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Original Paper

Evolution, resilience and causes of global petroleum gas trade networks: 1995–2020

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ABSTRACT

Based on the HS 4-digit code trade data in UNCOMTRADE from 1995 to 2020, this paper analyzes the characteristics of the evolution of the global PG trade network using the complex network approach and analyzes the changes in its resilience at the overall and country levels, respectively. The results illustrated that: (1) The scale of the global PG trade network tends to expand, and the connection is gradually tightened, experiencing a change from a “supply-oriented” to a “supply-and-demand” pattern, in which the U.S., Russia, Qatar, and Australia have gradually replaced Canada, Japan, and Russia to become the core trade status, while OPEC countries such as Qatar, Algeria, and Kuwait mainly rely on PG exports to occupy the core of the global supply, and the trade status of other countries has been dynamically alternating and evolving. (2) The resilience of the global PG trade network is lower than that of the random network and decreases non-linearly with more disrupted countries. Moreover, the impact of the U.S. is more significant than the rest of countries. Simulations using the exponential random graph model (ERGM) model revealed that national GDP, institutional quality, common border and RTA network are the determinants of PG trade network formation, and the positive impact of the four factors not only varies significantly across regions and stages, but also increases with national network status.

1. Introduction

As a major global energy fuel, petroleum gas (PG) is an indispensable strategic resource for the survival and development of nations, is a core strategic resource for country's energy security. In 2021, the world's energy production amounted to 14,154,610,000 tons of standard oil, of which 3,817,460,000 tons of standard oil was produced from PG and its feedstocks, which accounted for 26.9%, and the import and export trade of PG and its feedstocks accounted for about 31.6% (National Statistical Office, 2021). The PG mainly consists of liquefied natural gas (LNG), liquefied petroleum gas (LPG), and their gaseous forms like compressed natural gas (CNG). Compared with fossil energy, PG has less pollution to the environment in the process of production and consumption. Besides, the world's major crude oil producers have a significant impact on the global energy trade pattern. In 2022, the production of “OPEC+” member countries declined by 770,000 barrels per day (bpd) to 29.02 million bpd, while the production of non-OPEC member countries increased by 270,000 bpd to 15.37 million bpd. The strictly planned production cuts and increases of the OPEC + coalition have played a key role in maintaining supply stability and avoiding major ups and downs due to unforeseen factors, and have become an important indicator of changes in prices in the international energy market. The unequal distribution of PG in different geographical regions and the contradiction between supply and demand have accelerated its trade process. Most countries participate in international oil and gas trade to obtain PG resources and thus a complex network has been formed by the intricate competition between oil and gas exporters. Therefore, it is important to study the pattern of the global PG trade network, identify the influence and control of major countries over global energy, examining the resilience patterns of the trade networks to shocks and explore the causes behind it.

Based on complex network analysis (CNA), existing studies examined the schema of the LNG and LPG trade network as well as the changes of trade position in major countries. They found that

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the global trade network prefers to expanding and becoming greatly connected (Bhattacharya et al., 2008; Fagiolo et al., 2008; Kali and Reyes, 2010; Kandogan, 2017) with an immutable "core-edge" hierarchy (Kali and Reyes, 2007) and a local "rich club" behavior (Garlaschelli and Loffredo, 2004). A competitive relationship between imports and exports is formed in PG network. The expansion of trade connections can make risks and enhance energy security weaker (An et al., 2014; Ji et al., 2014). Many joint trading partners make the establishment of fossil energy trade collaboration promoting (Guan and An, 2017).

However, scholars mainly analyze the evolutionary features of global oil trade networks based on stable scenarios, and neglect the impact of national PG supply or demand disruptions caused by external shocks. Such as the Russia-Ukraine conflict and the Iraq war can affect network resilience. In fact, the increase of uncertainties has had a disruptive influence on the global energy trade form threatening the sustainability of global energy trade and national energy security directly (Wang et al., 2021). One of the reasons is that PG is given more strategic resources and political attributes, and its trade is more influenced by geopolitical events. If one country stops supplying or cuts off demand to other countries, this can be transmitted through partner countries to other countries or even to the entire network, thus having a "cascading" effect on the entire network. Russia cut gas deliveries to Germany via the Nord Stream pipeline by 60% on June 15, 2022. The disruption of the Nord Stream 1 pipeline, which affects winter heating and power generation in Europe, has led to a significant increase in PG imports from the U.S.

