Fighting Alone or Mutual Benefit and Win? A Study on Forestry Embodied Energy Competition Network Based on MRIO

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Abstract

Measuring energy usage in the forestry trade is a topic of great significance. In this article, we use the World Input–Output Database and the multiregional input–output model to establish an embodied energy competition network and assess the influence of global value chain (GVC) integration on competition. The results show that (1) the intensity of competition for embodied energy in forestry is higher for exports compared with imports. Additionally, the import competition network exhibits lower connectivity and overall efficiency. (2) The core regions of the competitive network are primarily found in Europe, Asia, and the Americas. The United States consistently maintains a competitive advantage. However, forestry policies have led to a decline in the status of the United States, (3) The hierarchical structure of export competition is more pronounced. When the weighting degree exceeds 200, this phenomenon becomes more pronounced. (4) From the perspective of GVC, positive embedding in the GVC is negatively correlated with import competition. Backward GVC embedding is positively correlated with import and export competition. On the basis of the above results, this article proposes that countries where backward embedding is the main method should actively participate in building appropriate export international associations, participating in international organizations, and building a relatively harmonious and stable export competition market, thereby helping to maintain economic development and energy environment management.

The forestry industry, as a high-energy and resource-consuming industry, consumes a huge amount of energy directly and indirectly in the production process. How to analyze the embodied energy use in the production process is a topic that has not yet been widely explored in current research. Meanwhile, because of the continuous development of the global value chain (GVC), countries around the world are increasingly involved in the forestry trade and becoming members of the forestry trade network. Because of the different positions of GVC, countries have different positions in participating in the forestry trade network, and there are also differences in the energy use involved in forestry production and competition generated in trade (Korhonen et al. 2001). Forests not only have ecologic attributes, but also economic attributes. On the one hand, forests can absorb carbon dioxide from the earth through photosynthesis, which helps to slow the greenhouse effect (Liang et al. 2023). On the other hand, forests serve as a significant source of biomass energy worldwide and provide a material foundation for economic development (Nayan Yadava and Sinha 2019). The policy management of forestry development strives to achieve the synergy between environmental protection and economic benefits, and the core content is to manage the resource and energy consumption of forestry development well. (Korhonen et al. 2001; Côté et al. 2002, Shabbir and Mirzaeian 2017, Zhao et al. 2019). Forestry operations, such as logging and wood processing, require energy-intensive machinery and equipment. This includes activities like felling, transportation, and milling of trees. The extraction and processing of timber result in the consumption of fossil fuels and electricity and lead to greenhouse gas emissions. From 1992 to 2015 alone, the annual average content of wood products produced globally was 278 Tg of carbon

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(TgC), with a total of 2,938 TgC in the carbon stocks of in-use wood products produced (Song et al. 2024). A study conducted on forests in the Legal Amazon Region of Brazil found that during deforestation, 612 ± 212 tons of carbon dioxide equivalent emissions will be generated. These emissions contribute to climate change and can have detrimental effects on the environment (Cederberg et al. 2011). However, with the continuous development of environmental protection requirements and international trade, the forestry industry chain and supply chain are constantly deepening and subdividing, and the former is mainly reflected in strict environmental protection requirements for forestry production and new production processes such as increasing information technology control over production; the latter mainly focuses on refining production to enhance trade competitiveness (Chen et al. 2023), which includes stages such as forestry cultivation, timber logging, raw material production, product manufacturing, and product sales (Côté et al. 2002; Comodi et al. 2013). In different stages of forestry, the main energy consumed in production is electricity and fossil fuels (Kayo et al. 2012).

At the same time, GVC is increasingly intertwining with national trade, consolidating diverse industries from various countries around the world. (Hummels et al. 2001). Because of the resource endowment, production technology, and economic factors of different countries, their positions in GVC vary. Meanwhile, because of the high energy consumption characteristics of forestry production, different countries are more inclined to undertake links with lower energy consumption to protect their own environment. This leads to competition for embodied energy in the forestry production process (Sun et al. 2023). In this process, the involvement of international production inputs can result in more complex and unequal industrial production, which is not only an opportunity but also a challenge for different countries (Pan et al. 2022). This phenomenon also underscores an important issue in national trade governance: how to properly distinguish the division of interests and responsibilities in international trade. Although there are various approaches to addressing this question, within the current research context, GVC must be included in trade analysis to comprehensively assess the position of both imports and exports in trade (Wei et al. 2024). Given the premise of considering GVC, whether there are differences in status and interests among countries in different locations, and how to protect the interests of various countries in GVC, such issues still need to be solved. Further research and development in this area are essential to explore potential solutions.

The multiregional input–output (MRIO) model, one of the important methods in current academic research on the trade environment, originated from the input–output analysis (IOA) model proposed by Leontief (1970) for studying input and output. In the continuous evolution of research on the IOA model, the model has progressed from the single regional input–output model, used for studying input–output relationships within a single region, to the bilateral regional input–output model, which examines bilateral input and output, and finally to the MRIO model, which is used to study multiregional input and output (Bullard and Herendeen 1975, Costanza 1980, Lenzen 1998). The methods for analyzing embodied energy include not only IOA, but also structural analysis (Su and Ang, 2017, Su et al. 2019, Li et al. 2020) and life-cycle analysis (Guan et al. 2016, Tao et al. 2018, Lv et al. 2021). However, in comparison with the aforementioned methods, MRIO analysis excels in its ability to investigate the interrelationships between different countries and sectors, along with capturing the dynamic changes in embodied energy inflows and outflows. Therefore, MRIO is extensively used in the study of embodied energy, with research perspectives including national, regional, and industry levels. Research on embodied energy at the national and regional levels involves global perspectives (Chen and Chen 2011, Rocco and Colombo 2016), national perspectives (Liu et al. 2010, Moreau and Vuille 2018), and regional perspectives (Liu et al. 2015; Zhang et al. 2016, 2023; Guo et al. 2020), among others; research on embodied energy at the industry level includes aspects such as oil (Wu and Chen 2019), coal (Xia et al. 2017), and natural gas (Kan et al. 2019). It is evident that because of the intricate energy flow in contemporary international trade, integrating IOA with embodied energy can provide theoretical support for addressing energy and environmental management challenges.

Complex networks, as a crucial approach to studying trade among countries, regions, and departments, have been proposed by researchers in recent years to link international trade competition with complex networks, construct trade competition networks, and study network structures and characteristics. Building competition networks is grounded in the competition intensity index (Zhang et al. 2014), and current research involves fields such as oil (An et al. 2014), chromium (Li et al. 2022), and natural gas (Zhu et al. 2023). From this research, the competition network is concentrated in actual trade, but energy competition in trade cannot be comprehensively summarized from the perspective of real energy.

Research on GVC can provide valuable insights into energy consumption within global production processes and facilitate the analysis of energy attribution in trade by decomposing GVC. In recent years, there has been an increasing amount of research on the value decomposition of GVC and researchers can effectively measure the position of different countries participating in GVC by calculating the added value of domestic and foreign production (Koopman et al. 2012, Wang 2013). On the basis of such research methods, research on GVC decomposition has continuously deepened, and the analysis of GVC additions has continuously improved. Meanwhile, during the research process, the degree of national participation in GVC is continuously quantified and further used as an important influencing factor in other studies (Wang 2013, Koopman et al. 2014). Throughout this process, an increasing number of researchers has established connections between GVC and environmental energy, and by combining flow in international trade with GVC, they have studied the environmental footprint and energy footprint (Dietzenbacher et al. 2012, Wang 2013) and found a fairly close relationship between the two (Turner et al. 2007, Meng et al. 2018, Jakubik and Stolzenburg 2021). However, some researchers have also raised objections, arguing that GVC is not related to environmental energy footprint or that the relationship is weak (Jin et al. 2022, Sun and Shi 2022). Therefore, studying the relationship between GVC and embodied energy competition in forestry can offer a comprehensive exploration of this issue and provide different perspectives for global energy management research.

