Resilient structure and increasing concentration of the roundwood trade: a network analysis perspective

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Abstract

[TO EDIT] While the use of wood products is increasingly linked to sustainability and climate change issues, forest resources are unevenly distributed among countries and have different regional forest dynamics. Redistributing surpluses resulting from overproduction of wood products to countries with demand deficits to address sustainability issues can be achieved through trade. The literature offers a comprehensive study of the international timber trade, but few studies to date consider the physical structure of the trade network in their analyses. We conduct a diagnosis of the international roundwood trade from 1997 to 2017 using a network-theoretic approach, which provides a deeper understanding of the inherent structure of the trade of wood products and complements the existing literature. We expect the global roundwood trade network to be concentrated and to follow global trends in economic growth, but also to be sensitive to major economic and political events and natural disasters. Our results show that the roundwood trade network has increased in value, while varying slightly in size, and has become more interconnected over the study period. We also observed changes in network structure over time that can be explained by three broad categories of events: economic disruptions, political events, and natural disasters. Most importantly, our results show the growing market power of China: in 2017, more than 50% of the network's total trade value was due to Chinese imports, China was among the most connected countries, and countries preferentially traded with China. Lastly, our results have implications for forest policy, as the structure of the network may dictate potential cascades of local or regional shocks to the global trade market, and as the growing polarization around China exacerbates trade tensions in roundwood.

Keywords: Globalization, Trade, Wood products, Network theory, Forest policy

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1. Introduction

International wood product trade stands as an increasingly complex and interdependent component of the global economy, intricately tied to environmental concerns, geopolitical shifts, evolving competition schemes, and macroeconomic trends. The uneven global distribution of forest resources, concentrated in a few countries (*e.g.*, Russia, Brazil, Canada, the United States, and China) (FAO, 2024b), necessitates international trade to balance supply and demand to satisfy domestic consumption (Long et al., 2019; Huang et al., 2024).

The 21st century has witnessed significant acceleration in international wood product trade, driven by convergent economic and technological determinants. Primary drivers include sustained global economic growth, escalating demand for construction materials fueled by urbanization, trade liberalization, and technological innovations enhancing forestry value chain operational efficiency[1] (Prestemon et al., 2003; UNECE/FAO, 2021). Furthermore, global value chains (GVC) proliferation has restructured production paradigms through the spatial fragmentation of manufacturing processes, leading to new market dynamics and more complex supply chain configurations (Amador and Cabral, 2017).

This trade intensification has precipitated systematic displacement of deforestation pressures, characterized by distinct geographic redistribution patterns. Resource accumulation occurs in nations with predominantly non-indigenous, plantation-based forest systems — typically developed economies with established silviculture infrastructure — while simultaneously exerting extractive pressure on regions where indigenous forest ecosystems face depletion, predominantly within developing nations (Prestemon et al., 2003; Leblois et al., 2017; Pendrill et al., 2019; Abman and Lundberg, 2020). This spatial divergence highlights how trade-mediated demand drives forest degradation. In particular, illegal logging and associated trade represent significant drivers of deforestation and forest degradation globally, exacerbating climate change (Lawson, Sam and MacFaul, Larry, 2010).[2]

This acceleration of the international wood trade has also coincided with growing environmental consciousness and a rising preference for "green" materials with carbon storage capacity, driven by climate change mitigation goals, leading to various environmental regulations and sustainability initiatives (Prestemon et al., 2003). The emerging forest-based bioeconomy, exemplified by strategies like the European Bioeconomy Strategy, aims to replace non-renewable resources with high-value-added products from woody biomass (Wolfslehner et al.,

[1]These innovations encompass advancements in plantation management systems, forest harvesting operations, and manufacturing processes.

[2]Illegal logging and its associated trade also extensively contribute to wider environmental damage, such as global anthropogenic carbon dioxide emissions, loss of biodiversity, deprive governments of billions of dollars in vital revenues, foster corruption, undermine the rule of law, and can fuel conflict (Lawson, Sam and MacFaul, Larry, 2010).

2016; Winkel, 2017). This creates a paradox: while increased wood demand can support decarbonization and sustainable development, unsustainable and illegally sourcing risks exacerbating deforestation and forest degradation. Consequently, market-based tools like forest certification schemes[3] promote sustainable practices, sometimes restricting wood products trade (Guan and Ip Ping Sheong, 2019; Chen et al., 2020; Boubacar and Sissoko, 2025). Furthermore, timber trade regulations, primarily enforced by developed countries, aim to exclude illegal timber from domestic markets, hindering trade volumes (Moral-Pajares et al., 2020; Rougieux and Jonsson, 2021; Apeti and N'doua, 2023; Kim et al., 2024).[4]

While tariff barriers have declined due to international trade agreements, these trade regulations demonstrate that non-tariff barriers (NTBs) increasingly influence wood product trade (UNECE/FAO, 2021). NTBs include quotas, embargoes, economic sanctions, export bans, stringent environmental policies, and phytosanitary controls (Li et al., 2007; Sun et al., 2010; Buongiorno and Johnston, 2018; UNECE/FAO, 2022; FAO, 2024a). Notable trade disputes over wood products, such as those between China and the U.S. (Muhammad and Jones, 2021; Pan et al., 2021), Russian roundwood export restrictions (Turner et al., 2008; Solberg et al., 2010; Lin and Zhang, 2017; Guan and Yang, 2024), and the Canada-U.S. softwood lumber dispute (van Kooten and Johnston, 2014; Johnston and van Kooten, 2017), underscore a tension between free trade principles and national policy objectives. Such measures, while often aiming for sustainability or industry protection, can disrupt trade, raise prices, and shift production and consumption patterns.

In recent years, significant economic and geopolitical disruptions have affected the global supply chain for wood products, leading to volatility in timber prices and shipping costs (FAO, 2024a; UNECE/FAO, 2022). The COVID-19 pandemic initially introduced considerable uncertainty into forest product markets but was swiftly followed by a robust economic rebound in 2021, indicating strong underlying demand and inherent resilience (UNECE/FAO, 2022). However, the war in Ukraine from mid-2022 exacerbated supply chain disruptions, intensified inflation, and eroded consumer confidence, leading to a demand decline (UNECE/FAO, 2022) Climate change impact on forests ecosystems worsens such instability, increasing the frequency and severity of natural disturbances like storms, wildfires, and pest outbreaks (Seidl et al., 2011; Seidl and Rammer, 2017; Curtis et al., 2018; Tyukavina et al., 2022; Patacca et al., 2023), directly disrupting timber supply chains and market stability and deteriorating wood quality (García-Jácome et al., 2025). This apparent vulnerability to external shocks suggests that trade resilience is not absolute but contingent on global economic, environmental, and political stability (García-Jácome et al., 2025; Ma et al., 2025).

Understanding the intricate web of these relationships and trade flows is paramount for policy formulation

[3] Such as the Forest Stewardship Council (FSC) and the Program for the Endorsement of Forest Certification (PEFC).

[4] Examples are the European Union's Action Plan for Forest Law Enforcement, Governance and Trade (FLEGT), the European Union Timber Regulation (EUTR), the US Lacey Act, the Australia Illegal Logging Prohibition Act, or the Japan Clean Wood Act.

and strategic planning. The literature extensively studies the international timber market and trade, spanning from global to subnational scales and various wood products (*e.g.*, Müller et al., 2004; Raunikar et al., 2010; Caurla et al., 2013; van Kooten and Johnston, 2014; Buongiorno, 2015; Rougieux, 2017; Rougieux and Jonsson, 2021, Shen and Lovrić (2022)). These studies employ three primary perspectives: trade mechanism analysis, forecasting, and policy analysis (Buongiorno, 2016; Rivière and Caurla, 2020; Mathieu and Roda, 2023).

Overall, the literature on international wood trade draws on models. Traditional approaches, primarily forest sector models and econometric models (including gravity models) rooted in economic theory (Buongiorno, 1996; Kallio et al., 2004; Latta et al., 2013; Northway et al., 2013; Buongiorno, 2015), rely on nationally reported data and treat countries as the main unit of analysis, focusing on discrete bilateral trade relationships (Amador and Cabral, 2017; Shen and Lovrić, 2022).

However, these approaches face significant limitations in accounting for multilateral network effects, indirect trade linkages, and cascading interdependencies inherent in modern international trade and contemporary global value chain structures (De Benedictis and Tajoli, 2011; Amador and Cabral, 2017; Liu et al., 2025). Consequently, traditional approaches offer limited structural insights and may systematically underestimate critical systemic vulnerabilities such as supply chain fragility, contagion effects, and network resilience, while simultaneously overlooking strategic opportunities revealed by comprehensive network topology analysis (Fèvre et al., 2006; Huang et al., 2024). Furthermore, the existing literature exhibits considerable heterogeneity in analytical frameworks, temporal specifications, and spatial delimitations, hindering systematic meta-analysis and comprehensive understanding of global trade network dynamics.

We address this gap by adopting a network theoretic approach that considers the trade flows between countries as the unit of analysis (De Benedictis and Tajoli, 2011; Amador and Cabral, 2017). This perspective offers a deeper, holistic view of wood product trade inherent structure, providing insights into its underlying organization and evolution (Long et al., 2019; Shen and Lovrić, 2022). Indeed, network analysis has been a powerful tool for studying complex global interactions.[5]

Network analysis has significantly advanced the understanding of global wood forest product trade dynamics, moving beyond traditional economic models to reveal structural characteristics, intricate relationships, competitive dynamics, evolutionary trends, network resilience to external shocks, and vulnerabilities (Lovrić et al., 2018; Long et al., 2019; Gao et al., 2024; Huang et al., 2024). Previous research indicates these trade networks have significantly evolved and expanded in the 21st century, showing increased complexity and interdependence, broader participation, and enhanced overall trade efficiency and resilience (Wang et al.,

[5] See, for example, (Fèvre et al., 2006), who construct networks of the live animal trade to explain the spread of disease.

2020; Gao et al., 2024; Huang et al., 2024; Liu et al., 2024). While network density remains stable, average trade value has risen (Zhou et al., 2021).

Network analysis has also identified key players and their evolving roles. Historically, North American and European countries were central, but emerging economies like China have become dominant importers and increasingly central players across the supply chain, with their influence growing annually (Zhou et al., 2021; Gao et al., 2024; Huang et al., 2024; Liu et al., 2024). Russia and Canada remain major timber exporters, and New Zealand is a significant raw material exporter (Zhou et al., 2021). Despite dynamic changes, these networks maintain a relatively stable core-periphery structure, with China and India now prominent in the core (Wang et al., 2020). While core countries boost network resilience, their dominance introduces vulnerabilities (Huang et al., 2024).