The original define of resilience refers to the skill of the ecosystem to assimilate, transform and recover to a stable state when it is impacted and disturbed (Ahmadian et al., 2020). In PG trade network, it can be regarded as the restoration, maintenance and even improvement of network functions in the whole region when it is impacted or interfered by the outside world. Therefore, it is significant to identify the evolution form of global PG trade, characterize the control force of different countries and model how energy supply and demand disruptions affect the PG trade support network.

This paper analyzes the characteristics of the evolution of the global PG trade network using the complex network approach and analyzes the changes in its resilience. The results illustrated that the scale of the global PG trade network show a shift from a "supply-oriented" to a "supply-and-demand" pattern, in which the U.S., Russia, Qatar, and Australia have gradually replaced Canada, Japan, and Russia to become the core trade status, while OPEC countries such as Qatar, Algeria, and Kuwait mainly rely on PG exports to occupy the core of the global supply, and the trade status of other countries has been dynamically alternating and evolving. The resilience of the global PG trade network is lower than that of the random network and decreases non-linearly with more disrupted countries. Moreover, the impact of the U.S. is more significant than the rest of countries.

The contributions are as follows: Firstly, determine the oil and gas trade pattern from multiple perspectives such as the overall network structure, internal nodes by using the complex network method. This is a new enlightenment on the relationship of competition and collaboration among countries which treat PG as a strategic resource. Furthermore, reveal the structural characteristics such as the evolution process of the global PG trade network, so as to provide a reference for understanding the global crude oil trade network and its evolution process. Secondly, investigate the influence of exogenous shocks on the resilience of global PG trade network in an unstable state through interruption simulation and measure the overall network resilience in key years. Compare the difference between resilience of real and random network in the interruption process. Describe the economic connotation behind the interruption models so as to promote global multilateral coordinated governance, formulate energy trade rules, thus provide inspiration for ensuring global energy security. Third, numerical simulations using the ERGM model are used to statistically compare with the observed network to identify the driving factors behind the evolution of the global LPG trade network.

2. Methods and data

2.1. Global PG trading network construction

Based on the research of Wasserman and Faust (1994), we adopt the social network approach (SNA) to construct global PG trading network, and select indicators to portray the structural changes in trade. In the network, countries are regard as nodes, and the PG import and export relationships are regard as edges. We can form a topological network $\boldsymbol{G}$:

$$\boldsymbol{G} = (\boldsymbol{V}, \boldsymbol{E}, \boldsymbol{w}) \tag{1}$$

where $\boldsymbol{V}$ stands for a set of nodes v_i $(i = 1, 2, \ldots, N)$ for each country or region (abbreviated as country). $\boldsymbol{E}$ is the edges of imports and exports between countries. w_{ij} is regard as the weight for each edge, meaning the value of trades between countries i and j, and $\boldsymbol{W}_{1\le i,j\le N}$ is the PG trade network matrix corresponding to $\boldsymbol{E}$. The countries differ yearly, and the scale of unilateral trade is small, which make it impossible to construct a trade network matrix that encompasses all countries. Besides, With the import and export countries reporting the trade size according to CIF and FOB prices, the bilateral data statistics have some inconsistencies. For clarity, we follow Fagiolo et al.'s convention (Fagiolo et al., 2008) to assume the average PG trade value as the actual trade value.

2.2. Degree centrality

This paper selects degree centrality as trade status metrics and import dependence as trade dependence index to reveal the size and strength of each country. Degree centrality is the incoming *indegree* added to *outdegree* centrality:

$$Degree_i = \sum_i {w_{ij}}^{+} + \sum_i {w_{ij}}^{-} = indegree_i + outdegree_i \tag{2}$$

where the $\sum_i {w_{ij}}^{+} = indegree_i$ is defined as the amount of export from all j nodes to i nodes representing the import trade status and $\sum_i {w_{ij}}^{-} = outdegree_i$ captures the reverse direction and represents the export trade status. A more extensive $Degree_i$ is regarded as a more complicated range of partner countries or larger scale of trade in the i country, and thus i country has a more significant impact on other countries. A higher import trade position indicates that country i carries out more PG imports from or with more countries, the stronger its demand impact on the network. A higher export trade position indicates that country i exports more PG to other countries in the network, with a stronger supply impact on the network. The three indicators are differentiated by portraying the status of trade in different dimensions: aggregate, demand and supply.