This article first uses an input–output model to calculate the embodied energy flow in international trade and selects forestry-related departments to construct a trade network for forestry embodied energy. On the basis of this, the concept of trade competition is further adopted to construct the forest-embodied energy competition network. The study investigates the characteristics of the embodied energy competition network and the relationship between competition and GVC. The main objectives include delineating the pattern of the forestry trade embodied energy competition network and exploring the presence of any imbalance phenomenon within the competition network. Furthermore, by integrating GVC analysis, the study seeks to analyze potential imbalances and the relationship among different GVCs. Utilizing the MRIO model, the study calculates the embodied energy of forestry trade across 43 countries and regions worldwide from 2000 to 2014. The competition network is constructed using the competition index, and we conducted network analysis on 43 countries to identify the overall characteristics and node characteristics of the network. Finally, because of differences in data among databases, when analyzing embodied energy competition in forestry, data were screened. Therefore, when conducting regression, data from 39 countries were selected for calculation and we examined the influence of GVC embedding on embodied energy competition.

This article contributes to the existing literature in several ways. First, there has been a significant amount of research linking IOA with commodity trade, studying the flow of embodied carbon and embodied energy. However, the focus of this study is on the forestry sector, given the sector's growing significance in global trade, particularly concerning energy and environmental management. This research advances and expands the application of IOA within the realm of energy issues. Second, current research on trade competition networks mostly starts from physical trade, and further exploration of competition networks for virtual products such as embodied energy is still needed. This research can provide new perspectives and models for studying trade. Third, considering the potential imbalances in international competition, from the perspective of GVC, it is an innovation in the governance of embodied energy competition in the international arena, better safeguarding equality in international trade.

Materials and Methods

Forestry embodied energy trade competition

In the current landscape of increasingly intricate trade competition, it is common for different countries to engage in import and export trade with the same source and destination countries. This will lead to intensified competition between countries. With the slowdown of economic development, the focus shifts from incremental growth to competing over existing market shares. To protect their own interests, the intensity of trade competition will further increase. Additionally, because of the different development status between countries, it is difficult for domestic production to meet their own needs. Importing products from other countries can only meet these needs. Taking forestry as an example, the distribution of forestry resources is uneven, and only some countries can process them. Analyzing competition in forestry trade can shed light on energy usage in the production process of forestry resources, thereby better reflecting the characteristics of embodied energy flow under trade competition. Therefore, this article applies complex network theory and MRIO models to construct a competition model. It analyzes the evolution of the import and export competition relationship of forestry embodied energy separately.

This network model consists of nodes and edges, and the network is a weighted undirected symmetric network. The network nodes are the countries participating in trade, and all competition relationships involving forestry embodied energy from these countries are aggregated into nodes. The edges represent the competition relationships between corresponding nodes regarding embodied energy. The left image in Figure 1 shows countries with embodied energy flows in forestry, whereas the right image shows countries with competition. Among them, nodes I, J, K represent the countries participating in trade, im represents the import trade relationship between different countries, arrows point to the importing country, ex represents the export trade relationship between different countries, and arrows point to the export destination country. In the right figure, the competition relationship between the two countries is undirected, indicating the intensity of import and export competition between them.

Regarding the calculation of embodied energy in forestry, the MRIO model is used to mainly allocate the total output of forestry production to intermediate goods, and further use the environmental account to calculate the energy use of intermediate production (Rocco and Colombo 2016). The formula is as follows:

$$e_i + \sum_{i,j=1}^{n} \varepsilon_i \times x_{i,j} = \varepsilon_i \times \sum_{i,j=1}^{n} x_{j,i} + \varepsilon_i \times f_i \tag{1}$$

where e_i represents direct energy import, ε_i is the embodied energy intensity of the input–output unit for country i, $x_{i,j}$ is the intermediate input between country i and country j, f_i is the final demand for country i, and $\sum_{i,j=1}^{m} \varepsilon_i \times x_{i,j}$ and $\varepsilon_i \times \sum_{i,j=1}^{m} x_{j,i}$ represent a country's import of embodied energy and total output of exported embodied energy to other sectors, respectively. In the world economic system, by extending the above model to trade between multiple countries, Equation 2 can be obtained as follows:

$$I + E \times X = E \times IN + E \times FN = E \times Y \tag{2}$$

where I is the direct energy import used for domestic production, E is the unit of embodied energy intensity, X is the intermediate input, IN is the intermediate product flowing to other sectors, FN is the final domestic demand, and Y is

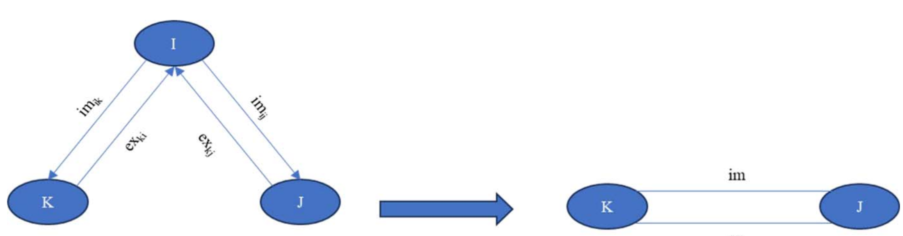

Figure 1.—Competition model.

the total output encompassing the portion of intermediate products and domestic final use. After a matrix forming the equation, it is possible to have a more intuitive understanding of the calculation process. It should be noted that the final output needs to be a diagonal matrix formed as follows:

$$\begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_n \end{bmatrix} + \begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,n} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n,1} & x_{n,2} & \cdots & x_{n,n} \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{bmatrix} = \begin{bmatrix} y_1 & 0 & \cdots & 0 \\ 0 & y_1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & y_1 \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{bmatrix} \tag{3}$$

The matrix is further transformed to obtain the following equation:

$$E = I \times (Y - X)^{-1} \tag{4}$$

The equation and matrix form for the embodied energy flow between regions are as follows:

$$e_{i,j} = \sum_{i=1}^{n} \sum_{j=1}^{n} \varepsilon_{i,j} \times x_{i,j} \tag{5}$$

$$E = \begin{bmatrix} e_{1,1} & e_{1,2} & \cdots & e_{1,n} \\ e_{2,1} & e_{2,2} & \cdots & e_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ e_{n,1} & e_{n,2} & \cdots & e_{n,n} \end{bmatrix} \tag{6}$$

where $e_{i,j}$ represents the embodied energy flow between country i and country j.

After obtaining data on embodied energy in forestry, further construction of a competitive network is carried out. The determination of import competition and export competition is calculated by constructing a competition index (Glick and Rose 1999). This indicator is utilized to measure the competitive relationship between imports or exports from the same country to the same country.

$$S_{ij} = \sum_{c} \left\{ \left(\frac{E_{ic} + E_{jc}}{E_w} \right) \times \left[\left(1 - \frac{|(E_{ic}/E_i) - (E_{jc}/E_j)|}{(E_{ic}/E_i) + (E_{jc}/E_j)} \right) \right] \right\} \times 100 \tag{7}$$

where S_{ij} represents the intensity of competition in forestry-embodied energy imported or exported from the same country by country i and country j to the same country. E_{ic} and E_{jc} represent the forestry-embodied energy imported or exported from the same country by country i and country j to the same country, whereas E_i and E_j represent the total forestry embodied energy imports or exports from country i and country j to the same country, and E_w represents the total world forestry embodied energy imports or exports. Because the import competition in network nodes involves a bidirectional relationship, the network edges are undirected. The final constructed competitive network can reflect the competitive relationship of energy embodied in national forestry in international trade.