Beyond structural descriptions, the literature has also investigated factors influencing network evolution, including economic scale, geographical distance, cultural differences, and forest resource endowment (Gao et al., 2024), internal trade effects (reciprocity and transitivity) (Shen and Lovrić, 2022), and policy changes (Huang et al., 2024).

Current research on forest product trade networks, while foundational, needs deeper methodological and empirical exploration. Most studies take a broad, macroscopic view, often combining different wood product types, potentially distorting network understanding and leading to less effective trade policies (Gao et al., 2024; Liu et al., 2024). A significant gap exists in comprehensively characterizing the structure and temporal evolution of international roundwood trade networks. This gap is critical because roundwood — unprocessed timber directly harvested from forests — represents the primary commodity in global forest product supply chains, directly linked to sustainable forest management and deforestation issues. As the second most traded wood product by volume over the last decade,[6] roundwood forms the foundational stratum of international forest product trade, linking forest resource extraction with processing industries through complex international trade relationships. The lack of detailed analysis on roundwood trade patterns, both structurally and over time, is a major gap in forest economics research, limiting policy insights for sustainable forest governance.

The present work addresses this gap through a comprehensive network analysis of global roundwood trade dynamics spanning the period 1996–2022. First, we conduct a multidimensional network topology analysis using complementary quantitative metrics to systematically characterize roundwood trade network structural properties and their temporal evolution. This employs graph theory-based methodologies alongside traditional trade analysis metrics for comprehensive structural characterization. Second, we use information

[6] According to FAOSTAT data

of past market behaviour to explain changes in network structure. We hypothesise that global roundwood trade networks demonstrate systematic concentration in exports (due to concentrated forest endowments) while exhibiting structural sensitivity to exogenous disruption events, including economic crises, geopolitical instabilities, and natural disasters. This hypothesis framework incorporates three propositions: (1) network concentration in exports remains moderately high over the study period; (2) trade network demonstrates systematic vulnerability to major disruption events; and (3) trade network demonstrates short-term structural recovery patterns following disruption events.

2. Material and methods

2.1. Bilateral trade data collection

We extracted trade data from the UN Comtrade database in Python 3.12.2 using the Python package "comtradeapicall" 1.2.1 (untradestats, 2024).[7] The UN Comtrade data provides detailed information on bilateral trade flows by recording the trade reports from almost 200 countries. National statistical reports of trade may be produced on an annual or monthly basis. They cover a wide range of traded commodities, including wood products. Traded commodities are commonly classified under the Harmonized System (HS) nomenclature (World Customs Organization, 1983). The HS nomenclature encodes each commodity under a 6-digit code, classifying them into chapters (2 digits), headings (4 digits), and subheadings (6 digits). Each trade flow is described through a set of information, including:

- the reporter, *i.e.*, the country that reports the trade flow;
- the partner, *i.e.*, the country with which the reporter trades;
- the period of reporting, *i.e.*, year of trade and, if reported monthly, month of trade;
- the type of trade flow, *i.e.*, import, export, re-import, re-export
- the product HS code and description
- the trade flow's net weight and traded value (in current US dollars)

Since its creation, the HS nomenclature has been updated approximately every five years. It currently comprises six editions (1996, 2002, 2007, 2012, 2017 and 2022). Each update to the HS nomenclature may result in changes to commodity codes. For instance, new products may be added, some products may be removed due to, for example, low trade volume, or a product may be specified more precisely and divided into several products.[8] Although there are corresponding tables between different editions of the HS nomenclature,

[7] The Python package "comtradeapicall" extracts and downloads UN Comtrade data through API calls.

[8] For instance, between the 2007 and the 2012 HS nomenclature editions, the product "Sawdust and wood waste and scrap, whether or not agglomerated in logs, briquettes, pellets or similar forms" (code 440130) was subdivided into "Wood pellets" (code 440131) and "Other sawdust and wood waste and scrap, whether or not agglomerated in logs, briquettes, pellets or similar forms" (code 440139).

tracking its evolution is difficult, and changes in product nomenclature can result in gaps in time series.

Furthermore, although the HS nomenclature provides a common language for trade in all commodities between more than 200 countries, it can lack relevance to industry sectors. Wood products, for example, may be grouped together with bamboo materials or plastic furniture in a single chapter. To ensure consistency, we base our extraction on the sector-specific 2022 FAO Classification of Forest Products (FAO, 2022), which provides corresponding tables between the FAO classification and the 2017 and 2022 HS nomenclatures. We extract the corresponding HS product codes for FAO code 012, "Wood in the rough other than wood fuel" (hereafter referred to as "roundwood"), and we ensure consistency between different HS codes across the successive editions of the HS nomenclature.[9] The correspondence between FAO product code 012 and HS product codes across successive HS nomenclature editions is provided in supplementary material X. All trade flows are then aggregated by HS product codes, enabling the analysis to focus on roundwood trade flows as defined by the FAO's Classification of Forest Products. This approach ensures the sectorial relevance and continuity of the time series for the analysis.

As country reports in the UN Comtrade database can be updated or corrected within two years, we collect trade data from 1996 to 2022 to base our analysis on consolidated data. We only extract data on imports and exports. We also remove poorly specified trade flows, *e.g.*, those with a "non-elsewhere specified" (NES) partners. Finally, to reduce the noise in the data and remove unrealistic trade flows,[10] we remove the 5% of trade flows with the lowest net weight or value from the dataset.

2.2. Trade network building from bilateral trade data

Based on this data, we define the roundwood trade network for each year by computing edge lists. In network theory, an edge list is a mathematical representation of a network, which is made up of nodes (*e.g.*, countries, individuals, or entities such as banks or websites) and edges or vertices (*e.g.*, the movement of goods or people between countries, physical interactions between people, or the exchange of information or money) (Albert and Barabási, 2002; Newman, 2003). An example of an edge list for a simple network is provided in Figure 1. In our case, the edge lists are $N \times 2$ matrices that correspond to a roundwood trade network with N edges in year t. Each edge represents a trade flow (either export or import) between nodes (countries), from the country of origin (*i.e.*, the exporter, indexed o), to the country of destination, (*i.e.*, the importer, indexed d), in year $t \in 1996, 1998, ..., 2022$. The elements of the edge list are nodes that represent countries that engaged in either the export or import of roundwood, in a given year t.

We take the roundwood trade network for each year of the data as a weighted and directed network, *i.e.*, we consider whether or not two countries are connected by trade, the direction of the trade flows, and the

[9]Data were extracted on June 2025.

[10]For example, unrealistic trade flows typically correspond to trade flows with a net weight of a few kilograms.

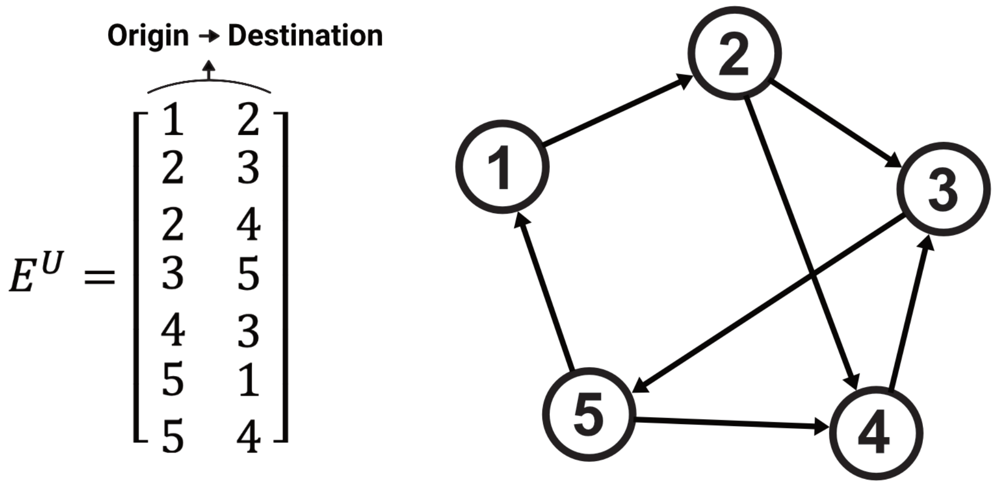

Figure 1: Illustration of an edge list, E^U, and its corresponding network graph for an *unweighted* and *directed* network of 5 nodes. In the edge list, each row corresponds to an edge from an origin (first column) to a destination (second column). In the network graph, circles indicate nodes and arrows the edges between them.

"weight" (or quantity/value) of the trade flows. In our case, we consider the traded value to be the "weight" of the trade flow. This is in contrast to using the net weight in metric tons, which is not an appropriate unit of volume for roundwood as the mass of the roundwood depends on its moisture content.[11] Due to data discrepancies, the reported trade value from the exporter and importer of the same trade flow may differ for at least two reasons: (1) import reports are expressed as "cost, insurance and freight" (CIF), while export reports are expressed as "free on board" (FOB), which excludes CIF costs from trade value, leading to bilateral asymmetries; (2) one of the trading partners may not report the trade (Gaulier and Zignago, 2010; Rougieux et al., 2017; Kallio and Solberg, 2018; Chen et al., 2022; Mitikj and Kaushik, 2024). To minimise the bias that such inconsistencies may cause, we consider both the exporter's and importer's reports of trade: $a_{o,d}$ and $a_{d,o}$, respectively. The edge list corresponding to the weighted, directed trade network is now a matrix of size $N \times 4$.[12] Each row represents a trade flow for a given year t, including the country of origin, the country of destination, and the trade values reported by the exporter and importer, as shown in Figure 2.[13] We therefore define 28 edge lists to describe the roundwood trade network for each year of trade.

[11]UN Comtrade data provides an alternative "quantity" variable (encoded *qty*)to the net weight of the trade flows. However, this variable is poorly reported: (i) units may differ depending on the reporter and range from cubic metres to metres to kilograms, and so on; (ii) the "quantity" variable is not recorded in 7.8% of the dataset.

[12]In fact, edge lists are close to mirror flows that can be derived from bilateral trade data, such as that provided by the UN Comtrade database.

[13]See Rayfield et al. (2011) and Thompson et al. (2017) for examples of this approach in ecological networks.