2.3. Network resilience index

Network resilience evolved from the concept of resilience proposed by Holling (1973), which refers to the skill of a network structure to keep or restore function when the network is subjected to exogenous shocks. Networks of trade relations can occur between countries that are not in direct contact or even geographically distant (Caldara and Iacoviello, 2022). For this reason, we refer to Han and Shin (2016) and Mou et al. (2020), using Eq. (3) to measure network resilience.

$$Resilience = \frac{C*N}{Density*Avdegree} \tag{3}$$

where *Resilience* is regard as the resilience of the trade network, C is regard as the connectivity, N is regard as the number of nodes, and *Avdegree* is regard as the weighted-average degree centrality. The advantage of Eq. (3) is that it can examine the impact of PG supply or demand disruptions based on external shocks on network elasticity from the perspective of internal network structure (e.g., network density, mean path length). It overcomes the strong assumption that only direct connection can be transmitted in the virus propagation model, and is therefore more widely applicable. Among them, connectivity is the prime factor and this effect is more pronounced during the recovery periods. When the network is disturbed, a well-connected one could provide alternative connections to help it recover from the shock. Based on the above, network connectivity is positively related to network resilience, and we focus on the viewpoint of network transmission. The equation is expressed as:

$$C = \frac{\sum_{i \neq j \in G} \frac{1}{d_{ij}}}{N(N-1)} \tag{4}$$

where C ranges from 0 to 1, and d_{ij} is the shortest path among every node. The d_{ij} is the second shortest, and the more connection can be achieved by other nodes. Larger N denotes the rest of nodes, so that more nodes will spread the influence compromising the effectiveness of network when the local nodes are impacted. Meanwhile, greater *Density* denotes more connections among nodes. If the local nodes are impacted, more nodes will be affected. This phenomenon leads to a worse network in terms of resilience. Finally, $Avdegree = \frac{Degree}{N}$ denotes the central position of all nodes on average. The wider range of communication is established between the network nodes and other nodes, the stronger degree of connection is established. If the local nodes of the network are affected, the greater *Avdegree* will direct to a worse resilience of the network.

2.4. Data description and analysis

As defined by HS1992 code, PG is mainly composed of LNG, LPG, and other gases. The data are gained from the UN COMTRADE database (https://comtrade.un.org/db/). The PG products are related to code HS2711 in the HS1992 4-digit code, and the sample observation period is 1995–2020. The number of countries with PG trade varies yearly as not all countries submit bilateral trade data to the United Nations normatively. Specifically, the number of countries involved in the PG trade in each year from 1995 to 2020 ranges from 194 to 221, with specific comparisons shown in Fig. 1.[1] As can be seen: the number of countries that traded in 1995–2020 is not equal to the number of countries selected for this paper, and the countries excluded from it are also not equal. The number of countries involved in PG trade shows a fluctuating increasing trend, indicating that the global PG trade network scale shows a gradual expanding trend, and globalization is a general trend. From 1995 to

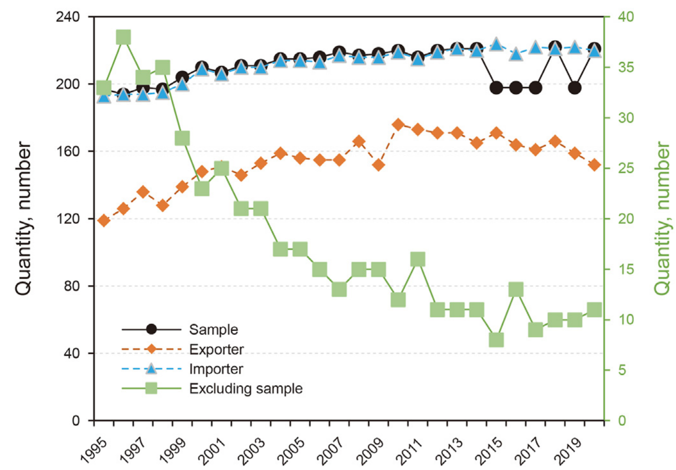


Fig. 1. Comparative change in sample and excluded sample size.