To further construct an embodied energy import competition network on the basis of the above information, we establish a complex network model $E = (V, S)$ where node V represents a country, $V = \{v_i : i = 1, 2 \cdots n\}$; there are n countries in the trade network. S represents an edge, $S = \{S_{i,j} : i, j = 1, 2 \cdots n\}$, and the complex network equations are as follows:

$$S_{ij} = \begin{cases} S_{ij} & S_{ij} > 1 \\ 0 & S_{ij} \leq 1 \end{cases} \tag{8}$$

$$E = (V, S) = \begin{bmatrix} 0 & s_{1,2} & \cdots & s_{1,n} \\ s_{2,1} & 0 & \cdots & s_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ s_{n,1} & s_{n,2} & \cdots & 0 \end{bmatrix} \tag{9}$$

Network indicators

Weighting degree refers to the competitiveness of countries participating in trade within the network. It is calculated by summing all competition intensities. The higher this indicator, the higher the competitiveness. $\mathrm{w}_i(t)$ is the node weighting degree, where a_{ij} represents the forestry embodied energy flow between i and j at time t, and w_{ij} represents the corresponding node strength.

$$\mathrm{w}_i(t) = \sum_{i,j=1}^{N(t)} a_{ij} w_{ij}(t) \tag{10}$$

The clustering coefficient can be used to measure the degree of competition between nodes. A higher clustering coefficient of a node indicates a greater likelihood of connections with nearby nodes in the network, implying closer competition relationships with other nodes and higher importance of the node within the network. The specific calculation formula is as follows (Shao et al. 2021):

$$\mathrm{C}_i^w = \frac{1}{s_i(k_i - 1)} \sum_{i,j=1}^{N(t)} \frac{(w_{ik} + w_{jk})}{2} e_{ij} e_{ik} e_{jk} \tag{11}$$

The PageRank centrality is a measure that evaluates the importance of nodes in an undirected weighted network by considering both the degree of nodes in the network and the degree of adjacent nodes. The calculation method for this index is as follows (Xu et al. 2023):

$$\mathrm{C}_p(v_i) = \alpha \sum_{j=1}^{N} a_{ij} \frac{\mathrm{C}_p(v_j)}{\mathrm{d}_{out}(v_j)} + (1 - \alpha) \frac{1}{N} \sum_{i=1}^{N} \mathrm{C}_p(v_i) = 1 \tag{12}$$

Regression model

To further study the impact of GVCs on embodied energy competition in forestry, this article combines competition networks and selects data from corresponding years for regression analysis. For the selection of variables, a structural decomposition model is used, mainly starting from scale effects, outcome effects, technological effects, and economic effects (Shi et al. 2022). The final construction model is as follows:

$$FFEC_{it} = \alpha_0 + \alpha_1 GVC_{it} + \alpha_2 X_{it} + \lambda_{it} + \gamma_{it} + \varepsilon_{it} \tag{13}$$

During the unit root test on the data, the data were stable. After conducting multicollinearity tests on the data using the variance influence factor (VIF), it was found that the maximum VIF did not exceed 10, indicating no multicollinearity issues. Finally, using the Hausman test, we determined that the data adopt a fixed-effects model.

In the benchmark model, i represents the country; t represents time; $FFEC_{it}$ represents the embodied energy competition index of the forestry sector in t year, including import competition and export competition; GVC_{it} is the value chain embedding index; and X_{it} is the control variable, including the country's gross domestic product; λ_{it} is the fixed effect of the year; γ_{it} is an individual fixed effect; ε_{it} is a random perturbation term.

The equations for calculating the relevant indicators of GVC is as follows (http://gvcdb.uibe.edu.cn/):

$$gvcp\_f = VA\_CVC/SVA \tag{14}$$

$$gvcp\_fs = 3a\_VA\_GVC\_R/SVA \tag{15}$$

$$gvcp\_fc = (3b\_VA\_GVC\_D - 3c\_VA\_GVC\_F)/SVA \tag{16}$$

$$gvcp\_b = FGY\_CVC/FGY \tag{17}$$

$$gvcp\_bs = 3a\_FGY\_GVC\_R/FGY \tag{18}$$

$$gvcp\_bc = (3b\_FGY\_GVC\_D - 3c\_FGY\_GVC\_F)/FGY \tag{19}$$

where VA_CVC is the gross domestic product (GDP) of intermediate goods trade, which is used in the export production process between two or more countries. SVA is the GDP of a country divided by sector and industry. The forward embedding represents the proportion of intermediate commodity trade to sector GDP, which in forestry trade is the value-added part of imported forestry intermediate goods after production and the proportion of forestry GDP. The forward value chain embedding index can be further subdivided into the simple forward value chain embedding index ($gvcp\_fs$) and the complex forward value chain embedding index ($gvcp\_fc$). $3a\_VA\_GVC\_R$ is a simple cross-border production sharing activity, where importers absorb the export value added of intermediate products. $3b\_VA\_GVC\_D$ is the intermediate product value added in the production process of products re-exported to the domestic market. $3c\_VA\_GVC\_F$ is the intermediate product value added in the final foreign consumer goods. The backward value chain embedding represents the proportion of foreign added value of imported intermediate goods in the final production and services of the industry. FGY_CVC is the foreign value added of intermediate goods imported by various intermediate departments, and FGY is the final product and service produced according to the classification of various departments in the country. It can be further subdivided into the simple backward value chain embedding index ($gvcp\_bs$) and the complex backward value chain embedding index ($gvcp\_bc$). $3a\_FGY\_GVC\_R$ is the part of the imported intermediate products used to produce the final product, which only passes through once and only involves domestic production after entering the country. The added value in the final product used for production, export, or domestic consumption in the intermediate goods imported from $3b\_FGY\_GVC\_D$. $3c\_FGY\_GVC\_F$ is the added value from foreign countries, which is reflected in the intermediate goods imported by a country for production of export products, and the added value absorbed by foreign countries in this part.

Data

This article selects the latest data from the World Input–Output Database (WIOD), which has the advantage of more detailed departmental classification compared with other databases, and the supporting environmental account data of the database is more complete. The latest version of the database was updated in 2016. GVC data are sourced from the University of International Business and Economics Database (http://gvcdb.uibe.edu.cn/). The other data mainly come from World Development Indicators (WDI) database and commodity trade database. Due to data matching, the final data consist of 15 years of data from 39 countries, excluding Taiwan, Cyprus, the Netherlands, and Luxembourg, mainly because of missing data in the corresponding WDI database, which includes the entire study period. Therefore, the missing data in this section will be deleted during the empirical analysis, and only the 15-year data of the remaining 39 countries will be analyzed.

Results

Overall analysis of competitive networks

This article initially examines the network indicators, including network density, average clustering coefficient, and average path length of competitive networks. As illustrated in Figure 2, network density serves to reflect the overall cohesion of the network. From the perspective of network density, the connections within the import competition network and export competition network exhibit constant fluctuations. Import competition shows an overall downward trajectory, declining from 0.616 in 2000 to 0.563 in 2014, whereas export competition shows an upward trend, rising from 0.582 in 2000 to 0.65 in 2014. This indicates that the degree of import competition for forestry embodied energy is lower than that of export competition. For the flow of embodied energy in forestry trade, export destination countries are more abundant than import source countries and can export forestry embodied energy to more countries. However, the import countries of forestry embodied energy are relatively concentrated, aligning with the concentrated distribution of world forestry resources. Thus, export competition is more intense. From the perspective of density values, both imports and exports have network densities around 0.5 and 0.6. Compared with other networks, this network has a relatively low density, indicating that not all countries have connections with other nodes in the network (Liu et al. 2024).