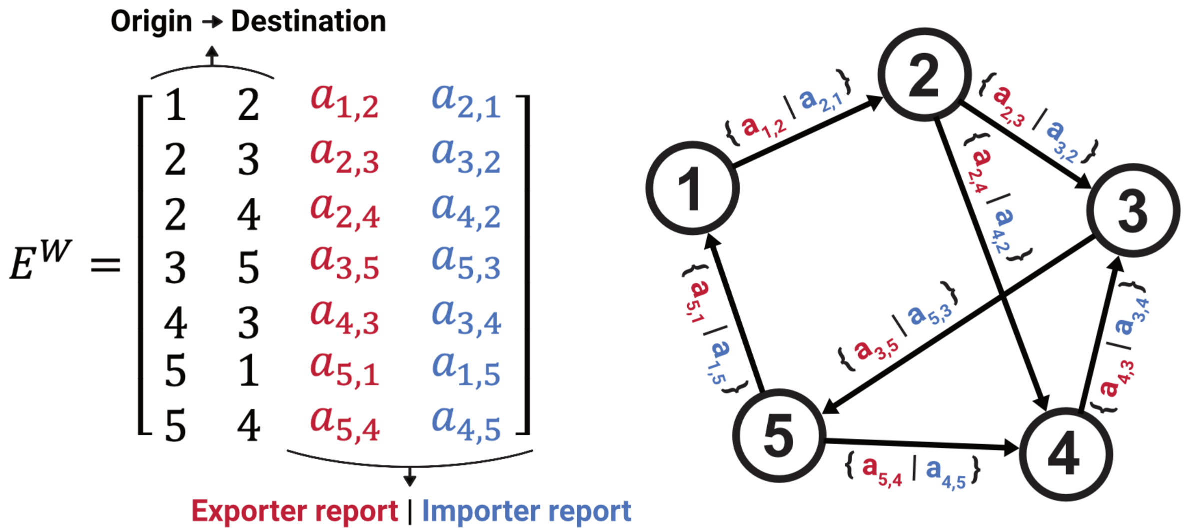

Figure 2: Illustration of an edge list, E^W, and its corresponding network graph for a *weighted* and *directed* trade network of 5 nodes. In the edge list, each row corresponds to an edge from an origin (first column) to a destination (second column) and include trade values reported by the country of origin (third column, red) and the country of destination (fourth column, blue). In the network graph, circles indicate nodes and arrows the edges between them.

2.3. Trade network properties assessment

Edge lists and any other network objects or raw visualisations are often difficult to read and interpret. Alone, they do not enable a thorough analysis of the structure of a trade network. In order to assess the structural characteristics of trade networks, we computed a series of network metrics for each year, differentiating between exports and imports.[14] The Python package “networkx” 3.4.2 (Hagberg et al., 2008) is used to facilitate the measurement network metrics.

First, we assess the composition of the trade network. For each year, we compute the total number of nodes in the network, *i.e.*, the total number of trading countries. These countries are then divided into three more detailed groups: pure exporters (countries that only export roundwood), pure importers (countries that only import roundwood) and mixed countries (countries that both export and import roundwood). To obtain more detailed information on the composition of the network, we then cross-reference the export and import values of each trading country accounting for at least 1% of to the global export or import value with the number of its export and import trading partners. This provides country trade profiles for each year, allowing trade behaviours and groups to be inferred and their evolution observed over time. This set of metrics provides a general overview of the roundwood trade network.

[14]Considering directed networks enables analysis from either the origin (exporter) or destination (importer) country perspective, allowing exporter or importer trade behaviour to be inferred.

Secondly, to understand the finer details of the network structure, we then computed a set of metrics that assess the connectivity of the trade network, *i.e.*, the mean, variance, skewness, and kurtosis of the number of connections per node (Albert and Barabási, 2002; Newman, 2003). Again, we assess network connectivity differentiating exports and imports. The mean number of connections per node, or node degree, is an average indicator of the degree of connectedness of the network. A high mean number of connections per node means that each country in the network has, on average, a high number of trading partners. The variance of the number of connections per node provides additional information about the dispersion of the number of connections. If the variance is close to zero, then the nodes in the network have more or less the same degree. A high variance indicates that the degree of connectivity of countries largely deviates from the mean. Skewness provides information about the proportion of low to highly connected nodes in the network. If the skewness is negative, the network consists of a higher proportion of highly connected nodes. Conversely, if the skewness is positive, then the network has a higher proportion of lowly connected nodes. Zero skewness implies an equal ratio of low to high connected nodes. Kurtosis provides information on how the degree distribution compares with a normal distribution in terms of its "tailedness" or "flatness". A positive kurtosis[15] indicates that tailed outliers are more prevalent than in a normal distribution, meaning countries that diverge from the mean are rare. Conversely, negative kurtosis corresponds to a situation in which outliers are common, *i.e.*, where most countries diverge from the mean.

Lastly, we assess market concentration by combining our network approach with a traditional Herfindahl-Hirschman market concentration index (HHI). The HHI is defined as follows:

$$HHI = \sum_{i=1}^{N} (MS_i)^2 \tag{1}$$

where N is the number of countries involved in trade and MS_i the market share of the country i, that is, the ratio of the value traded by country i to the global value traded. We computed two HHI, one for exports and one for imports. The HHI values can range from $1/N$ to 1. According to the HHI value, the US Federal Trade Commission differentiates three types of markets (U.S. Department of Justice and the Federal Trade Commission, 2010):

- An HHI between 0.01 and 0.15 corresponds to an unconcentrated market, *i.e.*, a market with no anti-competitive effects presumed;
- An HHI between 0.15 and 0.25 indicates a moderately concentrated market, *i.e.*, a market with potential or significant anti-competitive effects;

[15]We consider Fisher's definition of kurtosis. A Pearson's definition would have necessitated the comparison of kurtosis values with 3 instead of 0.

- An HHI greater than 0.25 indicates a highly concentrated market, *i.e.*, a market with presumption of anti-competitive effects.

To obtain a more detailed understanding of market concentration, we calculated each country's annual contribution to the global trade value, *i.e.*, the reduction in total trade value if a given country were removed from the network. This is equivalent to estimating the share of total trade value that "flows" through a given country in a particular year. Consequently, the sum of all countries' contributions does not add up to 100%, due to the bilateral nature of trade flows. This approach allows us to identify dominant countries in the roundwood trade. In cases of high market concentration, the removal of a dominant country is expected to result in a substantial loss in trade value.

Combining multiple complementary metrics offers a more comprehensive understanding of the network's structure than any single metric alone can provide (Shanafelt et al., 2017; Salau et al., 2022). For example, networks may have the same average number of connections but exhibit vastly different variances, resulting in markedly different topologies. Moreover, we consider our selected set of metrics sufficient for analyzing trade network structure, as many network metrics tend to be correlated (Baggio et al., 2011). The metrics used and their interpretations are summarized in Table 1.

2.4. Computational workflow and reproducibility

A sustainable data analysis workflow was undertaken using Snakemake 9.6.0 (Mölder et al., 2021). Snakemake is a workflow management system that ensures the reproducibility, adaptability, and transparency of the data analysis. This workflow is available on a GitHub repository,[16] which provides access to the analysis and version control (Braga et al., 2023).

3. Results

3.1. Composition of the trade network over time

Over the study period, the number of countries involved in the roundwood trade fluctuated slightly, ranging from 189 in 1997 to 214 in 2008 and 2015 (Figure 3). On average, 206 countries were involved in roundwood trade from 1996 to 2022. After a moderate increase in the number of countries involved in trade between 1996 and 2008 (an increase of 11.46%, from 192 to 214 countries), the number of countries stabilised until 2015. From 2015 to 2022, the number of trading countries decreased slightly from 214 to 198 (an 8.08% decrease). Aside from these trends, we found short-term slight decreases in the number of trading countries after 2008, 2015, 2019, and 2021, which, as we will discuss later, can likely be attributed to major global events. In

[16]GitHub repository address: https://github.com/vlmathieu/trade_network_analysis

Table 1: List of the metrics used to describe the trade network and their interpretation.

Network metrics	Interpretation
Trade network composition	
Number of nodes	Number of countries involved in trade.
Number of pure exporter	Number of countries that only export roundwood.
Number of pure importer	Number of countries that only import roundwood.
Number of mixed countries	Number of countries that both export and import roundwood.
Country profiles	Trade behaviour of countries in relation to exports and imports.
Trade network connectivity	
Mean number of connections per node	Average number of trading partners per country; indicator of the overall connectedness of the network.
Variance in the number of connections per node	Variation in the number of trading partners relative to the mean.
Skewness in the number of connections per node	Proportion of low to highly connected countries in the network.
Kurtosis in the number of connections per node	Scarcity or abundance of countries that diverge from the mean connectivity.
Market concentration	
Herfindahl-Hirschman index	Market concentration in the trade of roundwood.
Country contributions to trade value	Share of total trade value that 'flows' through a given country.

addition, we can observe several trends in the share of pure exporters, pure importers, and countries that both export and import roundwood. The number of pure exporters has decreased markedly since 1996, falling from 17 to 7 (a decline of around 59%). In 2022, pure exporters represented only 3% of trading countries compared to an average of 6.2% over the studied period. In contrast, the number of pure importers decreased from 51 to 38 between 1996 and 2007 (a decline of 25%), before rising again to 60 between 2007 and 2015 (an increase of 58%). Since 2015, there has been a moderate decrease to 44 countries (a fall of 27%). In 2022, pure importers represented a larger share (21%) of trading countries than pure exporters (23.2% on average over the study period). Throughout the years, there were consistently more pure importers than pure exporters engaged in the international trade of roundwood, with an average difference of 35 countries. The number of countries that both export and import roundwood ("mixed countries") constituted the vast majority of trading countries (70.6% on average over the studied period, 69% in 2022). The number of mixed countries has increased moderately since 1996, rising from 124 to 147 (an increase of around 19%). As for the total number of trading countries, we noticed short terms drops in the number of pure exporters, pure importers, and mixed countries over the studied period. Some drops are common to pure importers and mixed countries (*e.g.*, following 2008 and 2019), while others are group-specific (*e.g.*, following 1997 for pure exporters and 2001 for pure importers).