2020, the number of countries not included in the sample varies from year to year, with an overall 60. The reasons for the absence of these countries are mainly as follows: first, the data on the export trade or import of individual countries are missing. Second, some countries have only import or only export, or neither, which is not easy to analyze. Thirdly, some countries were excluded because they had not been trading during 1995–2020 or because there were entries and exits. Finally, these countries are all missing or few countries in the global LPG trade, and they are not big oil producing or consuming countries, so if they are put into the network, they are also in a marginal position, and thus will not have a systematic impact on the pattern of the whole global LPG trade network. Even if they were excluded, this would not affect the main conclusions.

Further from Fig. 2, there are some countries that are missing all the time in different years, and most of them are missing only in stages, while individual countries are alternately missing. Specifically, of the total of 60 excluded countries, they can be roughly analyzed in four broad categories as follows.

(1) Basically persistent. It mainly includes Armenia, Cocos Islands, Ethiopia, Iraqi, Kyrgyzstan, Madagascar, Nepali, St Helena, Sao Tome and Principe, Turks and Caicos Islands, Tajikistan, Tonga, indicating that the country occasionally trades in PG in these years, trades in most years, and has a relatively stable situation of entering and exiting international markets.
(2) Alternate culling. Including American Samoa, Bhutan, Central African Republic, Cyprus, Falkland Islands, Guinea-Bissau, Lesotho, Norfolk Island, Solomon Islands, Chad, Tokelau, Tuvalu and Wallis and Futuna, etc., which indicates that these countries have irregular entry and exit from the international market of PG, and the stability is not high.
(3) With the Libyan war as the boundary, basically all of them were eliminated before 2011. Including Caribbean Netherlands, St. Barthelemy, Bahrain, South Sudan, Somalia and other countries, the war may have impacted these countries to a certain extent.
(4) All the years were excluded. Such as Czechoslovakia, Bahrain and Suriname, indicating that these countries hardly conduct international trade in PG or the trade data is really serious, and these countries have the worst stability in entering and leaving the international market.

However, regardless of the variations, these countries are

[1] This paper includes 236 countries (listed in Appendix A with ISO codes).

Excluding sample	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
AFG	1	1		1			1																			
ANT																	1	1	1	1	1	1	1	1	1	1
ARM	1																									
ASM	1	1	1	1	1									1												
ATF			1		1									1	1	1	1	1	1	1					1	
BES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1		1	1
BLM	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1											1
BTN	1	1	1				1	1		1																
BWA	1	1	1	1	1																					
CAF																	1	1	1					1		
CCK							1																			
COK			1				1																			
CSK	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
CUW	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1										
CXR					1																					
CYM						1	1		1																	
DDR	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
DJI						1			1			1														
ERI	1	1		1		1	1	1				1					1	1	1					1		
ETH		1																								
FLK	1			1		1																				
GNB								1				1													1	
GNQ	1	1		1										1												
GUM	1	1	1	1	1																					
IOT	1	1	1	1	1				1	1	1		1	1	1	1	1	1	1	1	1	1				1
IRQ		1																								
KGZ					1																					
LSO	1	1	1	1	1						1		1													
LUX	1	1	1	1																						
MDG		1																								
MNE	1	1	1	1	1	1	1	1	1	1	1															
MNP								1				1	1	1			1		1							
MSR				1																		1	1	1	1	
MYT	1	1	1	1	1	1														1	1	1	1	1	1	1
NAM	1	1	1	1	1																					
NFK							1	1			1						1					1	1			
NIU	1	1	1	1	1	1	1	1	1																	
NPL	1	1																								
NRU		1	1						1				1													
PCN		1	1	1	1	1	1		1								1	1		1		1		1		
PLW	1	1	1			1	1	1	1	1																
PSE	1	1	1	1	1	1	1	1	1	1	1	1														
SCG												1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SHN																										1
SLB			1				1	1		1	1															
SMR	1	1	1	1	1	1	1	1	1	1	1	1			1	1										
SOM	1	1	1	1			1	1	1								1									
SRB	1	1	1	1	1	1	1	1	1	1	1															
SSD	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1									
STP			1	1											1											
SUN	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SWZ	1	1	1	1	1																					
SXM		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1										
TCA	1																									
TCD				1	1	1																				
TJK											1															
TKL	1	1	1	1	1	1				1				1	1	1	1	1		1		1				1
TLS	1	1	1	1	1																					
TON				1			1																			
TUV		1				1			1						1											
WLF	1	1	1	1																		1				