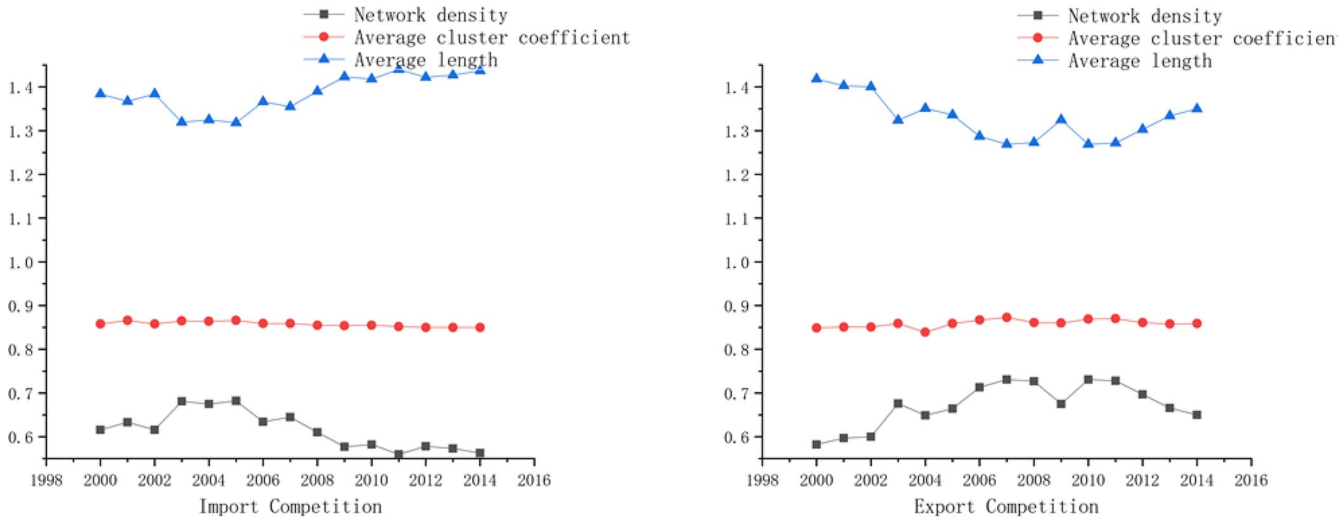

Figure 2.—Overall analysis of forestry embodied energy competition network.

The change in average path length and density shows an inverse trend. The overall average path length of the import competition network has increased, rising from 1.384 in 2000 to 1.437 in 2014, indicating a decrease in connectivity between import competition networks and overall efficiency. This is because the concentration of import source countries has weakened the competitive relationship among different countries. The average path length of the export competition network has decreased overall, from 1.418 in 2000 to 1.35 in 2014, indicating a higher number of export destination countries and a widespread export competition relationship among countries, resulting in stronger network connectivity. The average clustering coefficients of import competition and export competition did not show significant changes, both fluctuating around 0.85, indicating that the clustering degree of countries in the network has not changed significantly. Meanwhile, compared with other networks, the higher clustering coefficient also indicates the existence of relatively fierce competitive relationships in the network (Zhu et al. 2023). This is related to the relatively fixed differences in forestry resource endowments and the relatively concentrated forestry production; the clustering degree will not change significantly in a short time. From the size of the clustering coefficient, the clustering coefficient value is relatively high compared with other networks, indicating the phenomenon of regional competition in the network and the existence of competition between relatively fixed countries.

Analysis of major countries in competitive networks

To further analyze the competitive relationship between imports and exports, the country relationships in the import and export competition network are ranked, and the results are shown in Tables 1 and 2. Table 1 presents analysis of the countries with relatively large competitive relationships. The country that has always been at the forefront of import competition indicates that two countries are among the top in the world in importing forestry embodied energy from the same country, indicating competition between the two in forestry embodied energy imports. This means that in the future, if they want to ensure the normal inflow of their own forestry embodied energy, the two countries will inevitably engage in friction and competition with each other. In countries with higher export competition rankings, two countries will export forestry embodied energy to the same country. If a country wants to maintain its own interests in trade and occupy a larger share of the forestry trade, there will be mutual crowding between the two countries. From 2000 to 2014, the United States ranked at the forefront of export competition. This can be attributed to the fact that during this period, Russia, Brazil, Canada, the United States, and China were among the top five countries in the world in terms of forest rankings, which is related to competition rankings. Because of its own resource and economic development advantages, the United States has been at the forefront of import and export competition in the world, establishing a relatively stable competitive relationship with major countries.

Apart from the United States, countries in Europe and Asia are also an important component of embodied energy competition in forestry. Among them, the countries that are at the forefront of export competition with the United States have undergone certain changes. Germany and Italy in 2000 have changed to China and Germany in 2014. At the same time, it is not difficult to see that India's ranking has risen and gradually stabilized. The main export competition regions have gradually shifted from the United States and Europe to the United States

Table 1.—Total export competition ranking.

Rank	2000	2005	2010	2014
1	USA-DEU[a]	USA-DEU	USA-DEU	USA-CHN
2	USA-ITA	USA-ITA	USA-CHN	USA-DEU
3	USA-IND	USA-GBR	USA-IND	USA-IND
4	USA-AUT	USA-AUT	USA-ITA	CHN-DEU
5	USA-FRA	USA-FRA	DEU-CHN	CHN-IND
6	USA-CHN	USA-ESP	DEU-ITA	DEU-IND
7	USA-ESP	USA-JPN	DEU-IND	USA-ITA
8	USA-GBR	USA-CHN	USA-AUT	USA-GBR
9	USA-BRA	USA-SWE	USA-GBR	USA-AUT
10	USA-SWE	USA-IND	USA-BRA	USA-POL

[a] USA = United States; DEU = Germany; CHN = China; ITA = Italy; IND = India; GBR = Great Britain; AUT = Austria; FRA = France; ESP = Spain; JPN = Japan; BRA = Brazil; SWE = Sweden; POL = Poland.

Table 2.—Total import competition ranking.

Rank	2000	2005	2010	2014
1	USA-RUS	CHN-RUS	CHN-CAN	CHN-RUS
2	USA-CHN[a]	CHN-USA	CHN-IDN	CHN-USA
3	RUS-CHN	CHN-CAN	CHN-RUS	CHN-IND
4	USA-GBR	CHN-GBR	USA-CHN	CHN-CAN
5	USA-CAN	CHN-IDN	USA-RUS	CHN-ESP
6	RUS-GBR	CHN-POL	USA-CAN	CHN-IDN
7	RUS-CAN	CHN-BRA	USA-BRA	CHN-BRA
8	USA-IDN	CHN-JPN	USA-IDN	CHN-MEX
9	USA-JPN	CHN-DEU	USA-IND	CHN-GBR
10	USA-POL	RUS-USA	USA-ESP	CHN-DEU

[a] USA = United States; CHN = China; IDN = Indonesia; RUS = Russia; CAN = Canada; IND = India; GBR = Great Britain; ESP = Spain; POL = Poland; BRA = Brazil; MEX = Mexico; JPN = Japan; DEU = Germany.

and Asia, with Asian countries such as China and India taking on more energy consumption in the forestry production process. This region's countries compete with the United States in the export process, leading to an increase in the ranking of export competition relationships. In terms of import competition, significant changes have occurred, from the import competition relationship dominated by the United States in 2000 to the import competition relationship dominated by China in 2014. This indicates that in the process of transferring the forestry industry, the demand for resources in production has increased. For China to further develop forestry, it is necessary to increase imports, which inevitably leads to import competition with other countries. Therefore, the ranking relationship continues to rise.

We ranked the countries with relatively abundant forestry resources in the world on the basis of the national competition index from 2000 to 2014 and analyzed the ranking changes. We mainly selected countries with high rankings in forestry hidden energy for analysis. As depicted in Figure 3, it is not difficult to find that the trend of national ranking is consistent with the trend of major competitive relationships. Among them, the United States, as a top ranked country in competitive rankings, has always been in the top three in export competition, whereas in import competition, its ranking fluctuated significantly. After 2012, the import competition ranking dropped to fourth place. As a major country in forestry resources, Russia ranks lower in export competition and higher in import competition. Analyzing the main competitive relationships, Russia's export competition is relatively concentrated, but its import sources are relatively scattered, resulting in a higher ranking in import competition. However, China's ranking in import and export competition is showing an upward trend, which is determined by the mismatch between the development of China's forestry industry and its own resources. The development of China's forestry industry requires the establishment of export relations with more countries, leading to competition with existing export countries (Sun et al. 2023). Insufficient resources require the need to import from more countries to meet production needs, resulting in more import competition relationships. Germany and Italy have both declined in rankings, consistent with the analysis above that the main competitive regions have shifted from Europe to Asia. This indicates that to better study the embodied energy flow and competition in forestry trade, the research perspective should be shifted to regions such as Asia.