While 200 countries were involved in the global roundwood trade in 2020, only 31 countries (15.5% of the total) contributed to at least 1% of the export or import value (Figure 4). This suggests a certain degree of market concentration in the trade of roundwood. These 31 countries showed different behaviours, and we identified roughly three groups. First, Asian countries, namely China, India, Japan, the Republic of Korea and Vietnam, form a group of importers. Importers have a higher trade value for imports than for exports and have diversified their import connections more than their export connections. Second, several countries belong to the group of exporters. Their export value is higher than their import value, they have a higher number of export partners compared to their import partners, but their number of export trading partners varies. While Papua New Guinea only export to a limited number of 13 countries, net exporters such as Australia, New Zealand, Congo, Cameroon, Brazil and the Russian Federation, have moderately diversified their number of export trading partners (between 20 and 45). New Zealand,the USA, and the Russian Federation stand out as the world's three largest suppliers of roundwood. In particular, the USA shows a unique export pattern with a high diversification of its export trading partners (95 export connections). Finally, we can draw a third group of countries that tend to export as much as they import in trade value, with a balanced number of exporting and importing partners. This group is mainly made up of European countries but also includes countries such as Canada and Malaysia.

The trade situation has changed significantly between 2000 and 2020 (Figure 4). In 20 years, China has overtaken Japan as the main importer of roundwood. Japan's import value decreased dramatically from

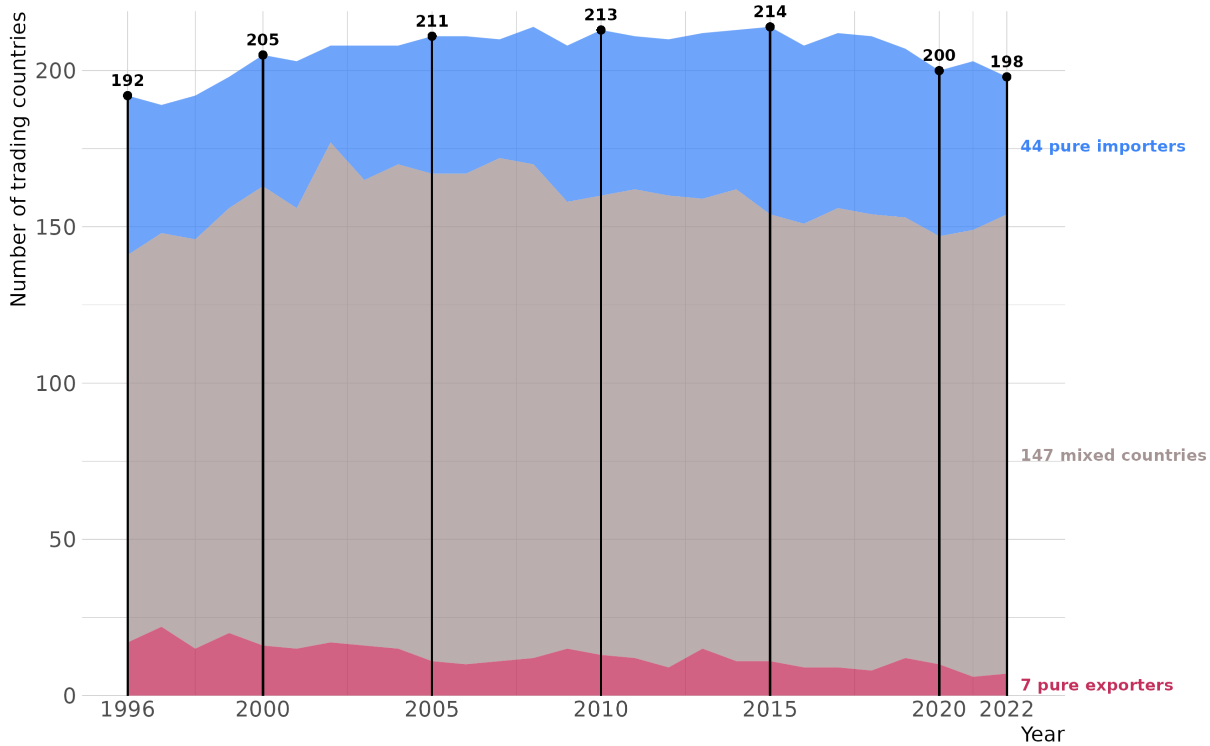

Figure 3: Number of trading countries in total and per group: pure exporters (red), pure importers (blue), mixed countries (grey); for each year of trade.

more than \$2.33 billion in 2000 to about \$562 million in 2020, a decrease of 76%. On the other hand, China's import value increased considerably from more than \$1.654 billion in 2000 to more than \$8.376 billion in 2020, an increase of about 406%. Surprisingly, the number of China's export trading partners increased sharply by about 133% between 2000 and 2020 (32 new export trading partners), while the value of Chinese export trade decreased by more than \$1.2 million on the same period (a decline of about 16%), which seems unlikely. In terms of trade value, New Zealand has emerged as the world's top exporter of roundwood, while maintaining a relatively stable number of trading partners. Although the USA and the Russian Federation remained major exporters of roundwood, they appeared to be less integrated into global roundwood trade. Between 2000 and 2020, the USA has lost a large share of its trading partners to import (a fall of 42%), while slightly reducing its export diversification (a fall of only 8%). Similarly, the Russian Federation lost 14 export trading partners (25%) and 6 import trading partners (46%) in the same period.

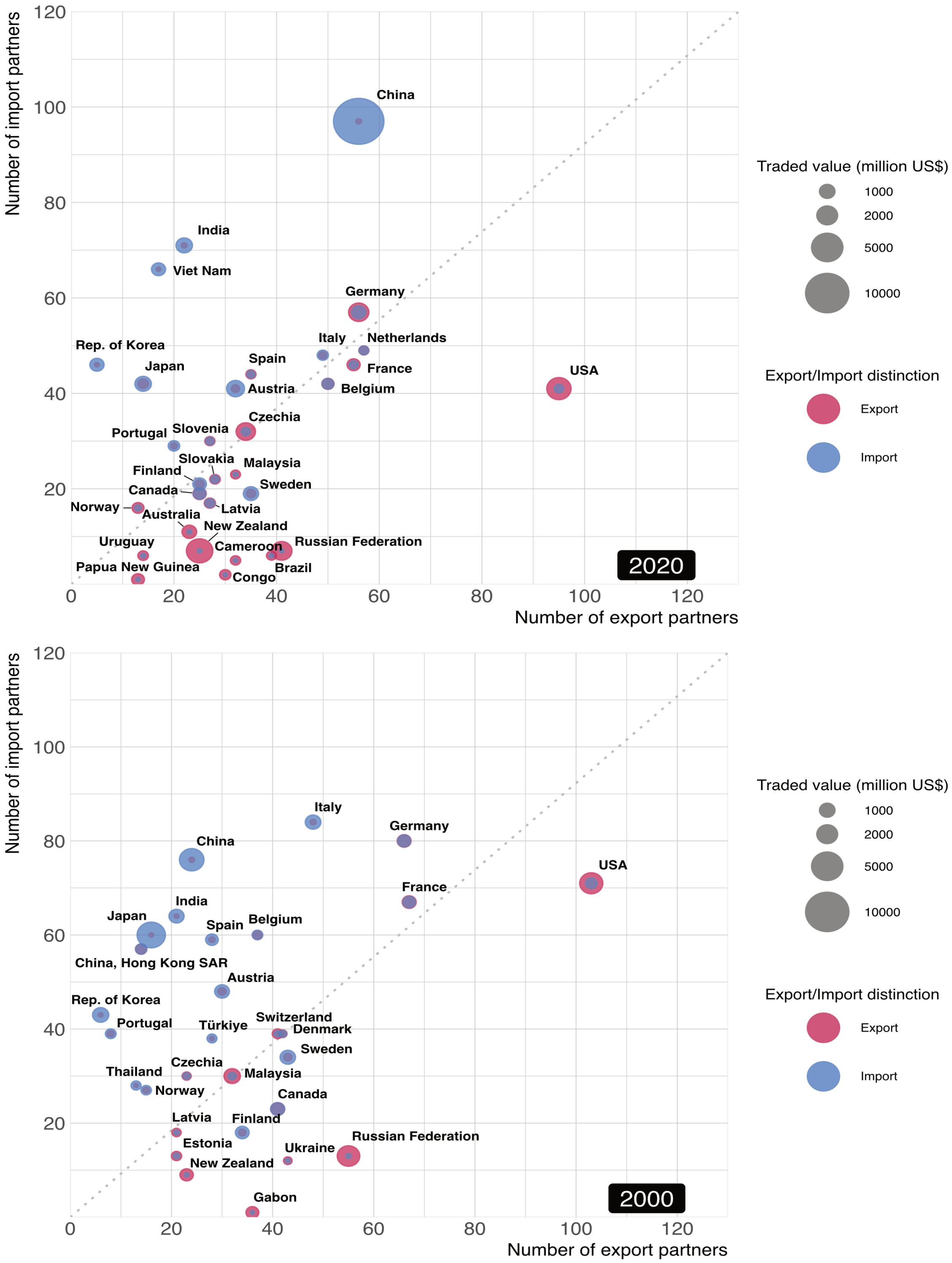

Figure 4: Bubble graph showing the profiles of trading countries in 2020 (top) and in 2000 (bottom). Countries are displayed according to the number of partners with whom the trade exports and imports. The size of the bubbles increases with the value of trade. Blue bubbles refer to imports and red bubbles refer to exports. Only countries accounting for at least 1% of the value of exports or imports in 1996 or 2022 are shown.

