The FFD_DVA network showed a much stronger fit to the ideal core–periphery structure than the EXGR network. China and the United States consistently formed the core, although their relative positions varied by metric. The FFD_DVA network became more stable over time and more hierarchical, confirming that value-added measures better reflect the structure of global agricultural trade.

Implications & Recommendations: Value-added metrics should be prioritised in assessing trade dependencies and risks, as they reveal structural patterns not visible in gross flows. Policy makers and researchers should apply value-added diagnostics to better identify vulnerabilities and understand the organisation of global agri-food supply chains.

Contribution & Value Added: The study offers a rare direct comparison of EXGR and FFD_DVA networks using identical core–periphery methods. It introduces a compact, multi-metric framework for analysing trade structures and demonstrates the added value of incorporating value-added data into agricultural trade research.

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INTRODUCTION

International trade in agricultural products plays a vital role in the global economy (Wood *et al.*, 2018). Agricultural production is inherently dependent on natural factors such as climate and soil conditions, leading to an uneven spatial distribution of output throughout the world (Ray *et al.*, 2015). Simultaneously, the demand for agricultural goods is also asymmetrically distributed due to demographic, cultural, and economic differences (D'Amour & Anderson, 2020; Distefano *et al.*, 2018). This structural imbalance creates a strong rationale for trade, making agricultural exchanges a key mechanism for meeting global food and raw material needs.

This study builds on the world systems theory (Wallerstein, 1974), which conceptualises the world economy as a hierarchically organised system composed of core, semi-peripheral, and peripheral zones. These zones differ in terms of their roles in production, control over capital and technological flows, and levels of integration into the global market. To operationalise this framework, we applied the core-periphery model developed by Borgatti and Everett (1999), which allows the identification of structurally cohesive cores and weakly integrated peripheries within a given network. We used both categorical and continuous approaches to the model to capture idealised binary structures and graded centrality profiles, respectively.

Moreover, we applied this approach to investigate global agricultural trade networks and explore the extent to which they exhibit core-periphery characteristics. Importantly, we compared two distinct representations of trade: gross export flows (EXGR) and domestic value added in foreign final demand (FFD_DVA). Although gross exports are a standard metric in trade analysis, they can overstate the role of intermediary countries and obscure structural dependencies (Johnson, 2014). Despite growing recognition of these limitations, existing network-based studies of agricultural trade rarely compare gross and value-added representations using identical methodological frameworks, leaving uncertainty as to how trade measurement affects observed core–periphery structures. In contrast, scholars increasingly acknowledge value-added-based measures, particularly domestic value added in foreign final demand (FFD_DVA) for their capacity to reveal more durable, functionally integrated, and hierarchically organised trade relationships (Guilhoto *et al.*, 2022). This distinction is especially relevant for the global agri-food system marked by intersectoral linkages, regional production specialisation, and power asymmetries along supply chains (Bialowas & Budzynska, 2022).

The primary objective of this study was to identify and explain the structural differences in global agricultural trade networks, depending on the applied trade metric, gross exports versus domestic value-added embedded in foreign final demand. Specifically, we aimed to evaluate the degree of hierarchy, structural coherence, and temporal stability of the core-periphery patterns within these networks using social network analysis (SNA) techniques. We addressed the following research questions:

RQ1: Which countries consistently occupy core positions in global agricultural trade networks based on EXGR and FFD_DVA data between 2011 and 2020?

RQ2: To what extent do the EXGR and FFD_DVA networks exhibit characteristics of an ideal core-periphery structure in terms of coherence and hierarchical stratification?

To what extent does the value-added-based representation of trade (FFD_DVA) differ from the gross exports-based network (EXGR) in capturing hierarchical and durable economic relationships? The novelty of this study manifests itself on several levels. Firstly, it offers a rare direct comparison between two representations of the global agricultural trade network, based on gross exports (EXGR) and value added in foreign final demand (FFD_DVA), using identical network analysis techniques. This ensures that observed structural differences were attributable solely to differences in trade measurement. Second, the analysis applied both discrete (blockmodeling) and continuous (coreness scores) core-periphery models in parallel, allowing for a multidimensional interpretation of network hierarchies, an approach rarely adopted in existing research. Thirdly, we used data from the OECD TiVA database, which, despite its increasing popularity, remains underused in structural network research on the agricultural sector. By integrating advanced network methodologies with a modern value-added trade framework, this article contributes to a dynamic yet still niche field of inquiry.

The remainder of the article is structured as follows. Section 2 reviews the relevant literature on core-periphery structures in trade networks and value-added trade measurement. Section 3 outlines the data sources, methodology, and operationalisation of the network models. Section 4 presents the results of the core-periphery analyses based on EXGR and FFD_DVA data and discusses their implications in light of the research questions and hypotheses. Finally, Section 5 concludes with a summary of contributions, limitations, and future research directions.

LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

The agricultural sector plays a key role in international trade, shaping global food security, production diversity, and economic interdependence. Trade is crucial for countries with limited resources, particularly in the Global South, where imports of staple crops introduce both stabilising and destabilising effects (D'Amour & Anderson, 2020). Although trade helps reduce distributional inequalities, it also increases vulnerability to production shocks in exporting regions. Despite comparative advantage theories, many countries maintain diverse agricultural outputs for resilience and cultural reasons (Nelson *et al.*, 2016). Agricultural trade networks have become denser and more interconnected, increasing systemic exposure to cascading disruptions (Burkholz & Schweitzer, 2019). Globalisation further intensifies this by homogenising production patterns (Aguiar *et al.*, 2020). Understanding these interactions is essential to improving the resilience of global agri-food systems.