The above changes are related to the characteristics of forestry development. Forestry is not only a component of economic development, but also an important part of the ecosystem (Nayan Yadava and Sinha 2019, Liang et al. 2023). Therefore, the country needs to formulate policies for forestry and meet the dual requirements of development and environmental protection. Taking China as an example, the introduction of logging bans has led to China's dependence on imports to meet forestry development and has continuously elevated China's position in trade (Zhang et al. 2024). Similar policies have also been introduced by other countries to assist in the development of their own forestry, which is also an important factor influencing the changes in competition between countries.

Evolution of competitive network structure

To analyze the main structure of the competitive network, the clustering coefficient and weighting degree were first calculated and a distribution map was constructed as shown in Figure 4. From the results, one can see that the distribution of clustering coefficients in import competition is more concentrated. In the import competition network, when the weighting degree is <200, the clustering coefficient is widely distributed

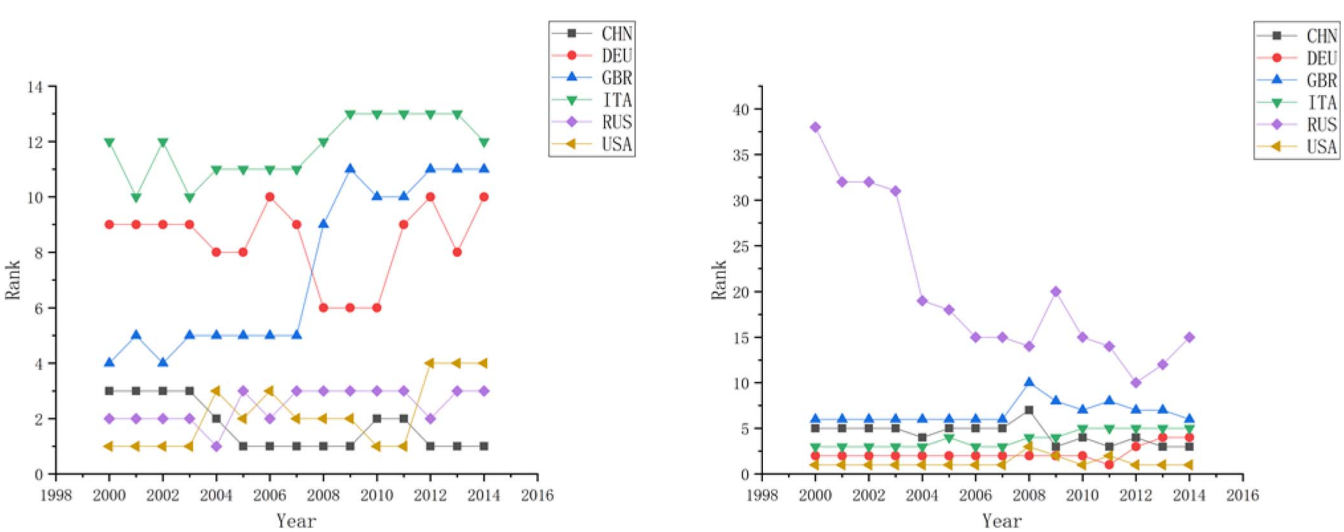

Figure 3.—Changes in rankings of major competing countries (left import, right export).

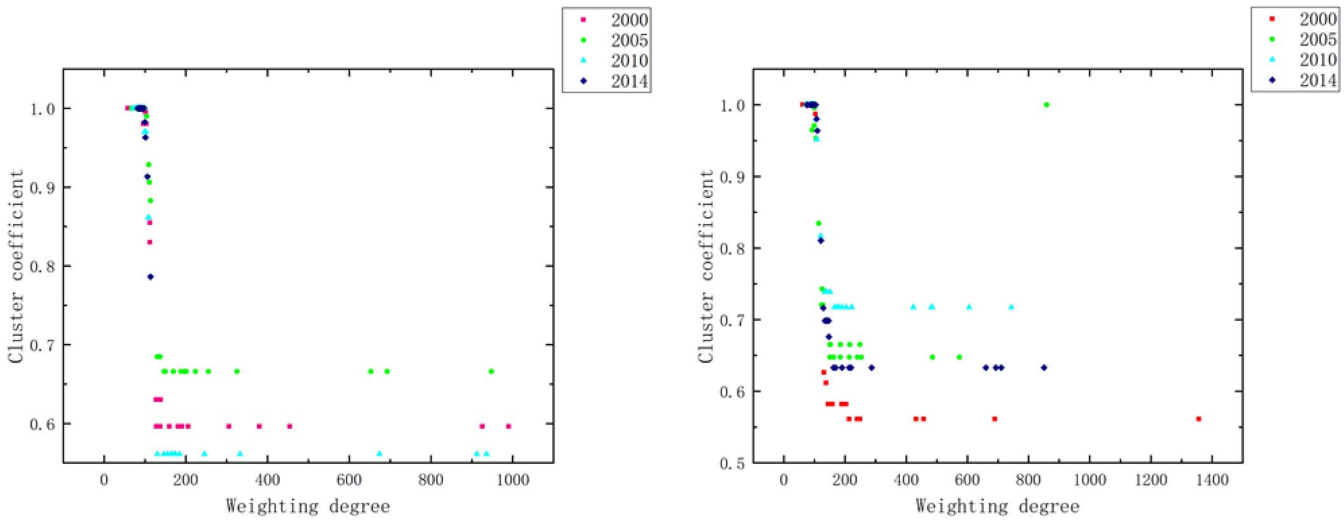

Figure 4.—Cluster coefficient and weighted distribution (left represents import competition, right represents export competition).

between 0 and 1. When the weighting degree is >200, nodes in different years show different characteristics. Specifically, there is a concentration around 0.6 in 2000, >0.6 in 2005, and <0.6 in 2010. In the export competition network, when the node's weighting is <200, the clustering coefficients are scattered from 0 to 1, which is basically consistent with the import competition network. However, when the node's weighting is >200, different structural characteristics are also generated. However, compared with the import competition network, the structure is more dispersed, with a concentration of around 0.55 in 2000, 0.7 or above in 2010, and an average distribution of around 0.65 in 2005 and 2014. This result indicates that in a competitive network, when the weighting degree is >200, there is a clear hierarchical structure, reflecting that in the competitive network there are fewer competitors that compete with the country, and the competition between them is more intense. However, countries with more competitive relationships, due to the relatively large number of import sources and export countries, have relatively weaker competition relationships with each other. The reason for the difference in the hierarchical structure between import competition and export competition may be that because of the relative concentration of forestry resources, the competition relationship between imports is also relatively concentrated, resulting in a less obvious hierarchical structure. However, in exports, because of the widespread presence of exporting countries, the competition relationship among exports is richer, resulting in a more obvious hierarchical division, Moreover, there are significant differences in the advantages of exports among different countries, so the range of structural levels in export competition is more diverse than that in import competition. Therefore, to better maintain the development of domestic forestry, in addition to maintaining the stability of import sources, it is also necessary to actively expand export countries and reduce competitive pressure.

For further analysis of the structure in the network using the PageRank metric, with the years 2000, 2005, 2010, and 2014 as examples, we selected the top 10 countries for analysis. The results are shown in Table 3. From the results, one can see that in export competition, countries such as China, Germany, India, and Italy are in an upward and stable position, and the United States rises to fifth place in 2014. This result indicates that in the export competition network, the structure is more unstable and the status of major countries will change. The development of the Eurasian region and the United States, the European Union, Australia, and other regions have all introduced policies that regulate the use of wood in forestry development, which has had a significant impact on global forestry development. The United States proposed a revised Lacey Act in 2008, making it the first country to ban the import and sale of illegally sourced wood (Zhang et al. 2024). This has had a significant impact on the development of forestry production in the United States. By reducing the sources of forestry production materials, the position of forestry exports in export competition with the United States has been lowered, and the evolution of the world economic development pattern has had a significant impact on export competition, causing structural changes. In terms of import competition, because of the relative fixation of industries and resources, the export competition pattern is relatively fixed. Among them, Brazil's geographic location, close to ports and climate suitable for forestry development, gives it an advantageous position in import competition. This phenomenon indicates that the import competition structure is more stable than the export competition, and future research on embodied energy in forestry should focus more on exports.