Fig. 2. Excluding changes in countries entry and exit dynamics.
Note: 1 represents the year of exclusion.

basically small PG trading countries, and their impact on the measurement of the global trade position of countries is relatively small. Of course, there are individual countries that have a certain amount of trade with the marginal countries in this paper's network, and the removal of these small trade volume countries will have a slight impact on the trade position of some other marginal countries, but will not change the latter's position in the global trade pattern. This is because even if all the excluded countries are put into the matrix, it will not have a significant impact on the core and non-core countries in the world.

The PG trade among selected samples is highly representative, which is important for the accuracy and reliability of this paper. We plotted the changes in global PG sample trade (Sample), actual trade (Real), and the ratio between them (Percentage) from 1995 to 2020 (in Fig. 3). The global PG sample trade (light red) and the actual trade (green) both show apparent fluctuating upward trends, and both are relatively close. Though the trade scale of excluded countries is small, the follow analysis shows that this does not affect the subsequent results significantly. The red line (Sample/Real) stays above 98% (98.2% at the lowest value in 1997), which indicates that the sample is highly representative of the global PG trade. As seen from the changes of the red bar graph, the global PG trade from 1995 to 2020 shows a rapid growth trend of climbing and then fluctuating decline, from $36.9 billion at the beginning of the period to $217.3 billion in 2020, with an average annual growth rate of 7.3%. According to different change characteristics, the global PG trade in 1995–2020 can be divided into three stages: rapid development (1995–2008), high stability (2009–2014), and fluctuating development (2015–2020). The global PG trade was about 36.9 billion U.S. dollars in 1995 and increasing to 64.2 billion U.S. dollars in 1997 slowly and then dropped to 51.1 billion U.S. dollars in 1998. The rapid decline in LPG trade in 1998–1999 may be related to the 1998 financial crisis in South-East Asia (SA). The rapid decline in LPG trade in 1998–1999 may be related to the plunge in international crude oil prices in 1998. From the demand side, the outbreak of the SA in 1998 led to a deceleration of global economic growth, which in turn led to a significant reduction in the growth rate of global oil demand. From the market side, oil prices from January 1997, to December 1998, nearly two years since the high point of Brent crude oil prices fell from 24.80 U.S. dollars/barrel to 9.75 U.S. dollars/barrel, the interval of the largest decline of 61%, the sharp decline in oil prices inhibited the release of production capacity of the major crude oil-producing countries. From the supply side, after 1999, OPEC in April and July 1998, twice announced plans to significantly reduce crude oil production, in September 2001, January 2002, twice announced production limits to protect prices, including Russia, including non-OPEC countries have also committed to reduce production, these factors oil prices to stop the decline back up, resulting in the global trade in oil and gas first appeared to be a declining trend, and then from 2000 to 2007 gradually and slowly climbed up. In contrast, the subprime lending crisis (SLC) in 2008 had a substantial destructive effect that the PG trade declined rapidly in 2009. In high stable stage (2009–2014), the PG trade climbed faster and reached a maximum value of 425.3 billion USD in 2014 and entering a “golden period” of development. Then, PG trade shows a rapid decline after 2015 and reaching $217.3 billion in 2020. However, it has increased about seven times compared to 1995. In conclusion, the research sample is highly representative, and the global PG trade tends to expand but shows various evolutionary characteristics at different stages.