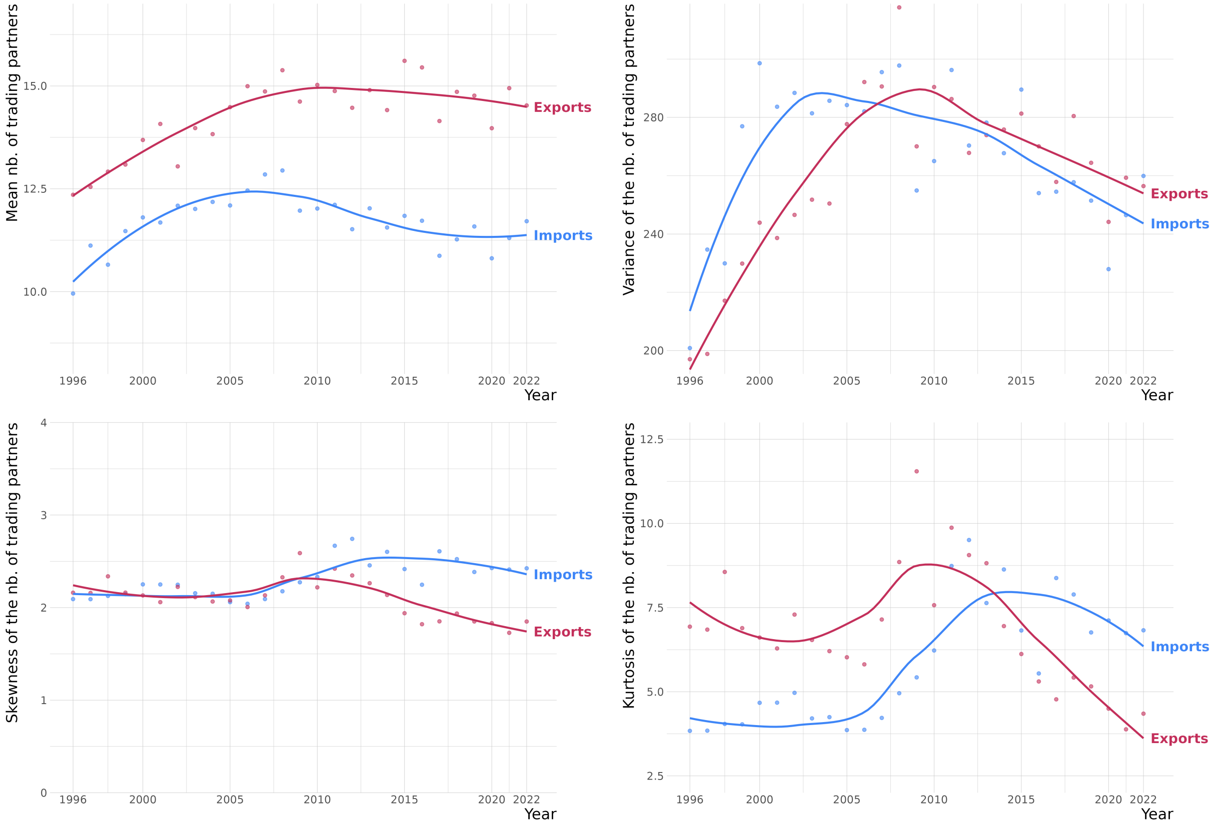

Figure 5: Mean number (top left), variance (top right), skewness (bottom left), and kurtosis (bottom right) of the connections per node. Metrics concerning exports are plotted in red, metrics concerning imports are plotted in blue. Smooth curve is based on a Loess function to highlight trends in the metrics.

3.2. Connectivity of the trade network over time

Results for mean, variance, skewness, and kurtosis of the connections per country are presented in Figure 5. Three general observations can be made regarding the average number of connections per country over time. Firstly, both exporters and importers of roundwood observed an increase in their mean connectivity during the first half of the study period (from 1996 to 2008). During this period, mean connectivity of exporters increased by 25% for exporters (from 12.4 to 15.4 connections per exporter), while that of importers increased by 30% (from 10 to 12.9 connections per importer). The average number of connections per country then stabilised for exporters. Conversely, mean connectivity of importers decreased by 9% (from 12.9 to 11.7 connections per importer) from 2008 to 2016 and has since stabilised. Secondly, exporters were, on average, 22% more connected than importers throughout the study period (14.3 connections per exporter versus 11.7 connections per importer). The gap widened between the first and second halves of the study period (17% between 1996 and 2008, 27% between 2008 and 2022). Thirdly, aside from general trends, short-term increases and decreases in mean connectivity were observed from year to year, with some shared by both by exporters and importers. For example, mean connectivity of both exporters and importers dropped in the years following 2008, 2016, and 2019.

The variance in the number of connections per node provides additional information on how the connectivity of each country diverges from the overall average. Overall, we observe higher variance in connectivity per country for exporters and importers. Exporters and importers comprise countries with a wide range of trading partners, some of which have a significantly lower number of connections than average (poorly connected countries), while others have a significantly higher number of connections than average (highly connected countries). Variance in the connectivity per country increased for importers from 1996 to 2003 and for exporters until 2010, before decreasing until 2022. Between 1996 and 2005, variance in connectivity per country was, on average, higher for importers than for exporters. This suggests that, during this time period, importers showed greater spread in connectivity compared to the mean. After 2005, exporters and importers displayed similar variances in connectivity. Similar short-term increases and decreases to those observed in mean connectivity per node were seen in the variance from year to year.

Skewness provides information about the distribution of highly and poorly connected nodes within a network. Skewness in connections per country is always positive for both exporters and importers, indicating a greater proportion of countries with low to high connectivity. It remained stable on average for both exporters and importers between 1996 and 2005, followed by an increase until 2010 for exporters and until 2013 for importers. Until 2010, the degree of skewness in connectivity was similar for exporters and importers. Since 2010, the skewness in connectivity has become, on average, higher for importers than for exporters, has slightly increased for importers and has decreased moderately for exporters. That is, there was a greater proportion of poorly connected countries among importers than among exporters, which supports and complements our findings regarding the mean number of connections.

Kurtosis indicates whether countries diverge from the mean connectivity in a scarce or abundant manner. During the study period, kurtosis of connections per country remained positive for both exporters and importers. This suggests that countries whose connectivity diverges from the mean connectivity are rarer than those whose connectivity is close to the mean. From 1996 to 2014, skewness of connectivity was higher for exporters than for importers, meaning that exporters diverging from the mean connectivity were, on average, rarer than importers. The reverse was true after 2014. Until 2022, kurtosis of connectivity decreased, while remaining positive. This fall is steeper for exporters than for importers. As with our other network metrics, we observed several short-term fluctuations in skewness and kurtosis over time from year to year, though these were less pronounced.

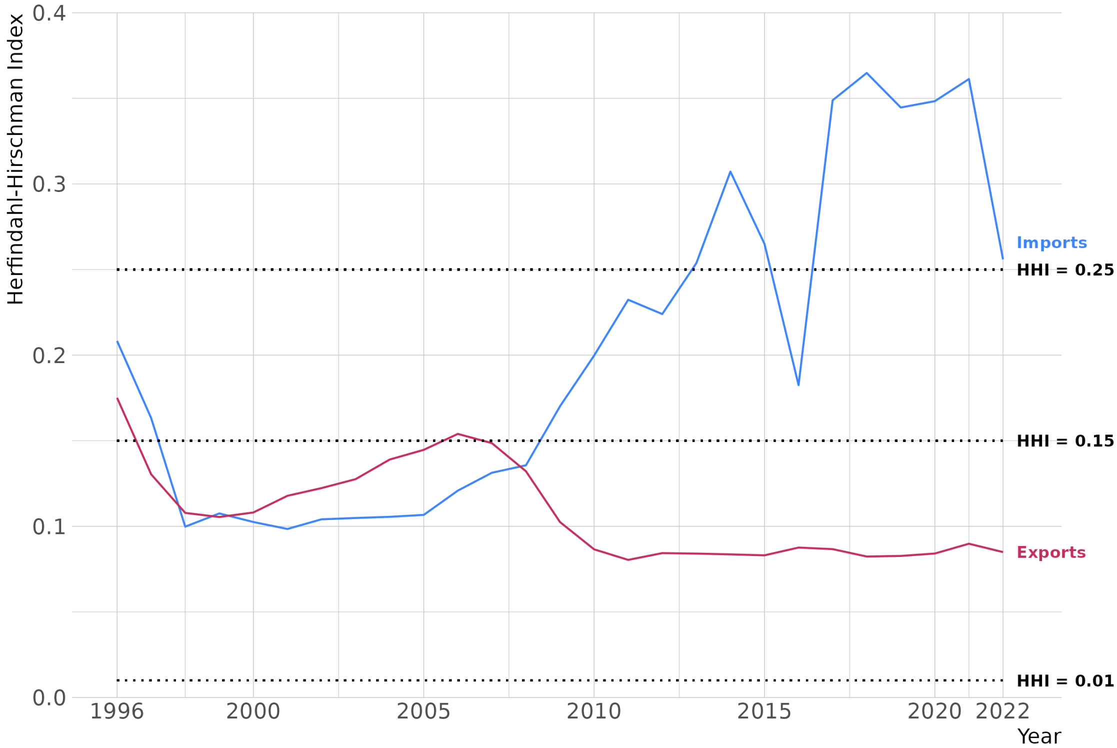

Figure 6: Herfindahl-Hirschman index values over time. Index related to exports are displayed in red, those related to imports in blue.

3.3. Market concentration in roundwood trade over time

Between 1996 and 1998, the Herfindahl-Hirschman Index (HHI) initially fell for both exports (a decline of 38%, from 0.18 to 0.11) and imports (a decline of 52%, from 0.21 to 0.1) indicating a rapid shift from moderate to low market concentration in roundwood trade (Figure 6). This decline was followed by an increase in the HHI for exporters until 2006, reaching a HHI of 0.15, before falling again until 2011 and reaching a HHI of 0.08. Market of roundwood exports then remained stable and lowly concentrated until 2022, with an average HHI of 0.08 since 2011. In contrast, market concentration of roundwood imports increased sharply, becoming moderately concentrated after 2009 (HHI of 0.17) and highly concentrated after 2013 (HHI of 0.25). After a steep decline from a HHI of 0.26 to 0.18 between 2015 and 2016, market concentration level recovered the following year to reach a HHI of 0.35. From 2017 to 2021, imports remained highly concentrated, with an average HHI of 0.35, before falling to 0.26 in 2022. On average, over the last decade, imports have remained highly concentrated, whereas exports have remained lowly concentrated for 26 years.