Core-periphery structures help explain persistent global economic inequalities and trade asymmetries. Rooted in world system theory (Wallerstein, 1974) and extended by dependency and structuralist approaches (Hryniewicz, 2014; Thomas, 2013), the framework highlights constraints on peripheral economies. Empirical operationalisation often follows Borgatti and Everett's model (1999), which detects cohesive cores and loosely connected peripheries (Chandra & Joba, 2015; Long *et al.*, 2019; Nordlund, 2018; Yu & Ma, 2020; Zhu *et al.*, 2023). Other models include spatial concentration theories (Akamatsu *et al.*, 2012) and game-theoretic frameworks (Su & Marbach, 2023). Network-based studies employing ERGM reveal hierarchical trade structures influenced by economic size and distance (Lewin *et al.*, 2013; Solanes *et al.*, 2025; Zhao, 2021). Core exporters maintain strong reciprocal ties (Smith & Sarabi, 2022), while peripheral countries remain marginalised. Applications from the EU and Asia highlight how integration and industrial policy reshape hierarchies (Antras & Chor, 2019; Fang *et al.*, 2023; Pascariu & Tiganasu, 2017). In global value chains, core countries dominate high-value segments, while peripheral regions face structural constraints and dependence (Chávez-Bustamante *et al.*, 2023; Long *et al.*, 2019). Borgatti and Everett's model (1999) is particularly useful in identifying strategic actors and vulnerabilities in trade networks (Long *et al.*, 2019; Zhu *et al.*, 2023).

Studies of agricultural trade increasingly use network analysis to capture hierarchical structures and spatial inequalities. Scholars model networks as directed weighted graphs based on trade flows (Torreggiani *et al.*, 2018). Centrality measures help identify core actors: betweenness (Ercsey-Ravasz *et al.*, 2012), and composite indices combining degree, eigenvector, and closeness (Qiang *et al.*, 2020; Dong *et al.*, 2024). Community-detection algorithms reveal clusters of closely connected countries (Dong *et al.*, 2024; Torreggiani *et al.*, 2018). Together, these methods highlight concentration and interdependence in global agri-food systems.

Value-added (VA) trade data address the limitations of gross trade by revealing the true economic contribution of countries and sectors. This is particularly relevant in agriculture, where GVCs differ from manufacturing due to perishability and regulatory diversity (Flaig & Greenville, 2021; Zdráhal, 2024). Agriculture contributes around 35% of VA in final consumption (Greenville *et al.*, 2017), and agricultural exports display higher domestic VA shares than processed foods. Furthermore, VA data shows that much agricultural value is embedded in foreign final demand, often indirectly through foreign processors, and key hubs such as China, the US, and Germany dominate global agri-food GVCs (Greenville *et al.*, 2019). Regional trade agreements also reveal deeper integration when measured in VA terms, as shown for AfCFTA (Fusacchia *et al.*, 2022), RCEP (Wei *et al.*, 2024), and APEC (Flaig & Greenville, 2021). In SSA, VA analysis identified stronger-than-expected GVC participation and significant tariff effects (Balié *et al.*, 2019). Environmental inequalities also emerged, with exporters like Brazil and China bearing disproportionate ecological costs (Zhai *et al.*, 2024). Differences between gross and VA trade can substantially alter comparative advantage assessments (Zdráhal, 2024). Building on prior empirical evidence showing that value-added trade measures better reflect structural integration and hierarchical positioning in global value chains, this study tests two key hypotheses:

H1: The FFD_DVA network demonstrates a higher degree of fit to the ideal core-periphery model (as measured by the final fitness index) than the EXGR network.

H2: The core structure of the FFD_DVA network is more temporally stable than that of the EXGR network over the 2011–2020 period.

In general, the literature shows that agriculture is central to global trade and economic interdependence. Core-periphery theory and VA trade analysis offer essential tools for understanding structural inequalities and real economic contributions in agri-food systems. These approaches reveal hidden dependencies, environmental burdens, and integration dynamics, underscoring the need for refined analytical frameworks – an agenda central to this study.

RESEARCH METHODOLOGY

We used data from the OECD trade in value added (TiVA) database, which provides detailed information on international trade flows broken down by value added. This data set enabled the trace of the value added embodied in exports and imports across countries and industries, capturing complex global production chains and the role of intermediate goods and services in trade.

To compute value added embodied in trade flows, we analysed the standard inter-country input-output approach (Folfas, 2024). Firstly, we constructed a global matrix of technical coefficients A, representing the direct intermediate input requirements in all countries and industries. Based on this matrix, we calculated the global Leontief inverse $\mathrm{B} = (\mathrm{I} - \mathrm{A})^{-1}$ to capture the total (direct and indirect) production needed to satisfy final demand. For each country i, we derived a vector of value-added coefficients v_i, while f_j denoted the vector of final demand in country j. We then obtained value-added exports from country i to country j using the standard formula

$$VAX_{ij} = v_i B f_j, \tag{1}$$

which measures the amount of domestic value added generated in i to meet the final demand in j. This methodology enabled us to identify the true domestic content of exports and the decomposition of global production chains into their underlying value-added components.

The TiVA database covered 62 economies and included data disaggregated into 35 sectors based on the ISIC Rev. 4 classification, making it a valuable source for analysing global value chains and the real origin and destination of economic value in cross-border trade. For this study, we restricted the analysis to Section A (ISIC Rev. 4 divisions 01–03), which included agriculture, forestry, and fishing. This sectoral scope comprised crop and animal production (including mixed farming and related service activities), forestry and logging (including the production of roundwood and non-wood forest products), as well as fishing and aquaculture (United Nations, 2008).