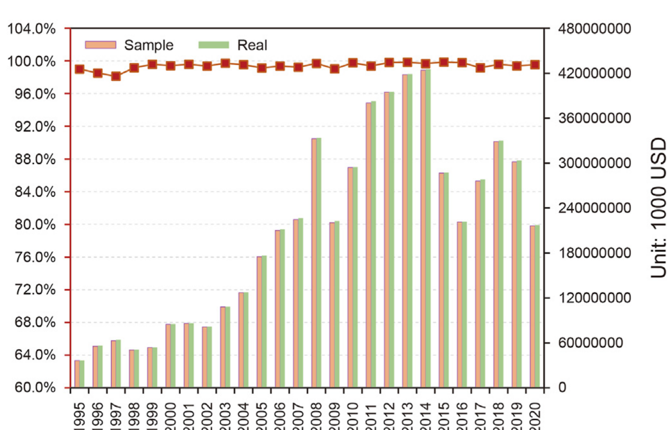


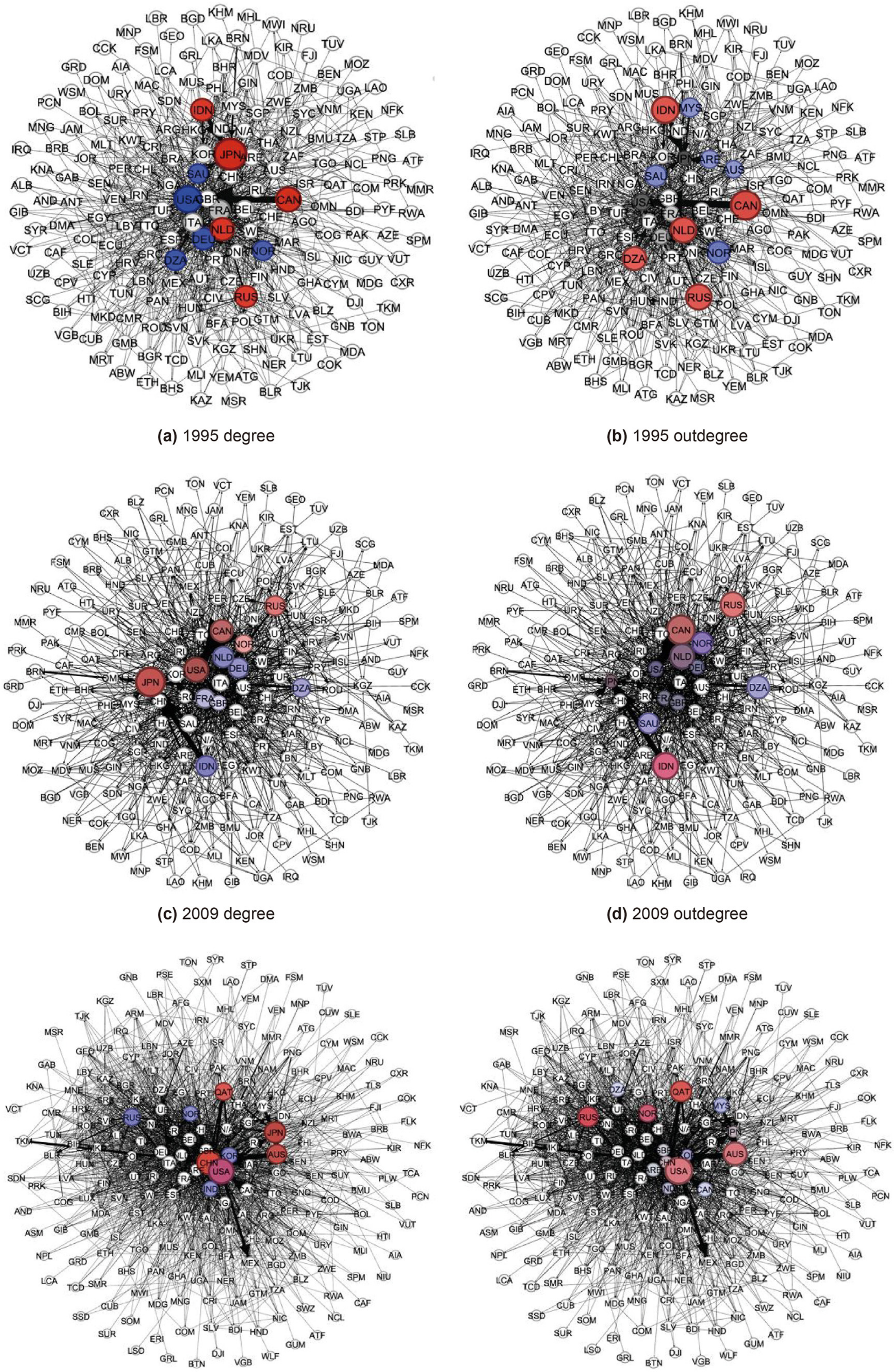
Fig. 3. Global PG selected sample, actual trade and its share change, 1995–2020.
Note: The left vertical coordinate corresponds to Percentage, and the right corresponds to Real and Sample.