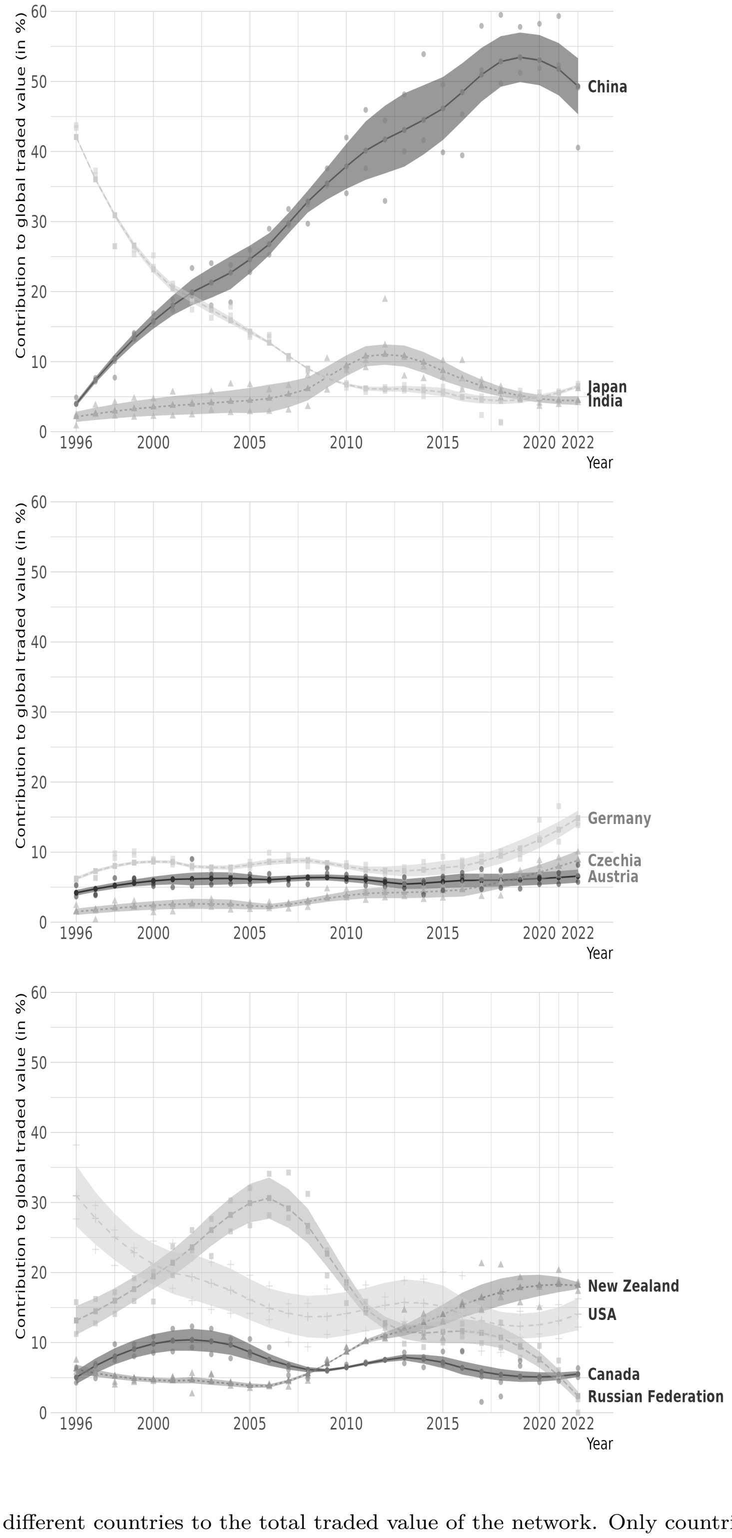

Figure 7: Contribution of different countries to the total traded value of the network. Only countries that have contributed to more than 5% of the total traded value at least once during the study period are shown. The envelope corresponds to the uncertainty in the reported values. Contributions are displayed by group of countries: importers (top); mixed countries (middle); and exporters (bottom).

Contributions from individual countries to the total network trade value provide a more detailed picture of market concentration (Figure 7). These contributions correspond to the proportion of the network's total trade value that would be lost if a particular country is omitted from the network, *i.e.*, the proportion of total trade value flowing through that country. Over the study period, only ten countries contributed at least 5% to the network's total trade value once. Referring to Figure 4, main contributors to the total trade value can be divided into three groups: importers (China, India and Japan); European countries (Germany, Czechia and Austria); and traditional wood exporters (Canada, New Zealand, the Russian Federation, and the USA).

Among importers, Japan's share of total trade value decreased considerably from around 44% in 1996 to less than 7% in 2022. On the other hand, India's contribution increased steadily from around 2% in 1996 to around 16% in 2012, after decreasing to 5% in 2022. Most notably, China's share of the total trade value increased sharply, from around 4% in 1996 to more than 56% in 2021, before decreasing to 45% in 2022. Together with results from Figures 4 and 6, this indicated that around 56% of the total trade value flowed through China in 2021 due to its imports, which is consistent with the high level of market concentration in roundwood imports in over the past decade.

Among European countries, on average, the contribution of Germany and the Czech Republic increased steadily from around 6% and 2% in 1996 to around 14% and 8% in 2022, respectively. In contrast, Austria's contribution rose only slightly from around 4% to 7% over the same period. These levels of contribution remain relatively low compared to those of main importers such as China.

Among exporters, the contribution of the USA significantly decreased over the studied period, falling from 33% in 1996 to 13% in 2007. It then stabilized at an average of around 13.7% over the 2007-2022 period. Canada's contribution to total trade value increased from 5% in 1996 to 11% in 2002, before decreasing to 6% in 2007. It has remained stable since then, averaging around 6.2%. By contrast, New Zealand's contribution initially slightly fell from 7% in 1996 to 4% in 1998, then stabilised at an average of around 4.4% between 1998 and 2008, before rising significantly to 18% in 2022. On the other hand, Russia exhibits a unique pattern of varying contributions to the total trade value throughout the studied period. Initially, Russian contributions increased from 13% in 1996 to 31% in 2007, before dropping sharply to 12% in 2012. This figure then stabilised at an average of around 11.4% between 2012 and 2018, before dropping again to below 1% in 2022. This correlates with findings presented in Figure 4, which suggests that Russian trade integration has decreased over time. Except for Russia, which appears to be influenced by short-term shocks, all contributors to the roundwood trade exhibit long-term variations in their contribution.

4. Discussion

Contrary to our expectations, the global roundwood trade network demonstrated significant resilience to exogenous disruptions. Rather than major short-term shifts, the network continued its long-term trend toward a greater concentration and polarization around China, whose market power has grown substantially in recent decades.

We found that while the number of countries participating in the roundwood trade network remained relatively stable, its composition changed significantly, with countries engaging more in both imports and exports (Figures 3, 4). The network's connectivity tightened at the turn of the 21st century (Figure 5), a trend consistent with broader globalization (Prestemon et al., 2003).

Our analysis of network connectivity further revealed a consistent structure: a few highly-connected countries (the hubs) dominate trade, a pattern that sharply diverges from the network's low overall mean connectivity (Figure 5). These hubs play a critical role in the network's functionality (Huang et al., 2024), and potentially have huge market power. Many of the major hubs in the international market, such as the USA, Canada, Western Europe, Scandinavia, and Russia, maintained a high number of trading partners throughout the study period.

However, our findings also highlight a significant shift in the trade landscape over recent decades. We observed a decline among traditional core importers and exporters, including Japan, Russia, and the USA, concurrent with the rise of new key players like China and New Zealand (Figures 4, 7). China, in particular, has become *the* central player in the roundwood trade, substantially increasing its number of import and export partners. By 2021, China's imports accounted for 56% of the total roundwood trade value, leading to a highly concentrated and polarized import market (Figures 6, 7). This confirms findings from other studies (Long et al., 2019; Zhou et al., 2021; Shen and Lovrić, 2022; Huang et al., 2024).

This could appear as a paradox: despite forest resources being geographically concentrated in a few countries, the roundwood export market is not similarly concentrated. Instead, the import market is highly concentrated, primarily due to demand from China, which paradoxically also possesses the fifth-highest forest endowment and presents the first-highest average annual net gain in forest area (FAO, 2024b). Indeed, due to Chinese government efforts in spending, as well as China's market and policy reforms driven by forest conservation demand, China has operated an drastic expansion of its forestry and planted forest extensive margins over the last decades (Démurger et al., 2009; Zhang, 2019; Zhao et al., 2022). However, despite an increase in China's forest area and volume, low economic tree planting efficiency and poor forest management have resulted in low stand quality and growth rates (Hoffmann et al., 2018; Hou et al., 2019; Zhang, 2019). As a result, domestic timber consumption — primarily for industrial and construction uses — has outpaced domestic production, making China highly dependent on imported wood products, which now account for approximately half of its total timber supply (Démurger et al., 2009; He and Xu, 2011; Hoffmann et al., 2018; Hou et al., 2019).

This overall suggests that roundwood trade flows are predominantly demand-driven rather than supply-pushed. In the case of China, the primary use of wood for industrial and construction uses (Hou et al., 2019) echoes the role of population and urbanization in shaping demand for materials, which has been identified in the literature (UNECE/FAO, 2021; Mathieu and Roda, 2023; Villamor et al., 2024). Explain a bit more, suggest that this will mechanically attract wood trade flows to regions that are increasing in population and getting urbanised, such as Africa and Asia. Explain that while these regions are (becoming) centers of gravity for wood trade flows, the role of countries may shift. In particular, China seems to initiate a decline in 2022 (Figure 7) which could announce the beginning of new phase in the development of the international trade of roundwood. Such decline may be relative to the building of more comprehensive domestic supply chains or to structural mutation, such as the ageing of the Chinese population and the industrial crisis.

Our findings reveal that the network's excessive reliance on China is a key feature, as its demand drives trade flows and influences global roundwood resource allocation (Huang et al., 2024). China's market power is significant enough to exacerbate disruption risks for less-connected countries, redirect trade flows in a competitive environment, and foster trade co-dependence. In fact, China serves as the main trading partner for most major exporters, making them highly reliant on its demand. For example, in 2020, China imported 46% of roundwood exports from the USA, 67% from Russia, 77% from Congo, 78% from Papua New Guinea, and 86% from New Zealand. The case of New Zealand perfectly illustrates this co-dependence. Its rise as a major exporter is closely tied to China's increasing demand. The share of New Zealand's roundwood exports to China surged from just 1.2% in 1996 to 89.3% in 2022. This increasing co-dependence raises concerns about a potential "after-China" era for these exporters (Villamor et al., 2024): where would their roundwood go if not to China? To mitigate risks from potential disruptions caused by hubs like China or to limit co-dependence, countries can diversify their trade relationships (Huang et al., 2024). The United States appears to have pursued this strategy throughout the study period, as shown in our results (Figure 4).

While we expected the network to exhibit structural sensitivity to exogenous disruption events, we found that the roundwood trade network was rather resilient to such disruptions and has followed long-term trends over the past decades. Certainly, the network structural metrics showed low to moderate sensitivity to shocks and disruptions. The number of pure exporters, pure importers, and mixed countries, showed slight short-term drops over the studied period (Figure 3). Short-term increases and decreases in connectivity metrics were also observed from year to year. Yet, such shocks seems to only impact the network structure on the short-term, "From 2002 to 2021, China became a superpower in importing upstream wood forest products, ranking first in import volume [...] This achievement indicates that China was highly dependent on wood imports and had strong resistance and recovery capabilities to deal with shocks."