We employed social network analysis (SNA), which is rooted in graph theory, matrix algebra, and statistics. This research method provides a robust framework for examining relational properties and dependencies that would be undetectable when viewed in isolation (Borgatti *et al.*, 2024). In international trade analysis, SNA facilitates the visualisation of trade networks as comprehensive structures, revealing previously unnoticed indirect trade connections (Yang *et al.*, 2016). The networks in SNA function as systems, with entities acting as nodes and their relationships as edges, providing deep insights into their structure and dynamics. Empirical research typically represents these networks as graphs, with nodes represented as circles and edges as straight lines connecting them (Nerurkar *et al.*, 2022).

Similarly to the studies by De Benedictis *et al.* (2014) and Nacewska-Twardowska and Brózda-Wilamek (2024), in this study, we represented the global trade system as a valued, directed network $G = (V, E)$, where the set of nodes V corresponded to countries and the set of edges E denotes bilateral trade relationships. Each directed edge $(i, j) \in E$ was assigned a non-negative weight c_{ij}, defined as exports from country i to country j. Thus, the full network can be expressed as an $n \times n$ weighted adjacency matrix $C = [c_{ij}]$, where $c_{ij} > 0$ indicates the existence and intensity of a trade flow, and $n = | V |$ denotes the total number of countries included in the network. These networks, constructed separately for EXGR and FFD_DVA, capture the asymmetry and intensity of international trade flows.

Consequently, while the EXGR weights capture the gross monetary volume of trade flows, the FFD_DVA weights reflect the contribution of domestic value added to the final demand abroad. This distinction allows the value-added network to better approximate the underlying production dependencies and long-term economic links between countries. To ensure comparability across years and network representations, we constructed all networks using identical node sets. Network density and edge distributions were allowed to vary endogenously, reflecting structural changes in global agricultural trade over time rather than methodological artefacts. The core-periphery model by Borgatti and Everett constitutes a foundational concept in SNA, designed to identify and differentiate core nodes, highly connected actors central to the network, from peripheral nodes, which are more loosely connected and structurally marginal (Borgatti & Everett, 1999). This model has found widespread application in analysing global trade networks, particularly in studies grounded in world-systems theory, which posit a hierarchical organisation of international economic relations (Kick & Davis, 2001).

In the literature, we may identify two main methodological approaches to detect the structures of the core-periphery. The first focuses on the classical framework introduced by Borgatti and Everett (1999), which has been extended by scholars such as Nordlund (2018) and Clark and Beckfield (2009). The second strand emphasises algorithmic refinements and alternative classifications, designed to classify countries as part of the core or the periphery (Boyd *et al.*, 2010; Elliott *et al.*, 2020; Kostoska *et al.*, 2020).

In this study, we based the identification of core-periphery structures on the seminal model proposed by Borgatti and Everett. There are two distinct approaches to identifying core-periphery structures by Borgatti and Everett (1999):

1. Categorical (discrete) model – it uses combinatorial optimisation to partition nodes into core and periphery sets such that core-core ties are maximised, and periphery-periphery ties are minimised.
2. Continuous model – it calculates the coreness of each node by modelling the existence (strength) of ties between pairs of nodes as a function of the coreness of each.

These models are particularly relevant for analysing trade networks, in which some countries serve as economic hubs while others play peripheral roles. In this study, both the discrete and continuous variants of the core-periphery model are applied using UCINET, a specialised software for SNA.

In this study, we employed the categorical core-periphery model implemented in UCINET to classify countries into two distinct structural roles, core and periphery, within global agricultural trade networks. The methodological approach began by generating initial partitions using eigenvector centrality measures and multiple randomised starting configurations. We then iteratively refined these preliminary assignments through a hill-climbing optimisation algorithm that maximises the correlation between the observed adjacency matrix and an idealised block model structure. In this ideal configuration, the core countries are densely interconnected, while the peripheral countries exhibit minimal or no interconnectivity. The final binary classification reflects the configuration that yields the highest structural fit, thereby exposing hierarchical patterns in international trade architecture (Borgatti *et al.*, 2002). To assess the quality of this partitioning, we computed the final fitness statistic, which quantifies the degree of correspondence between the empirical network and the ideal core-periphery model. Higher values of the fitness index (ranging from 0 to 1) indicate a stronger structural fit (Chandra & Joba, 2015).

A straightforward assessment of how closely the observed structure approximates the ideal one is provided by the equations listed below (Borgatti & Everett, 1999).

$$\rho = \sum_{i,j} c_{ij}\delta_{ij},$$
$$\boldsymbol{\delta}_{ij} = \begin{Bmatrix} 1 \text{ if } k_i = \text{CORE or } k_j = \text{CORE} \\ 0 \text{ otherwise} \end{Bmatrix} \tag{2}$$

in which:

c_{ij} - the presence or absence of a tie in the observed data;
k_i - the class core or periphery that actor i is assigned to;
δ_{ij} - the ideal core-periphery pattern;
ρ - final fitness.

The final fitness is perfect when the observed matrix C (the matrix of c_{ij}) and the ideal matrix Δ (the matrix of δ_{ij}) are the same. The larger ρ, the closer the network is to a core–periphery structure.

Importantly, this methodological framework directly supports the objectives of the study by enabling a systematic comparison of hierarchical trade architectures based on two contrasting trade metrics, EXGR and FFD_DVA. By applying the same algorithmic procedure to both representations, we can evaluate which network better approximates the ideal core-periphery structure (based on the final fitness index), thereby empirically testing H1. Moreover, by repeating the model across the 2011–2020 time series, we could assess the temporal consistency of the core membership, facilitating the verification of H2 regarding the stability of the core in FFD_DVA-based networks. Thus, the use of the categorical core-periphery model and the associated final fitness statistic was essential to address the central research questions of this study.