3. Evolutionary features of global PG trading network and resilience results

3.1. Overall structure changes

Using the gravitational-directed algorithm and the research of Nooy et al. (2008), we plotted the PG trade topology in 1995, 2009, and 2020 by degree (left subfigure of Fig. 4) and outdegree (right subfigure of Fig. 4). The red and purple one represents the core and sub-core countries, while others represent marginal countries. It is worth clarifying that the core and sub-core countries is defined in terms of the size of trade and the size of the range of trading partners. Core countries engage in greater import and export trade in LPG with a larger number of countries, while non-core countries have relatively fewer. Typically, core countries have a stronger influence on the overall structure of the network than sub-core countries. It should be noted, however, that core countries are not necessarily major oil producers, but may also be large oil demanders, and that non-core countries, despite their smaller trade size, may occupy hub locations or transportation pipeline locations for global oil transportation and thus have a significant impact on global oil trade. Therefore, the definition of core and non-core countries is mainly analyzed from the perspective of trade linkages between countries, rather than from the perspective of whether individual countries have strong demand or supply capacity. We can observe the following conclusions through it.

(a) In 1995, the network was sparse, with few connected edges and uneven distribution of connections, which indicates that the PG trade is relatively small and unequal of control over PG resources among countries in its initial stage. Canada, Japan, Russia, Netherlands and Indonesia occupy the core position. The USA, Germany, Norway and United Arad Emirates are in the sub-core position. Most of the other countries are in a marginal position. France, Malaysia, Korea, Italy, Australia, United Kingdom and Kuwait, despite their non-core position, trade more with the core countries. Meanwhile, the other peripheral countries are mainly distributed in the periphery of the trade network, such as Cambodia, Mozambique, Myanmar, Kazakhstan, Mali, Albania, Mongolia, and Libya (in a clockwise direction), etc., which trade more than with the core countries. Their distribution in relation to the periphery of the network may be related to their geographic location, political factors, lack of transportation pipelines, and the structure of domestic energy sources, among other factors. As a result, the global PG trade has formed a “core-sub-core-edge” hierarchical network structure.



(a) 1995 degree

(b) 1995 outdegree

(c) 2009 degree

(d) 2009 outdegree

(e) 2020 degree

(f) 2020 outdegree

From the perspective of structural trade relations to analyze the trade status of countries may have errors. For example, there are some OPEC countries that are not mainly rely on PG exports, and their trade status is not high but can even compete with the core countries. Canada, the Netherlands, Indonesia, Russia and so on still occupy the core position, but one of the OPEC countries Algeria is also out of the core position, and Saudi Arabia, the United Arab Emirates and other OPEC members in the sub-core position. Overall, the number of OPEC members occupies three seats in the sub-core countries and above. Comparing the two subfigures, the main core countries rely on import and export trade to occupy the core position, while some OPEC countries rely on a large amount of export trade to occupy the core of the network, and their influence on the network pattern is significant.

(b) In 2009, the network became denser and more connected than in 1995, and global PG trade links became stronger. The core countries did not change fundamentally, but the number of OPEC members in the sub-core countries decreased.