Table 3.—PageRank ranking of export and import competitions.

	Export competition				Import competition			
Rank	2000	2005	2010	2014	2000	2005	2010	2014
1	AUT[a]	CHN	CHN	CHN	BRA	BRA	BRA	BRA
2	CHN	DEU	DEU	DEU	CAN	CAN	CAN	CAN
3	DEU	IND	IND	IND	CHN	CHN	CHN	CHN
4	GBR	ITA	ITA	ITA	DEU	DEU	DEU	DEU
5	IND	USA	USA	USA	GBR	GBR	GBR	GBR
6	ITA	ESP	ESP	FRA	IDN	IDN	IDN	IDN
7	USA	FRA	FRA	POL	IND	IND	IND	IND
8	BRA	POL	POL	BRA	POL	POL	POL	POL
9	ESP	TUR	TUR	AUT	RUS	RUS	RUS	RUS
10	FRA	BRA	BRA	GBR	USA	USA	USA	USA

[a] AUT = Austria; CHN = China; BRA = Brazil; DEU = Germany; CAN = Canada; IND = India; GBR = Great Britain; ITA = Italy; USA = United States; ESP = Spain; FRA = France; IDN = Indonesia; POL = Poland; TUR = Turkey.

Analysis of competitive influencing factors

This article further investigates the influencing factors of embodied energy competition in forestry and introduces GVC for regression analysis. On the basis of the indicators of GVC embedding in different ways mentioned earlier, we first explain the meaning of different embeddings for forestry. Among them, gvcp_f is used to measure the ratio of domestic value to the final product output value in forestry production. The larger the ratio, the greater the advantage in forestry. gvcp_b is used to measure the proportion of products from other countries in forestry production to the final product. The larger the ratio, the lower the position in the industry. Table 4 shows the regression results. The results indicate that for import competition, backward embedding shows a negative correlation, whereas forward embedding shows a positive correlation. For export competition, the main impact is backward embedding, and there is a positive correlation between the two.

On the basis of the above conclusions, this article further analyzes the potential influencing factors. First, the larger the forward embedding value, the more it represents the forestry production process, which occurs mainly through imported raw materials and occupies a relatively advantageous upstream position in the forestry industry chain. It may also create some barriers, including technological limitations, resulting in fewer objects competing with the country, and the intensity of competition is negatively correlated with forward embedding. Second, the larger the backward embedding value, the greater the indication that the country mainly exports raw materials or re-exports them after simple processing. This part often occupies a relatively low-end position in forestry production. Meanwhile, because of the relatively simple nature of this part, the improvement of backward embedding will lead to intensified import and export competition.

Suggestions

After conducting research and summarizing the conclusions, the following suggestions are proposed to promote the development of forestry:

(1) To address the impact of protection policies on forestry development, especially in response to the embedded energy competition brought about by forestry trade, different countries should reasonably coordinate domestic and foreign forestry resources to ensure the sustainable supply of timber. For countries with lower levels of development, it is necessary to build a better business environment and introduce advanced foreign technologies to better protect domestic forestry resources.

(2) In both import and export competition, export competition becomes more intense, indicating that exporters in the market do not have a competitive advantage, lack bargaining power, and face more uncertain risks. To this end, export relations should be widely established. We should actively participate in international organizations and build appropriate trade agreements, such as China's Belt and Road Initiative, which can help China's forestry development.

(3) Examine the impact of reducing trade barriers on exports. Because of the requirements of developed countries for forest products, taking the United States as an example, corresponding policies have been introduced to restrict the import of timber. To this end, it is necessary for the country to raise standards when exporting forest products to reach a level consistent with international standards, following the Program for the Endorsement of Forest Certification Schemes, to avoid potential trade barriers. At the same time, we focus on developing a complete domestic industrial chain to help enhance the country's position in GVC.

Table 4.—Regression results of competition intensity.

Explained variable	Variable[a]	Coefficient	Standard.error
Import competition	*gvcp_b*	0.146***	0.0449084
	gvcp_bs	0.106***	0.0426086
	gvcp_bc	0.031**	0.0463077
	gvcp_f	−0.007**	0.0038128
	gvcp_fs	−0.012*	0.0064319
	gvcp_fc	−0.019**	0.0092877
Export competition	*gvcp_b*	0.257***	0.0516563
	gvcp_bs	0.004	0.048337
	gvcp_bc	0.224***	0.0485962
	gvcp_f	0.001	0.0038488
	gvcp_fs	0.002	0.0063896
	gvcp_fc	−0.001	0.0095947

*** $P < 0.01$, ** $P < 0.05$, * $P < 0.1$.

[a] *gvcp_b* = global value chain (GVC) backward embedding; *gvcp_bs* = GVC backward simple embedding; *gvcp_bc* = GVC backward complex embedding; *gvcp_f* = GVC forward embedding; *gvcp_fs* = GVC forward simple embedding; *gvcp_fc* = GVC forward complex embedding.

The methods and conclusions of this study can be further extended to industries other than forestry in the future. At the same time, for the expansion of the model, combining MRIO with competitive networks is an extension of the research model. In the research process, layering the competitive network and combining it with GVC can further integrate GVC with the embodied energy of the industry in the future, laying a foundation for future research.

Conclusions

In this article, we constructed a competitive network model to study the embodied energy competition relationship in forestry among different countries. Using the latest version of the WIOD, a forestry embodied energy competition network from 2000 to 2014 was constructed, with countries as nodes and competition relationships as edges. Weighting, clustering coefficients, and PageRank indicators were calculated to analyze the competition network. The impact of GVC embedding on competition intensity was studied through GVC, and some conclusions were obtained, providing a basis for the management of forestry embodied energy:

(1) In the embodied energy competition network of forestry, the intensity of export competition is higher than that of import competition. Because of the relatively fixed nature of forestry resources and the difficulty of moving production facilities, countries with abundant and scarce resources have established a relatively stable import competition relationship. However, in the context of economic development,

the expansion of forestry exports has led to increasingly fierce export competition among different countries.

(2) The core regions of the competitive network are mainly concentrated in Europe, Asia, and the Americas. The United States has always been in a competitive advantage position, with India and Germany ranking higher in export competition and significant changes in import competition. China is gradually replacing the United States as the core of import competition. This indicates that in the process of forestry industry transfer, the demand for resources in forestry production increases, imports will further increase, and import competition will become increasingly fierce, resulting in a change in ranking.

(3) The hierarchical structure of export competition is more pronounced than that of import competition. In the competitive network, a weighting degree of 200 is used as the midpoint for hierarchical division. In import competition, because of the distribution of forestry resources endowment, forestry imports are relatively fixed, so the hierarchical structure of the competition relationship is not obvious. However, in exports, countries around the world can all serve as exporting countries, making export competition more intense and hierarchical division more obvious.

(4) From the analysis of regression results, different GVC embedding methods have different impacts on competition. Among them, import competition is positively correlated with forward embedding and negatively correlated with backward embedding. Export competition is positively correlated with backward embedding, positively correlated with complex forward, and negatively correlated with simple forward.