To complement the binary classification of countries into core and periphery, we also employed the continuous core-periphery model, which provides a more refined and scalable evaluation of structural positioning in global agricultural trade networks. Rather than assigning countries to discrete categories, this method estimates a coreness score for each country (ranging from 0 to 1) that indicates the extent to which a country occupies a central, trade-integrated role within the network. We computed these scores by identifying a coreness vector whose outer product best approximates the observed adjacency matrix, thereby preserving the directionality and intensity of trade relations (Borgatti *et al.*, 2024; Borgatti & Everett, 1999; Borgatti *et al.*, 2002).

This approach assumed that one can explain the network structure by a latent one-dimensional hierarchy, where each node i is assigned a non-negative coreness score $k_i \geq 0$. The model posits an ideal pattern matrix $\Delta = [\delta_{ij}]$, where the expected tie intensity between nodes i and j is defined as:

$$\delta_{ij} = k_i k_j \quad (3)$$

This implies that strong ties occur primarily between nodes that are both close to the core (high $k_i$and k_j), while ties between peripheral countries are weak.

We estimated the coreness vector $K = (k_1, k_2, \dots, k_n)$ by maximising the correspondence between the observed adjacency matrix C and the ideal structure Δ. Following Borgatti and Everett (1999), we achieved this by maximising the Pearson matrix correlation between C and Δ, or equivalently, by minimising the sum of squared errors:

$$\sum_{i,j} (c_{ij} - k_i k_j)^2 \quad (4)$$

The continuous model is particularly well-suited to the analysis of directed and weighted networks and allows for detailed comparisons across countries and over time.

In addition to coreness values at the node level, the model generated several global diagnostic indicators that provided a multidimensional assessment of the network structure. The Gini coefficient measured the inequality in the distribution of coreness scores; values approaching 1 suggested a highly hierarchical system dominated by a small group of central actors, while values closer to 0 indicated structural egalitarianism (Yu & Ma, 2020). The composite Gini-based core-periphery index builds on this by integrating inequality and topological fit, thereby reflecting how closely the empirical network resembles the idealised core-periphery model (Borgatti *et al.*, 2024). Finally, the heterogeneity index quantified the spread of coreness scores across the network, capturing the degree of polarisation between structurally central and peripheral countries (Yu & Ma, 2020).

This methodological extension played a critical role in achieving the central aim of the study, *i.e.*, identifying and explaining structural differences in global agricultural trade networks based on EXGR and FFD_DVA. By providing continuous and scalable measures of coreness and systemic inequality, this approach enabled a more precise and comparative assessment of structural dominance and integration. In operational terms, the analytical procedure linked specific network indicators to the tested hypotheses as follows. Specifically, it facilitated the empirical testing of H1 by comparing (i) the final fitness index obtained from the categorical core–periphery model and (ii) the global ine-quality measures (Gini coefficient and composite core-periphery index) derived from the continuous model across the EXGR and FFD_DVA networks. A higher fitness value and stronger hierarchical differentiation in FFD_DVA, relative to EXGR, constituted direct empirical evidence in support of H1. Moreover, by examining the temporal dynamics of coreness dispersion and polarisation through the heterogeneity index, as well as the year-to-year consistency of core membership and coreness rankings, it directly supported the evaluation of H2, which posits that the FFD_DVA network exhibited greater structural stability over time. Stability is assessed through a longitudinal comparison of (i) changes in core composition in the categorical model and (ii) variation in coreness scores and heterogeneity indices in the continuous model over the 2011–2020 period. Together, these metrics enabled a robust and nuanced investigation into the hierarchical organisation and resilience of international trade structures under alternative trade representations.

We supplemented the analysis with data visualisation. We used Gephi and the ForceAtlas2 layout algorithm to create spatial representations of global trade flows (Jacomy *et al.*, 2014). In the ForceAtlas2 layout, we conceptualised the network as a physical system in which nodes behave like charged bodies pushing one another apart, while edges operate as springs pulling their incident nodes closer (Brinkmann *et al.*, 2017; Gorgol & Salwa, 2025). The algorithm repeatedly updates node coordinates until the forces reach equilibrium. For connected pairs of nodes, attraction grows proportionally with their separation distance,

$$F_a(n_1, n_2) = d(n_1, n_2). \tag{5}$$

In turn, repulsive forces scale with the degrees of both nodes and decline with distance.

$$F_a(n_1, n_2) = k_r \frac{(\deg(n_1)+1)(\deg(n_2)+1)}{d(n_1, n_2)}, \tag{6}$$

A commonly used alternative, the LinLog mode, replaces the linear attraction with a logarithmic form,

$$F_a(n_1, n_2) = \log\big(1 + d(n_1, n_2)\big), \tag{7}$$

which enhances the separation of communities and makes modular structures more distinct. The algorithm also integrates several practical adjustments, including gravitational pull that stabilises low-degree nodes,

$$F_g(n) = k_g(\deg(n) + 1), \tag{8}$$

penalisation of hubs, avoidance of node overlap, and the treatment of weighted edges.