By considering multiple network metrics, we obtain a clearer picture of the evolution of the network's structure than using a single metric alone (Shanafelt et al., 2017; Salau et al., 2022). The mean number of connections gives us a global measure of network connectivity, but tells nothing of the distribution of connections throughout the network. By measuring variance, skewness, and kurtosis we observed changes in the variation of connections per node, the proportion of poorly to highly-connected nodes, and the scarcity or abundance of countries that diverge from the mean connectivity over time. As a complement to traditional market concentration indexes, measuring a country's contribution to traded value provides a detailed overview of each trader's relative market power. It is crucial to recognize that network analysis should not be viewed as a replacement for traditional methods but rather as a powerful complement. It offers a macro-level, systemic perspective that can inform and enrich the micro-level insights derived from econometric models or the aggregate flow analyses from gravity models. Such multi-methodological approach would allow to leverage the strengths of each technique, leading to a more holistic and robust understanding of complex trade phenomena.

However, our results show that, despite the powerful explanatory capacity of network analysis, the quality of the underlying trade data is paramount. The validity and interpretability of the results are directly influenced by the accuracy, completeness, and consistency of the data, as pointed out in the literature (Lovrić et al., 2018; Wang et al., 2020; Zhou et al., 2021; Huang et al., 2024). While network analysis partly deals with data discrepancies by simultaneously taking into account exports and imports, it reveals data discrepancies such as inconsistent reporting, missing values, and outliers (Kallio and Solberg, 2018; Chen et al., 2022). Hence, our results showed that China exported to 32 more countries in 2020 compared to 2000, while simultaneously reporting a decrease of $1.2 million in export value on the same period (a decline of about 16%), which seems unlikely (Figure 4). This further highlights the caution that should be brought by modelers and data scientists when analysing bilateral trade data, while emphasizes the need for methods to process trade data and correct quality issues or for harmonized and consistent data [Gaulier and Zignago (2010); rougieux2017forest].

Similarly, our results suggest that the country-level perspective is not always the most relevant in trade analysis. In particular, results highlight the singular trade balance of many European countries, which export as much roundwood as they import. This would suggest to rather consider the European Union as a whole, in order to get a clear vision that is not blurred by individual European countries behaviours and that will better reflect the trade weight of the European continent.

Network analysis capture complexity and describe its organisation but further exploration of the determinants and dynamics are necessary to understand what rule complexity organisation. “To comprehensively analyze the resilience of the global wood and forest products trade network, future research is required to refine and improve the construction of indicator systems.”

5. Conclusion

Declaration of generative AI and AI-assisted technologies in the writing process During the preparation of this work the author(s) used [NAME TOOL / SERVICE] in order to [REASON]. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

References

Abman, R., Lundberg, C., 2020. Does free trade increase deforestation? the effects of regional trade agreements. Journal of the Association of Environmental and Resource Economists 7, 35–72.

Albert, R., Barabási, A.L., 2002. Statistical mechanics of complex networks. Reviews of modern physics 74, 47.

Amador, J., Cabral, S., 2017. Networks of value-added trade. The World Economy 40, 1291–1313.

Apeti, A.E., N’doua, B.D., 2023. The impact of timber regulations on timber and timber product trade. Ecological Economics 213, 107943.

Baggio, J.A., Salau, K., Janssen, M.A., Schoon, M.L., Bodin, Ö., 2011. Landscape connectivity and predator–prey population dynamics. Landscape Ecology 26, 33–45.

Boubacar, I., Sissoko, Y., 2025. Sustainable forest management through certification and wood products trade: Analyzing the role of the fsc across diverse economic and climatic contexts. Journal of Cleaner Production , 145786.

Braga, P.H.P., Hébert, K., Hudgins, E.J., Scott, E.R., Edwards, B.P., Sánchez Reyes, L.L., Grainger, M.J., Foroughirad, V., Hillemann, F., Binley, A.D., et al., 2023. Not just for programmers: How github can accelerate collaborative and reproducible research in ecology and evolution. Methods in Ecology and Evolution 14, 1364–1380.

Buongiorno, J., 1996. Forest sector modeling: a synthesis of econometrics, mathematical programming, and system dynamics methods. International Journal of Forecasting 12, 329–343.

Buongiorno, J., 2015. Global modelling to predict timber production and prices: the gfpm approach. Forestry: An International Journal of Forest Research 88, 291–303.

Buongiorno, J., 2016. Gravity models of forest products trade: Applications to forecasting and policy analysis. Forestry 89, 117–126.

Buongiorno, J., Johnston, C., 2018. Potential effects of us protectionism and trade wars on the global forest sector. Forest Science 64, 121–128.

Caurla, S., Delacote, P., Lecocq, F., Barkaoui, A., 2013. Stimulating fuelwood consumption through public policies: An assessment of economic and resource impacts based on the french forest sector model. Energy Policy 63, 338–347.

Chen, C., Jiang, Z., Li, N., Wang, H., Wang, P., Zhang, Z., Zhang, C., Ma, F., Huang, Y., Lu, X., et al., 2022. Advancing un comtrade for physical trade flow analysis: review of data quality issues and solutions. Resources, Conservation and Recycling 186, 106526.

Chen, J., Wang, L., Li, L., Magalhães, J., Song, W., Lu, W., Xiong, L., Chang, W.Y., Sun, Y., 2020. Effect of forest certification on international trade in forest products. Forests 11, 1270.

Curtis, P.G., Slay, C.M., Harris, N.L., Tyukavina, A., Hansen, M.C., 2018. Classifying drivers of global forest loss. Science 361, 1108–1111.

De Benedictis, L., Tajoli, L., 2011. The world trade network. The World Economy 34, 1417–1454.

Démurger, S., Yuanzhao, H., Weiyong, Y., 2009. Forest management policies and resource balance in china: an assessment of the current situation. The Journal of Environment & Development 18, 17–41.

FAO, 2022. Classification of forest products 2022. Rome.

FAO, 2024a. Global forest products facts and figures 2023. FAO, Rome. URL: https://doi.org/10.4060/cd3650en.

FAO, 2024b. The State of the World's Forests 2024 – Forest-sector innovations towards a more sustainable future. FAO, Rome. URL: https://doi.org/10.4060/cd1211en.

Fèvre, E.M., Bronsvoort, B.M.d.C., Hamilton, K.A., Cleaveland, S., 2006. Animal movements and the spread of infectious diseases. Trends in microbiology 14, 125–131.

Gao, L., Pei, T., Tian, Y., 2024. Trade Creation or Diversion?—Evidence from China's Forest Wood Product Trade. Forests 15, 1276. URL: https://www.mdpi.com/1999-4907/15/7/1276, doi:10.3390/f15071276.

García-Jácome, S.P., Jankovskỳ, M., Hoeben, A.D., Lindner, M., Uzquiano, S., Stern, T., Nuhlíček, O., Vuletić, D., Marjanović, H., Picos, J., et al., 2025. Forest value chain resilience from a local perspective in five european countries: analysis of predictors and co-drivers. Frontiers in Forests and Global Change 7, 1461932.

Gaulier, G., Zignago, S., 2010. BACI: International Trade Database at the Product-Level. The 1994-2007 Version. Working Papers 2010-23. CEPII. URL: https://www.cepii.fr/CEPII/fr/publications/wp/abstract.asp?NoDoc=2726.

Guan, Z., Ip Ping Sheong, J.K.F., 2019. The restricting effects of forest certification on the international trade of wood products. Journal of Sustainable Forestry 38, 809–826.

Guan, Z., Yang, Y., 2024. The impact of changes in russian log export tariffs on china's log imports. International Wood Products Journal 15, 119–127.

Hagberg, A.A., Schult, D.A., Swart, P.J., 2008. Exploring network structure, dynamics, and function using networkx, in: Varoquaux, G., Vaught, T., Millman, J. (Eds.), Proceedings of the 7th Python in Science Conference, Pasadena, CA USA. pp. 11 – 15.

He, H., Xu, J., 2011. Projection of timber supply and demand trends in china based on an econometric model. Forest Products Journal 61, 543–551.

Hoffmann, S., Jaeger, D., Shuirong, W., 2018. Adapting chinese forest operations to socio-economic developments: what is the potential of plantations for strengthening domestic wood supply? Sustainability 10, 1042.

Hou, J., Yin, R., Wu, W., 2019. Intensifying forest management in china: what does it mean, why, and how? Forest Policy and Economics 98, 82–89.

Huang, X., Wang, Z., Pang, Y., Tian, W., Zhang, M., 2024. Static Resilience Evolution of the Global Wood Forest Products Trade Network: A Complex Directed Weighted Network Analysis. Forests 15, 1665. URL: https://www.mdpi.com/1999-4907/15/9/1665, doi:10.3390/f15091665.

Johnston, C.M., van Kooten, G.C., 2017. Impact of inefficient quota allocation under the canada-us softwood lumber dispute: A calibrated mixed complementarity approach. Forest policy and economics 74, 71–80.

Kallio, A.M.I., Moiseyev, A., Solberg, B., et al., 2004. The global forest sector model EFI-GTM—the model structure. Internal Report. European Forest Institute.

Kallio, A.M.I., Solberg, B., 2018. On the reliability of international forest sector statistics: problems and needs for improvements. Forests 9, 407.

Kim, D.H., Ahn, B.I., Shim, G., 2024. Analyzing the impact of eu's legality requirements policies on sustainable timber and sawnwood trade—focusing on tropical wood trade. Forests 15, 1879.

van Kooten, G.C., Johnston, C., 2014. Global impacts of russian log export restrictions and the canada–us lumber dispute:

Modeling trade in logs and lumber. Forest policy and economics 39, 54–66.

Latta, G.S., Sjølie, H.K., Solberg, B., 2013. A review of recent developments and applications of partial equilibrium models of the forest sector. Journal of Forest Economics 19, 350–360.

Lawson, Sam and MacFaul, Larry, 2010. Illegal logging and related trade: Indicators of the Global Response. Technical Report. Chatham House (The Royal Institute of International Affairs). London.