The above research conclusions can effectively expand the current research perspective on forestry development. Analyze the performance of different regions in the competitive network, and better present the energy competition in forestry trade. Combining import competition with export competition can help determine the factors that affect the differences between imports and exports. Analyzing the structure of imports and exports can deeply explore the differences in development. Combining GVC with energy for forestry development can better illustrate the impact of different participation methods in GVC on forestry development, compared with the research on the trade network of forestry products and the embodied energy network of forest products (Korhonen et al. 2001, Côté et al. 2002). The article delves deeper into the competitive relationship between forestry product trade and embodied energy flow compared with research on other competitive networks (An et al. 2014, Kan et al. 2019, Wu and Chen 2019). Unlike previous studies that have applied this method to resource trade, this study further expands the scope of the method's application by combining it with embodied energy in forestry. The above conclusion is a supplement to the exploration of the relationship between forestry development and energy management and can provide a more accurate basis for managing forestry development, especially forestry energy use. At the same time, it provides innovative research models for exploring the energy footprint in world forestry development.

This study still has certain limitations. First, because of data limitations and the fact that the research department is only the forestry department, the research period can only be from 2000 to 2014. Therefore, it is necessary to update the data in a timely manner, strengthen the tracking ability of the data, and improve the accuracy and timeliness of the research. The research conducted during this period can lay the foundation for subsequent research, in which the data can be extended to a national perspective. For example, China's data on domestic input and output has been updated to 2020, which can be updated to the maximum extent possible in terms of research time. Second, the analysis of influencing factors solely on the basis of GVC is not comprehensive enough. In the future, more influencing factors should be considered for analysis of the impact of different factors. For example, taking into account the factors of energy transformation is something that future research needs to consider. Finally, in the future, actual energy use should be combined with embodied energy use for joint analysis in forestry development and management.

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Literature Cited

An, H., W. Zhong, Y. Chen, H. Li, and X. Gao. 2014. Features and evolution of international crude oil trade relationships: A trading-based network analysis. *Energy (Oxford)* 74:254–259. https://doi.org/10.1016/j.energy.2014.06.095

Bullard, C. W. and R. A. Herendeen. 1975. The energy cost of goods and services. *Energy Policy* 3(4):268–278. https://doi.org/10.1016/0301-4215(75)90035-X

Cederberg, C., U. M. Persson, K. Neovius, S. Molander, and R. Clift. 2011. Including carbon emissions from deforestation in the carbon footprint of Brazilian beef. Environ. Sci. Technol. 45(5):1773–1779. https://doi.org/10.1021/es103240z

Chen, C., F. Yi, H. Xiao, W. Xie, B. Liu, and L. Wang. 2023. The digital economy, spatial spillovers and forestry green total factor productivity. *J. Clean. Prod*. 405:136890. https://doi.org/10.1016/j.jclepro.2023.136890

Chen, Z. M. and G. Q. Chen. 2011. An overview of energy consumption of the globalized world economy. *Energy Policy* 39(10):5920–5928. https://doi.org/10.1016/j.enpol.2011.06.046

Comodi, G., L. Cioccolanti, L. Pelagalli, M. Renzi, S. Vagni, and F. Caresana. 2013. A survey of cogeneration in the Italian pulp and paper sector. Appl. Therm. Eng. 54(1):336–344. 10.1016/j.applthermaleng.2013.01.038

Costanza, R. 1980. Embodied energy and economic valuation. *Science* 210(4475):1219–1224. https://doi.org/10.1126/science.210.4475.1219

Côté, W. A., R. J. Young, K. B. Risse, A. F. Costanza, J. P. Tonelli, and C. Lenocker. 2002. A carbon balance method for paper and wood products. *Environ. Pollut*. 116(suppl. 1):S1–S6. https://doi.org/10.1016/S0269-7491(01)00240-8

Dietzenbacher, E., J. Pei, and C. Yang. 2012. Trade, production fragmentation, and China's carbon dioxide emissions. *J. Environ. Econ. Manag*. 64(1):88–101. https://doi.org/10.1016/j.jeem.2011.12.003

Glick, R. and A. K. Rose. 1999. Contagion and trade: Why are currency crises regional? *J. Int. Money Finance*. 4(18):603–617. https://doi.org/10.1016/S0261-5606(99)00023-6

Guan, J., Z. Zhang, and C. Chu. 2016. Quantification of building embodied energy in China using an input–output-based hybrid LCA model. *Energy Build*. 110:443–452. https://doi.org/10.1016/j.enbuild.2015.11.032

Guo, S., M. Han, Y. Yang, and H. Di. 2020. Embodied energy flows in China's economic zones: Jing-Jin-Ji, Yangtze-River-Delta and Pearl-River-Delta. *J. Clean. Prod*. 268:121710. https://doi.org/10.1016/j.jclepro.2020.121710

Hummels, D., J. Ishii, and K.-M. Yi. 2001. The nature and growth of vertical specialization in world trade. *J. Int. Econ*. 54(1):75−96.

Jakubik, A. and V. Stolzenburg. 2021. The 'China Shock' revisited: Insights from value added trade flows. *J. Econ. Geogr.* 21(1):67−95. https://doi.org/10.1093/jeg/lbaa029

Jin, Z., J. Wang, M. Yang, and Z. Tang. 2022. The effects of participation in global value chains on energy intensity: Evidence from international industry-level decomposition. *Energy Strat. Rev*. 39:100780. https://doi.org/10.1016/j.esr.2021.100780

Kan, S. Y., B. Chen, X. F. Wu, Z. M. Chen, and G. Q. Chen. 2019. Natural gas overview for world economy: From primary supply to final demand via global supply chains. *Energy Policy* 124:215−225. https://doi.org/10.1016/j.enpol.2018.10.002

Kayo, C., S. Hashimoto, and Y. Moraguchi. 2012. Paper and paperboard demand and associated carbon dioxide emissions in Asia through 2050. *J. Ind. Ecol.* 4(16):529−540.

Koopman, R., Z. Wang, and S.-J. Wei. 2014. Tracing value-added and double counting in gross exports. *Am. Econ. Rev*. 2(102):459−494.

Koopman, R., Z. Wang, and S.-J. Wei. 2012. Estimating domestic content in exports when processing trade is pervasive. *J. Dev. Econ*. 99(1):178−189. https://doi.org/10.1016/j.jdeveco.2011.12.004

Korhonen, J., M. Wihersaari, and I. Savolainen. 2001. Industrial ecosystem in the Finnish forest industry: Using the material and energy flow model of a forest ecosystem in a forest industry system. *Ecol. Econ*. 39(1):145−161. https://doi.org/10.1016/S0921-8009(01)00204-X

Lenzen, M. 1998. Primary energy and greenhouse gases embodied in Australian final consumption: An input–output analysis. *Energy Policy* 26(6):495−506. https://doi.org/10.1016/S0301-4215(98)00012-3

Leontief, W. 1970. Environmental repercussions and the economics structure: An input–output approach. *Rev. Econ. Stat*. 52:262−711.

Li, W., D. Xu, G. Li, and B. Su. 2020. Structural path and decomposition analysis of aggregate embodied energy intensities in China, 2012–2017. *J. Clean. Prod.* 276:124185. https://doi.org/10.1016/j.jclepro.2020.124185

Li, X., H. Zhang, X. Zhou, and W. Zhong. 2022. Research on the evolution of the global import and export competition network of chromium resources from the perspective of the whole industrial chain. *Resour. Policy* 79:102987. https://doi.org/10.1016/j.resourpol.2022.102987

Liang, M., M. González-Roglich, P. Roehrdanz, K. Tabor, A. Zvoleff, V. Leitold, J. Silva, T. Fatoyinbo, M. Hansen, and L. Duncanson. 2023. Assessing protected area's carbon stocks and ecological structure at regional-scale using GEDI lidar. *Global Environ. Change* 78:102621. https://doi.org/10.1016/j.gloenvcha.2022.102621

Liu, H., Y. Xi, J. E. Guo, and X. Li. 2010. Energy embodied in the international trade of China: An energy input–output analysis. *Energy Policy* 38(8):3957−3964. https://doi.org/10.1016/j.enpol.2010.03.019