Node movements follow the combined effect of all forces, moderated by an adaptive speed parameter:

$$\Delta(n) = s(n)F(n). \tag{9}$$

The local speed depends on a 'swinging' measure, defined as

$$swg^{(t)}(n) = \left|\left|F^{(t)}(n) - F^{(t-1)}(n)\right|\right|, \tag{10}$$

which captures instability in the direction of motion. It serves to regulate step size,

$$s(n) = \frac{k_s s(G)}{1 + s(G)\sqrt{swg(n)}}. \tag{11}$$

In turn, global speed reflects the balance between effective traction and total swinging,

$$s(g) = t \cdot \frac{tra(G)}{swg(G)}, \tag{12}$$

For larger networks, ForceAtlas2 relies on the Barnes–Hut approximation to estimate repulsion, reducing the computational complexity to $O(n\,log\,n)$. One may quantify the overall quality of the layout using the Noack's measure,

$$Q(p) = \frac{1}{Q_{Noack}(p)}. \tag{13}$$

Through this combination of force formulations, adaptive optimisation, and computational shortcuts, ForceAtlas2 delivers stable and interpretable layouts suitable for medium- and large-scale graphs, while maintaining an interactive, continuous visualisation process.

RESULTS AND DISCUSSION

Data Analysis

We employed both categorical and continuous core-periphery models to analyse the hierarchical structure of global agricultural trade networks measured by EXGR and FFD_DVA. In the first step, the analysis spanned the period from 2011 to 2020. We conducted it using UCINET's combinatorial optimisation algorithm, which iteratively maximises the correlation between the empirical adjacency matrix and the idealised block model. The model identified countries as either part of the core, characterised by dense mutual interconnections. or as peripheral actors, marked by weak or absent interconnectivity. We used the final fitness statistic, a correlation-based indicator, to assess the structural fit of the observed network to the ideal core-periphery configuration. Table 1 presents the results of this classification, highlighting both the temporal stability of core memberships and the comparative fitness levels of the two types of networks.

Table 1. The results of discrete core-periphery models for EXGR and FFD_DVA networks in 2011-2020

Year	Core/periphery class memberships		Final fitness	
	EXGR	FFD_DVA	EXGR	FFD_DVA
2011	CHN USA	CHN USA	0.639	0.823
2012	CHN USA	CHN USA	0.667	0.850
2013	CHN USA	CHN USA	0.659	0.866
2014	CHN USA	CHN USA	0.675	0.853
2015	CHN USA	CHN USA	0.668	0.824
2016	CHN USA	CHN USA	0.673	0.841
2017	CHN USA	CHN USA	0.654	0.843
2018	CAN CHN USA	CHN USA	0.658	0.799
2019	BRA CHN USA	CHN USA	0.547	0.779
2020	CHN USA	CHN USA	0.652	0.851
Average 2011-2020	–	–	0.649	0.833

Note: *Fitness measure: CORR.
Source: own study using UCINET 6 software.

The results of the categorical modelling approach (Table 1) indicate that the FFD_DVA network exhibited a consistently higher fit to the ideal core-periphery structure compared to the EXGR network. The final fitness index, representing the correlation between the empirical and ideal core-periphery matrices, averaged 0.833 for FFD_DVA versus 0.649 for EXGR during the 2011–2020 period. This significant and persistent difference is consistent with H1, which posited that the value-added-based trade network more closely approximated an idealised core-periphery structure.

Both networks identified China (CHN) and the United States (USA) as the consistent core actors, which corresponds to their enduring centrality in global agricultural trade. However, the EXGR network displayed occasional fluctuations, with Canada (CAN) and Brazil (BRA) entering the core in 2018 and 2019, respectively. These episodic shifts indicate greater variability in core composition within the EXGR network over time. In contrast, the FFD_DVA network displays a more precise and more durable bifurcation between the core and periphery, associated with stronger structural integration within global value chains. This is consistent with H2, which contends that the core structure of the FFD_DVA network is more temporally stable than that of the EXGR network.

These findings are partially consistent with previous research. Dong *et al.* (2024) identified three persistent trade communities, each dominated by key core countries: Germany in Europe; the United States and China in North America and East Asia, respectively; and Brazil representing a central actor in the Global South. These regional hubs formed stable cores within the modular structure of agricultural trade networks. Similarly, Torreggiani *et al.* (2018) observed that China, the United States, and Brazil recurrently occupied central positions in multiple commodity-specific clusters, particularly in the trade of soy, cereals, and meat. Their multilayer network analysis demonstrated that despite differences between products, certain countries consistently held structurally advantageous positions within trade communities. Furthermore, Ercsey-Ravasz *et al.* (2012) identified a clearly defined core within the international agricultural trade network, composed of seven countries selected based on betweenness centrality and degree. The United States and China were among these structurally central economies.

In the second step, the continuous core-periphery model (Table 2) reinforced the structural contrasts between the two networks by assigning each country a degree of coreness along a continuous scale. In the EXGR network, the United States retained the highest average coreness score (0.706), indicating its role as a dominant agricultural export hub. Brazil (0.408) and Canada (0.232) followed, demonstrating their relatively strong positions as global suppliers. In particular, Brazil's core quality rose steadily from 0.338 in 2011 to 0.485 in 2020, corresponding to its expanding influence in global agri-food markets. However, China exhibited a relatively peripheral role in the EXGR network, with an average coreness score of just 0.175. Although it did not rank among the top exporters, China's position improved moderately over the decade, rising from 0.145 in 2011 to over 0.20 by 2020. This upward trend was consistent with a gradual increase in China's participation in gross agricultural exports, potentially driven by expanded new trade agreements and diversified sourcing strategies. Nonetheless, its relatively low coreness in the EXGR network suggests that, in terms of sheer export volumes, China functions more as a processing or transit economy rather than a primary exporter of agricultural raw goods.