Leblois, A., Damette, O., Wolfersberger, J., 2017. What has driven deforestation in developing countries since the 2000s? evidence from new remote-sensing data. World Development 92, 82–102.

Li, R., Buongiorno, J., Zhu, S., Turner, J., Prestemon, J., 2007. Potential economic impact of limiting the international trade of timber as a phytosanitary measure. International Forestry Review 9, 514–525.

Lin, Y., Zhang, D., 2017. Incidence of russian log export tax: A vertical log-lumber model. Journal of Forest Economics 29, 69–77.

Liu, D., Yang, Z., Qin, K., Li, K., 2025. Spatial-temporal analysis of the international trade network. Geo-spatial Information Science , 1–29.

Liu, L., Chen, Y., Yu, J., Cheng, R., 2024. Analysis of the Trade Network of Global Wood Forest Products and its Evolution from 1995 to 2020. Forest Products Journal 74, 121–129. URL: https://fpj.kglmeridian.com/view/journals/fpro/74/2/article-p121.xml, doi:10.13073/FPJ-D-23-00065.

Long, T., Pan, H., Dong, C., Qin, T., Ma, P., 2019. Exploring the competitive evolution of global wood forest product trade based on complex network analysis. Physica A: Statistical Mechanics and its Applications 525, 1224–1232. URL: https://www.sciencedirect.com/science/article/pii/S0378437119305436, doi:10.1016/j.physa.2019.04.187.

Lovrić, M., Da Re, R., Vidale, E., Pettenella, D., Mavsar, R., 2018. Social network analysis as a tool for the analysis of international trade of wood and non-wood forest products. Forest Policy and Economics 86, 45–66. URL: https://www.sciencedirect.com/science/article/pii/S1389934117302198, doi:10.1016/j.forpol.2017.10.006.

Ma, C., Zhang, L., Gao, X., Liu, C., 2025. Modelling and evaluating wood supply chain resilience factors based on system dynamics. Scientific Reports 15, 16207.

Mathieu, V., Roda, J.M., 2023. A meta-analysis on wood trade flow modeling concepts. Forest Policy and Economics 149, 102930.

Mitikj, S., Kaushik, S.V., 2024. Bridging the Gap in Trade Reporting: Insights from the Discrepancy Index. Technical Report. The World Bank.

Mölder, F., Jablonski, K.P., Letcher, B., Hall, M.B., Tomkins-Tinch, C.H., Sochat, V., Forster, J., Lee, S., Twardziok, S.O., Kanitz, A., et al., 2021. Sustainable data analysis with snakemake. F1000Research 10, 33.

Moral-Pajares, E., Martínez-Alcalá, C., Gallego-Valero, L., Caviedes-Conde, Á.A., 2020. Transparency index of the supplying countries' institutions and tree cover loss: Determining factors of eu timber imports? Forests 11, 1009.

Muhammad, A., Jones, K.G., 2021. The end of the trade war? effects of tariff exclusions on us forest products in china. Forest Policy and Economics 122, 102350.

Müller, D.B., Bader, H.P., Baccini, P., 2004. Long-term coordination of timber production and consumption using a dynamic material and energy flow analysis. Journal of Industrial Ecology 8, 65–88.

Newman, M.E., 2003. The structure and function of complex networks. SIAM review 45, 167–256.

Northway, S., Bull, G.Q., Nelson, J.D., 2013. Forest sector partial equilibrium models: Processing components. Forest Science 59, 151–156.

Pan, W., Chang, W.Y., Wu, T., Zhang, H., Ning, Z., Yang, H., 2021. Impacts of the china-us trade restrictions on the global forest sector: A bilateral trade flow analysis. Forest Policy and Economics 123, 102375.

Patacca, M., Lindner, M., Lucas-Borja, M.E., Cordonnier, T., Fidej, G., Gardiner, B., Hauf, Y., Jasinevičius, G., Labonne, S., Linkevičius, E., et al., 2023. Significant increase in natural disturbance impacts on european forests since 1950. Global change biology 29, 1359–1376.

Pendrill, F., Persson, U.M., Godar, J., Kastner, T., 2019. Deforestation displaced: trade in forest-risk commodities and the prospects for a global forest transition. Environmental Research Letters 14, 055003.

Prestemon, J.P., Buongiorno, J., Wear, D.N., Siry, J.P., 2003. International Trade In Forest Products. Springer Netherlands, Dordrecht. pp. 177–199. URL: https://doi.org/10.1007/978-94-017-0219-5_11, doi:10.1007/978-94-017-0219-5_11.

Raunikar, R., Buongiorno, J., Turner, J.A., Zhu, S., 2010. Global outlook for wood and forests with the bioenergy demand implied by scenarios of the intergovernmental panel on climate change. Forest Policy and Economics 12, 48–56.

Rayfield, B., Fortin, M.J., Fall, A., 2011. Connectivity for conservation: a framework to classify network measures. Ecology 92, 847–858.

Rivière, M., Caurla, S., 2020. Representations of the forest sector in economic models. Œconomia. History, Methodology, Philosophy , 521–553.

Rougieux, P., 2017. Modelling European forest products consumption and trade in a context of structural change. Ph.D. thesis. Université de Lorraine.

Rougieux, P., Brusselen, J.v., Lovrić, M., Kiljunen, J., Varis, S., Zudin, S., 2017. The Forest Products Trade Flow Database-a reproducible method and tool to support the analysis of international forest products trade. Technical Report. European Forest Institute.

Rougieux, P., Jonsson, R., 2021. Impacts of the flegt action plan and the eu timber regulation on eu trade in timber product. Sustainability 13, 6030.

Salau, K.R., Baggio, J.A., Shanafelt, D.W., Janssen, M.A., Abbott, J.K., Fenichel, E.P., 2022. Taking a moment to measure networks—an approach to species conservation. Landscape Ecology 37, 2551–2569.

Seidl, R., Rammer, W., 2017. Climate change amplifies the interactions between wind and bark beetle disturbances in forest landscapes. Landscape Ecology 32, 1485–1498.

Seidl, R., Schelhaas, M.J., Lexer, M.J., 2011. Unraveling the drivers of intensifying forest disturbance regimes in europe. Global Change Biology 17, 2842–2852.

Shanafelt, D.W., Salau, K., Baggio, J., 2017. Do-it-yourself networks: a novel method of generating weighted networks. Royal Society Open Science 4, 171227.

Shen, X., Lovrić, M., 2022. Structural determinants of global trade in graphic paper and pulp products. Forest Policy and Economics 134, 102629. URL: https://www.sciencedirect.com/science/article/pii/S1389934121002355, doi:10.1016/j.forpol.2021.102629.

Solberg, B., Moiseyev, A., Kallio, A.M.I., Toppinen, A., 2010. Forest sector market impacts of changed roundwood export tariffs and investment climate in russia. Forest Policy and Economics 12, 17–23.

Sun, L., Bogdanski, B., Stennes, B., Van Kooten, G.C., 2010. Impacts of tariff and non-tariff trade barriers on the global forest products trade: an application of the global forest product model. International Forestry Review 12, 49–65.

Thompson, P.L., Rayfield, B., Gonzalez, A., 2017. Loss of habitat and connectivity erodes species diversity, ecosystem functioning, and stability in metacommunity networks. Ecography 40, 98–108.

Turner, J.A., Buongiorno, J., Katz, A., Zhu, S., 2008. Implications of the russian roundwood export tax for the russian and global wood products sectors. Scandinavian Journal of Forest Research 23, 154–166.

Tyukavina, A., Potapov, P., Hansen, M.C., Pickens, A.H., Stehman, S.V., Turubanova, S., Parker, D., Zalles, V., Lima, A., Kommareddy, I., et al., 2022. Global trends of forest loss due to fire from 2001 to 2019. Frontiers in Remote Sensing 3, 825190.

UNECE/FAO, 2021. Forest Sector Outlook Study 2020-2040. UNECE/FAO. URL: https://unece.org/sites/default/files/2022-05/unece-fao-sp-51-main-report-forest-sector-outlook_0.pdf.

UNECE/FAO, 2022. Forest Products Annual Market Review 2021-2022. UNECE/FAO. URL: https://unece.org/sites/default/

files/2023-02/2228765E_Inside_final_signa_red.pdf.

untradestats, 2024. comtradeapicall. URL: https://pypi.org/project/comtradeapicall/.

U.S. Department of Justice and the Federal Trade Commission, 2010. Horizontal merger guidelines (08/19/2010).

Villamor, G.B., Clinton, P.W., Payn, T., 2024. Preparing for the change: Megatrends–navigating new zealand's future forestry challenges and opportunities. NZ Journal of Forestry 69, 37.

Wang, Y., Ren, F., Zhu, R., Du, Q., 2020. An Exploratory Analysis of Networked and Spatial Characteristics of International Natural Resource Trades (2000–2016). Sustainability 12, 7765. URL: https://www.mdpi.com/2071-1050/12/18/7765, doi:10.3390/su12187765.

Winkel, G., 2017. Towards a sustainable European forest-based bioeconomy – assessment and the way forward. What Science Can Tell Us 8. European Forest Institute. Joensuu, Finland. URL: https://efi.int/sites/default/files/files/publication-bank/2018/efi_wsctu8_2017.pdf.

Wolfslehner, B., Linser, S., Pülzl, H., Bastrup-Birk, A., Camia, A., Marchetti, M., et al., 2016. Forest bioeconomy – a new scope for sustainability indicators. From science to policy 4. European Forest Institute. Joensuu, Finland. URL: https://efi.int/sites/default/files/files/publication-bank/2018/efi_fstp_4_2016.pdf.

World Customs Organization, 1983. International convention on the harmonized commodity description and coding system. https://www.wcoomd.org/-/media/wco/public/global/pdf/topics/nomenclature/.

Zhang, D., 2019. China's forest expansion in the last three plus decades: Why and how? Forest Policy and Economics 98, 75–81.

Zhao, H., Wu, C., Wang, X., 2022. Large-scale forest conservation and restoration programs significantly contributed to land surface greening in china. Environmental Research Letters 17, 024023. URL: https://dx.doi.org/10.1088/1748-9326/ac44c5, doi:10.1088/1748-9326/ac44c5.

Zhou, Y., Hong, Y., Cheng, B., Xiong, L., 2021. The Spatial Correlation and Driving Mechanism of Wood-Based Products Trade Network in RCEP Countries. Sustainability 13, 10063. URL: https://www.mdpi.com/2071-1050/13/18/10063, doi:10.3390/su131810063.