Liu, L.-C., Q.-M. Liang, and Q. Wang 2015. Accounting for China's regional carbon emissions in 2002 and 2007: Production-based versus consumption-based principles. *J. Clean. Prod*. 103:384 392. https://doi.org/10.1016/j.jclepro.2014.07.009

Liu, Y., Y. Li, and Y. Pu. 2024. Exploring the endogenous structure and evolutionary mechanism of the global coal trade network. *Energy Econ*. 136:107710. https://doi.org/10.1016/j.eneco.2024.107710

Lv, L., G. Song, X. Zhao, and J. Chen. 2021. Environmental burdens of China's propylene manufacturing: Comparative life-cycle assessment and scenario analysis. *Sci. Total Environ*. 799:149451. https://doi.org/10.1016/j.scitotenv.2021.149451

Meng, B., G. P. Peters, Z. Wang, and M. Li. 2018. Tracing CO2 emissions in global value chains. *Energy Econ.* 73:24−42. https://doi.org/10.1016/j.eneco.2018.05.013

Moreau, V. and F. Vuille. 2018. Decoupling energy use and economic growth: Counter evidence from structural effects and embodied energy in trade. *Appl. Energy*, 215:54−62. https://doi.org/10.1016/j.apenergy.2018.01.044

Nayan Yadava, R. and B. Sinha. 2019. Developing energy access index for measuring energy poverty in forest fringe villages of Madhya Pradesh, India. *Sustain. Energy Technol. Assess*. 31:167−178. https://doi.org/10.1016/j.seta.2018.12.013

Pan, A., T. Xiao, L. Dai, and X. Shi. 2022. Global transfer of embodied energy: From source to sink through global value chains. *Sustain. Prod. Consump*. 31:39−51. https://doi.org/10.1016/j.spc.2022.01.030

Rocco, M. V. and E. Colombo. 2016. Evaluating energy embodied in national products through Input–Output analysis: Theoretical definition and practical application of international trades treatment methods. *J. Clean. Prod*. 139:1449−1462. https://doi.org/ w10.1016/j.jclepro.2016.09.026

Shabbir, I. M. Mirzaeian. 2017. Carbon emissions reduction potentials in pulp and paper mills by applying cogeneration technologies. *Energy Proc*. 112:142−149. https://doi.org/10.1016/j.egypro.2017.03.1075

Shao, L., J. Hu, and H. Zhang. 2021. Evolution of global lithium competition network pattern and its influence factors. *Resour. Policy* 74:102353. https://doi.org/10.1016/j.resourpol.2021.102353

Shi, Q., Y. Zhao, Z. Qian, L. Zheng, and S. Wang. 2022. Global value chains participation and carbon emissions: Evidence from Belt and Road countries. *Appl. Energy* 310:118505. https://doi.org/10.1016/j.apenergy.2021.118505

Song, B., J. Tang, F. Long, Y. Peng, F. Bi, Y. Kang, and D. Qian. 2024. Analysis of forestry management based on dynamic life cycle assessment of biogenic carbon: A case study of a forestry resource-based city in Northeast China. *J. Clean. Prod*. 442:141078. https://doi.org/10.1016/j.jclepro.2024.141078

Su, B. and B. W. Ang. 2017. Multiplicative structural analysis of aggregate embodied energy and emission intensities. *Energy Econ*. 65:137−147. https://doi.org/10.1016/j.eneco.2017.05.002

Su, B., B. W. Ang, and Y. Li. 2019. Structural path and decomposition analysis of aggregate embodied energy and emission intensities. *Energy Econ*. 83:345−360. https://doi.org/10.1016/j.eneco.2019.07.020

Sun, L., W. Zhou, X. Zhu, and X. Xia. 2023. Deforestation embodied in global trade: Integrating environmental extended input–output method and complex network analysis. *J. Environ. Manag*. 325(Pt A):116479. https://doi.org/10.1016/j.jenvman.2022.116479

Sun, X. and Q. Shi. 2022. Factors influencing embodied energy trade between the Belt and Road countries: A gravity approach. *Environ. Sci. Pollut. Res*. 29(8):11574−11589. https://doi.org/10.1007/s11356-021-16457-y

Tao, F., Z. Xu, A. Duncan, X. Xia, X. Wu, and J. Li. 2018. Driving forces of energy embodied in China-EU manufacturing trade from 1995 to 2011. *Resour. Cconserv. Recycl*. 136:324−334. https://doi.org/10.1016/j.resconrec.2018.04.021

Turner, K., M. Lenzen, T. Wiedmann, and J. Barrett. 2007. Examining the global environmental impact of regional consumption activities—Part 1: A technical note on combining input–output and ecological footprint analysis. *Ecol. Econ*. 62(1):37−44. https://doi.org/10.1016/j.ecolecon.2006.12.002

Wang, Y., R. Wang, K. Tanaka, P. Ciais, J. Penuelas, Y. Balkanski, J. Sardans, D. Hauglustaine, W. Liu, X. Xing, J. Li, S. Xu, Y. Xiong, R. Yang, J. Cao, J. Chen, L. Wang, X. Tang, and R. Zhang. 2023. Accelerating the energy transition towards photovoltaic and wind in China. *Nature* 619(7971):761−767. https://doi.org/10.1038/s41586-023-06180-8

Wang, Z., S.-J. Wei, and K. Zhu. 2013. Quantifying international production sharing at the bilateral and sector levels. NBER Working Paper, No. 19677. National Bureau of Economic Research, Cambridge, Massachusetts.

Wei, L., W. Li, and Z. Jin. 2024. Global value chains participation and trade-induced carbon inequality: A comparative analysis of developed and developing economies. *Ecol. Econ*. 220:108186. https://doi.org/10.1016/j.ecolecon.2024.108186

Wu, X. F. and G. Q. Chen. 2019. Global overview of crude oil use: From source to sink through inter-regional trade. *Energy Policy* 128:476−486. https://doi.org/10.1016/j.enpol.2019.01.022

Xia, X. H., B. Chen, X. D. Wu, Y. Hu, D. H. Liu, and C. Y. Hu. 2017. Coal use for world economy: Provision and transfer network by multi-region input–output analysis. *J. Clean. Prod*. 143:125−144. https://doi.org/10.1016/j.jclepro.2016.12.142

Xu, J., J. Li, V. Charles, and X. Zhao. 2023. Evolution of the rare earth trade network: A perspective of dependency and competition. *Geosci. Front*. 15(3):101653. https://doi.org/10.1016/j.gsf.2023.101653

Zhang, B., H. Qiao, Z. M. Chen, and B. Chen. 2016. Growth in embodied energy transfers via China's domestic trade: Evidence from multi-regional input–output analysis. *Appl. Energy* 184:1093−1105. https://doi.org/10.1016/j.apenergy.2015.09.076

Zhang, H., Q. Ji, and Y. Fan. 2014. Competition, transmission and pattern evolution: A network analysis of global oil trade. *Energy Policy* 73:312–322. https://doi.org/10.1016/j.enpol.2014.06.020

Zhang, K., Z. Yang, Q.-M. Liang, H. Liao, B.-Y. Yu, and Y.-M. Wei. 2023. China's carbon emissions and energy demand under different methods of global mitigation cooperation: Application of an extended RICE model with energy details. *Energy* 285:129290. https://doi.org/10.1016/j.energy.2023.129290

Zhang, Y., C. Chen, B. Ma, and S. Jin. 2024. Trade effects of transnational timber legality assurance regimes: Evidence from the Lacey Act amendment on China's forest product exports. *Forest Policy Econ*. 158:103117. https://doi.org/10.1016/j.forpol.2023.103117

Zhao, Q., S. Ding, Z. Wen, and A. Toppinen. 2019. Energy flows and carbon footprint in the forestry-pulp and paper industry. *Forests* 10(9):725. https://doi.org/10.3390/f10090725

Zhu, K., L. Hao, and Y. Zhao. 2023. Research on the evolution and influence mechanism of international liquefied natural gas import competition pattern. *J. Clean. Prod*. 414:137602. https://doi.org/10.1016/j.jclepro.2023.137602