In contrast, the FFD_DVA network presents a markedly different pattern. China emerged as the unequivocal core country, with an average coreness of 0.808, far surpassing other nations. This centrality reflects China's deeply embedded position in global agricultural value chains – not just as an exporter but as a key node in the transformation, processing and redistribution of agricultural products. Meanwhile, the position of the United States appeared considerably less central (average: 0.297), suggesting that much of its agricultural trade may consist of primary commodities with less embedded domestic value added.

Moreover, the continuous model points to a regional shift in trade centrality, with increasing coreness scores for countries such as India, Indonesia, and Thailand. This trend indicates an ongoing reconfiguration of the global agricultural trade landscape, in which emerging Asian economies are increasingly integrated into high-value food production and distribution segments.

The observed patterns are broadly consistent with previous studies. Qiang *et al.* (2020) analysed the long-term developments in agricultural trade networks and found that the most influential countries, measured by node strength, shifted over time. In 1986, the dominant hubs included the United States, Japan, France, Germany, and the USSR. By 2016, the core had expanded to include China, Brazil, India, Argentina, and Canada, illustrating the increasing multipolarity of global agricultural trade.

The structural coherence of the FFD_DVA network was also reflected in higher values for the Gini coefficient (0.675 vs. 0.651 for EXGR), composite core-peripheries (0.440 vs. 0.267), and heterogeneity index (0.060 vs. 0.042). These metrics suggest that the FFD_DVA network exhibit greater internal differentiation, more evident hierarchical stratification, and stronger central-peripheral distinctions than the EXGR network. These findings support H1, which proposed that the FFD_DVA network would more closely approximate the idealised core-periphery structure than the EXGR network.

Furthermore, such findings also support H2, which posited that the value-added-based trade structure would exhibit greater temporal and structural stability. Indeed, while the core of the EXGR network proved susceptible to short-term disruptions, the FFD_DVA network remained consistently structured around a stable set of central actors, particularly China.

First and foremost, the core-periphery analysis results underscore the analytical superiority of value-added-based trade networks. The consistently higher final fitness scores and more pronounced stratification indices observed in the FFD_DVA model suggest that this representation provides a more clearly differentiated depiction of the hierarchical nature of global trade. The presence of a well-defined and persistent core, dominated by China and the United States, alongside a differentiated periphery, indicates that value-added flows are associated with more stable structural patterns than gross trade flows. Moreover, the continuous model offers a more nuanced understanding of international trade positioning. Countries are no longer classified as either core or periphery, but instead assessed along a gradient of influence and integration. This allows for more granular evaluations of each country's strategic role within the evolving architecture of global trade.

Table 2. Level of coreness scores and coreness coefficients for EXGR and FFD_DVA networks in 2011–2020 (top 10 countries)

Variables	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Average 2011-2020
EXGR networks											
USA	0.755	0.736	0.721	0.736	0.698	0.735	0.700	0.667	0.639	0.673	0.706
BRA	0.338	0.361	0.382	0.377	0.418	0.358	0.424	0.474	0.463	0.485	0.408
CAN	0.218	0.224	0.237	0.246	0.258	0.236	0.230	0.242	0.234	0.199	0.232
CHN	0.145	0.144	0.149	0.157	0.188	0.196	0.186	0.178	0.205	0.202	0.175
FRA	0.193	0.176	0.191	0.168	0.173	0.152	0.144	0.160	0.163	0.137	0.166
NLD	0.177	0.166	0.173	0.159	0.162	0.170	0.160	0.149	0.175	0.160	0.165
ESP	0.145	0.144	0.162	0.163	0.176	0.183	0.175	0.171	0.176	0.154	0.165
AUS	0.155	0.188	0.186	0.155	0.147	0.162	0.180	0.136	0.122	0.123	0.155
VNM	0.092	0.088	0.093	0.103	0.126	0.137	0.146	0.151	0.162	0.162	0.126
RUS	0.122	0.140	0.108	0.140	0.107	0.088	0.109	0.126	0.133	0.106	0.118
gini coefficient	0.652	0.65	0.652	0.655	0.656	0.655	0.654	0.649	0.64	0.651	0.651
composite 'gini-based core / peripheriness'	0.264	0.244	0.254	0.274	0.287	0.306	0.271	0.245	0.267	0.261	0.267
heterogeneity	0.044	0.042	0.042	0.044	0.042	0.043	0.042	0.04	0.036	0.041	0.042
FFD_DVA networks											
CHN	0.742	0.769	0.797	0.843	0.881	0.839	0.793	0.797	0.800	0.818	0.808
USA	0.347	0.324	0.337	0.300	0.247	0.280	0.299	0.290	0.264	0.278	0.297
IND	0.320	0.283	0.272	0.218	0.196	0.225	0.257	0.258	0.284	0.252	0.257
BRA	0.236	0.222	0.221	0.200	0.179	0.201	0.241	0.244	0.222	0.238	0.220
IDN	0.159	0.143	0.131	0.119	0.116	0.134	0.156	0.152	0.146	0.140	0.140
CAN	0.113	0.111	0.112	0.096	0.099	0.109	0.120	0.109	0.105	0.095	0.107
ESP	0.097	0.089	0.095	0.089	0.087	0.109	0.118	0.120	0.119	0.101	0.102
THA	0.101	0.097	0.091	0.084	0.083	0.098	0.114	0.117	0.120	0.100	0.101
VNM	0.075	0.078	0.077	0.081	0.083	0.104	0.117	0.123	0.130	0.130	0.100
FRA	0.110	0.097	0.087	0.083	0.074	0.074	0.086	0.097	0.090	0.078	0.088
gini coefficient	0.675	0.683	0.682	0.681	0.694	0.681	0.668	0.662	0.656	0.668	0.675
composite 'gini-based core / peripheriness'	0.433	0.434	0.463	0.461	0.438	0.437	0.441	0.432	0.414	0.447	0.440
heterogeneity	0.051	0.054	0.061	0.068	0.082	0.066	0.055	0.054	0.053	0.06	0.060

Source: own study using UCINET 6 software.

These findings have significant implications for economic policy and international trade research. Analyses relying solely on gross export data may overemphasise countries that operate as trade intermediaries while underestimating those embedded more deeply in value-generating processes. In contrast, value-added trade metrics highlight structural interdependencies of global economic interdependence and provide a more accurate lens to assess power and influence within global supply chains.

Visual Analysis

Figure 1 illustrates the global agricultural trade network in 2011 and 2020, using gross export flows and domestic value added embodied in foreign final demand. The ForceAtlas2 layout positions the nodes to visualise the core–periphery structures: node colour reflects weighted degree centrality, and node size corresponds to coreness. Following earlier studies (Gorgoni *et al.*, 2018; Smith & Sarabi, 2021), we applied a coreness threshold of 0.05 to highlight the most central countries and reduce visual clutter. This facilitated a clear identification of dominant actors while omitting peripheral nodes with limited structural relevance.

Moreover, ForceAtlas2 enabled a meaningful comparison between network types and years. The spatial placement of countries and the density of their ties provide a readable representation of structural change, for example, by comparing the EXGR and FFD_DVA networks within a given year or tracing their evolution between 2011 and 2020.

In 2011, the EXGR centred strongly on the United States, forming a classic unipolar core–periphery pattern. By 2020, the structure appears more decentralised: Brazil, Canada, and China gain coreness, producing a more multipolar configuration and signalling a redistribution of trade influence.

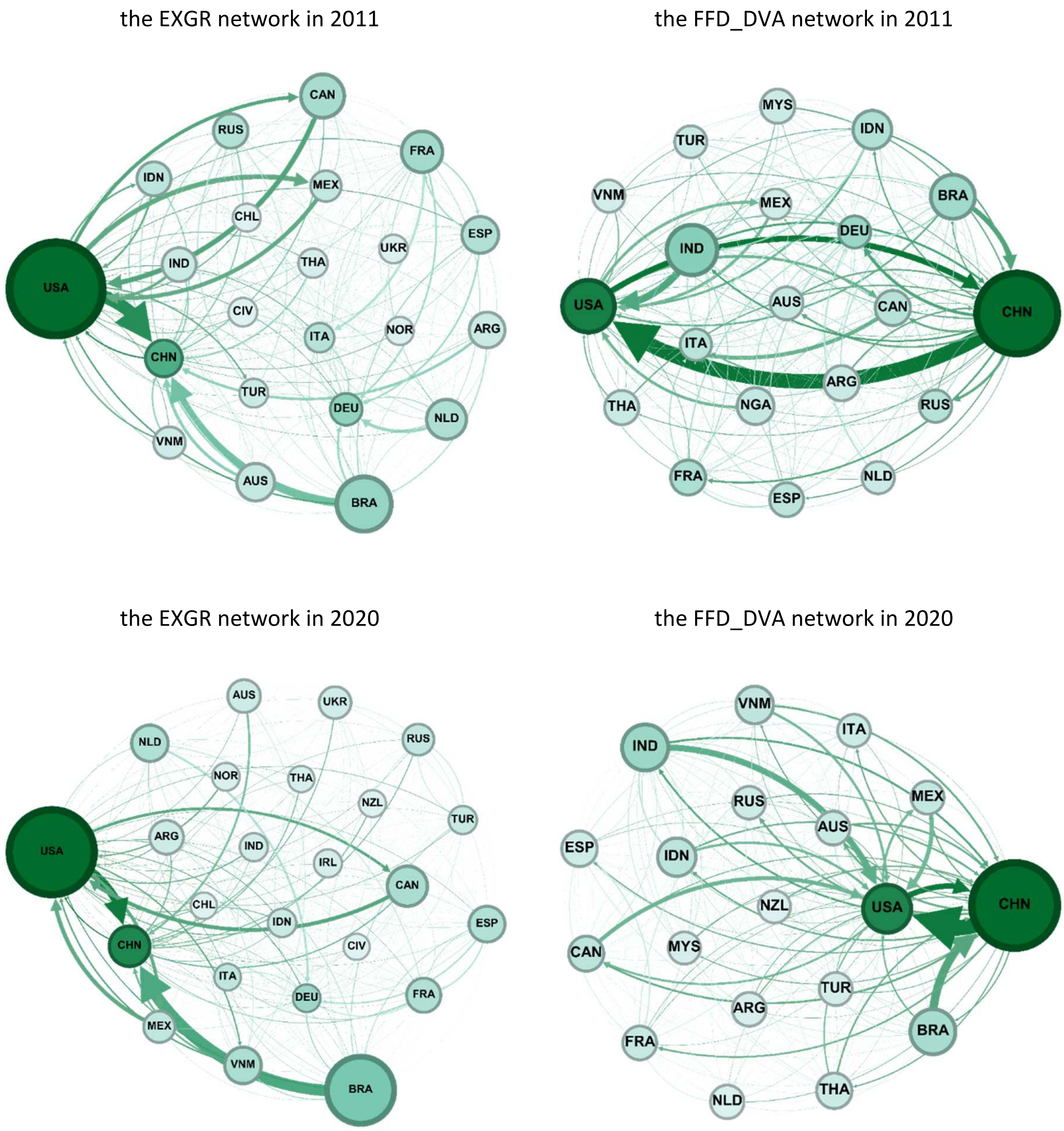

Figure 1. Global agricultural trade network in 2011 and 2020 based on gross export flows and domestic value added embodied in foreign final demand
Source: own elaboration in Gephi software.

Furthermore, the 2011 FFD_DVA network already displays a more balanced core, with both China and the United States occupying central positions. China appears more prominent than in the EXGR, reflecting its role as a hub in global value chains. By 2020, China had become the primary core actor, absorbing value added from most major economies, while the United States had remained important but less dominant. Countries such as Brazil and India strengthened their semi-peripheral roles. The denser and more cohesive structure supports the interpretation of FFD_DVA as a more stable representation of long-term trade relations.

Comparisons among metrics revealed substantial structural differences. In 2011, EXGR displayed a unipolar network dominated by the USA, whereas FFD_DVA showed a more distributed configuration in which China and other emerging economies (*e.g.*, India, Indonesia) played greater roles due to their participation in intermediate production. By 2020, EXGR shifted toward multipolarity, while FFD_DVA became more hierarchical and internally coherent. This provides empirical support for H1 (better fit of the FFD_DVA network to the core–periphery model) and H2 (greater temporal stability of the value-added structure).

CONCLUSIONS

This study offered evidence that value-added-based representations of trade provide an alternative and structurally differentiated framework for analysing the core-periphery structures of global agricultural trade networks. Through a comparative analysis of gross export (EXGR) and domestic value added in foreign final demand (FFD_DVA) networks from 2011 to 2020, we demonstrated that the FFD_DVA network aligns more closely with the theoretical ideal of a core-periphery configuration. Notably, the FFD_DVA network exhibited consistently higher fitness indices, greater structural coherence, and increased inequality in coreness distributions, which are hallmarks of a hierarchically stratified and functionally integrated global trade system.

The empirical results further validated our hypotheses. Firstly, the stronger fit of the FFD_DVA network with the idealised core-periphery model confirmed that value-added trade measures are more effective at capturing enduring economic relationships. Secondly, the temporal analysis revealed greater stability of core membership in the FFD_DVA network, suggesting that value-added flows reflect more deeply rooted trade interdependencies than those captured by gross exports, which appear to be more susceptible to short-term fluctuations.

Despite the significant insights offered by this study, we must acknowledge several limitations. Firstly, the value-added trade data employed were based on estimations, which introduced a degree of uncertainty and may have affected the results' accuracy. The analysis relied on multi-regional input-output tables, which are susceptible to aggregation bias and inconsistencies in reporting across countries and sectors. Another limitation lies in the restricted temporal scope of the data set, which may have limited the findings' generalisability. It is also important to note the absence of a formal statistical test to assess the fit of the core-periphery structure. As Borgatti and Everett (1999) note, although the model may appear to closely approximate network structures, there is no guarantee that such a fit could not have occurred by chance, particularly in the absence of a well-established null model for comparison.

Despite its limitations, the study contributes to the growing body of literature advocating the use of value-added metrics in the analysis of global trade networks. By demonstrating that FFD_DVA-based networks are more clearly differentiated in terms of hierarchical structures and temporal stability, the findings challenge the continued reliance on gross export data in structural trade analysis. Moreover, applying both discrete and continuous core-periphery models offers a methodological framework that can be replicated across other sectors or temporal scopes, thereby opening new avenues for comparative network research in international political economy, regional integration, and global value chains.

The practical implications are equally significant. For policymakers and trade analysts, adopting a value-added lens is essential to accurately diagnose structural dependencies and identify strategic trade partners. Gross export data may obscure the true nature of economic influence, especially in complex global supply chains. Conversely, FFD_DVA metrics highlight patterns of value creation offering a more precise basis for assessing trade vulnerabilities and leverage points in negotiations.

Future studies may expand on this research by exploring core-periphery structures across different sectors of the global economy, such as high-tech industries, energy, or services, to assess how sector-specific characteristics influence the durability and hierarchy of trade relationships. Moreover, incorporating additional network measures, such as betweenness centrality, modularity, or structural role indices, could offer a more nuanced understanding of countries' positions and functions within trade networks. Finally, a more in-depth regional and geopolitical perspective (*e.g*., EU. ASEAN. MERCOSUR. or Global North vs. Global South) would allow for the identification of structural divergences within trade blocs and help assess the impact of economic integration on network positioning.

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Authors

The contribution share of authors was equal and amounted to 50% for each of them. All authors have contributed significantly throughout this research in all its phases.

Dominika Brózda-Wilamek (corresponding author)

PhD, Assistant Professor at the Department of International Business and Trade at University of Lodz. Her research interests include social network analysis, with a particular interest in foreign direct investment and cross-border merger and acquisitions.

Correspondence to: Dominika Brózda-Wilamek, PhD, University of Lodz, Faculty of Economic and Sociology, Department of International Business and Trade, POW 3/5, 90-255 Lodz, Poland, e-mail: dominika.brozda@uni.lodz.pl

ORCID https://orcid.org/0000-0002-0513-2286

Aleksandra Nacewska-Twardowska

PhD, Assistant Professor at the Department of International Business and Trade at University of Lodz. Her research interests include international trade, global value chains, value added trade, and visual analysis of trade networks.

Correspondence to: Aleksandra Nacewska-Twardowska, PhD, University of Lodz, Faculty of Economic and Sociology, Department of International Business and Trade, POW 3/5, 90-255 Lodz, Poland, e-mail: aleksandra.nacewska-twardowska@uni.lodz.pl

ORCID https://orcid.org/0000-0002-8074-0361

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Use of Artificial Intelligence

We have used Grammarly, Writefull and ChatGPT for proofreading the text to eliminate grammar and spelling errors.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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