Further analysis of the right sub-figure shows that Indonesia occupies a central position in the export trade position, while Japan and the U.S. are in a non-central position and OPEC countries such as Saudi Arabia and Algeria are in a sub-central position. The analysis shows that, on the one hand, the global core status is realized mainly through export trade, while only some OPEC countries occupy the core status, which is realized mainly through a large number of exports, and Indonesia has a high export status, while the core status of the U.S. and Japan is mainly due to a large number of imports.

(c) In 2020, the overall density of the network is more pronounced and many countries established extensive and well-connected trade relations. Following the above analytical line of thought, this paper further draws the following basic conclusions: in 2020, the U.S., Russia, Qatar and Australia are the core countries of global PG trade, and these countries rely on a large number of exports to achieve a consolidated trade position, while China relies mainly on a large number of imports to achieve a core position in trade, and the other countries, such as Algeria, Malaysia, the UAE of Canada, and Norway have a high position in the export trade.

The above analysis shows that from 1995 to 2020, the distribution structure of global core countries, sub-core countries and peripheral countries presents a relatively stable hierarchical structure, and undergoes a change from “supply-led” to “supply and demand co-exist”. The structural change lies in the fact that the trade pattern of OPEC countries is constrained and affected by the demand of the U.S., China and Russia. Of course, the evolution of the PG trade pattern mentioned above is also the result of a comprehensive game of political economy and other multiple factors among countries.

3.2. Changes in the distribution of export trade status

Since it is difficult to reflect the source of countries' trade position in terms of the structure of supply or demand, we further calculate the centrality of countries' exports in 1995, 2010 and 2020 and plot the changes in the distribution of the top 20 countries' export trade positions and their contribution to trade (in Fig. 5). In 1995, Canada, Japan, Indonesia, Netherlands, and Russia were the top 5 countries, each with an outdegree centrality of more than USD 8.1 billion, occupying the core position and being the highest PG trading countries in the world. Among the top 20 countries, only Mexico, France, Germany, and the U.S. have an export contribution of less than 80%, which suggests that these countries rely mainly on PG imports to achieve their climbing trade position, while the top 5 countries rely mainly on exports to achieve their core position. The follow with outdegree centers between $4–8 billion, they are the USA, Algeria, Norway, Saudi Arabia, and German. Other countries have a low trade position and most are marginalized. For example, France, the United Kingdom, Belgium, the Republic of Korea and, in Fig. 5(b), the Republic of Vanuatu, Bangladesh, Mongolia, Samoa, Rwanda, São Tomé and Príncipe, Guinea-Bissau, Singapore and Mauritius, which trade even only a few tens of thousands of dollars.

In 2010, the distribution of the top 20 countries is similar to that of 1995, with the major difference being that those countries such as Qatar, Russia and Norway, and Algeria, respectively, have replaced the core countries of 1995 as the new core countries for trade, while others such as Indonesia, Malaysia, Australia and Nigeria have become sub-core countries. Moreover, the outdegree centrality of trade position of the above countries is mainly achieved through exporting PG exports, while other countries such as the U.S., the Netherlands, Germany and the United Kingdom are still relying on imports to achieve a non-marginalized trade position. The rest of the countries, as shown in Fig. 5(d), have a smaller trade size and partners, and thus are marginalized.

In 2020, the U.S. and Australia's export position replaces Qatar and Russia, Qatar drops two places to replace Norway, and the three countries become the most important core countries, and their impact on PG imports of all countries in the world is huge. Secondly, some OPEC countries including Algeria, Nigeria, UAE, Saudi Arabia, etc., as well as Russia, Norway, Malaysia, and Canada, etc., respectively, occupy a sub-core position globally, and the impact of these countries on the global supply of PG resources is significantly larger than that of the very peripheral countries in the graph of Fig. 5(f), the latter such as Eritrea, Warris and Futuna, and Norfolk Island. the strategic competition for PG resources among the core powers tends to be intense, with the U.S., Australia and major OPEC countries having substantial influence. The U.S. has formulated and implemented energy independence policies actively, then the oil dependence on foreign countries fell to below 50% in 2011. The U.S. developed a sound system of commercial reserves to maintain control of the international oil market and pricing power. It has made the Malacca Strait, Taiwan Strait, Strait of Hormuz, Suez Canal, Strait of Gibraltar, and other water transport channels becoming the focus of strategic control. Because almost all of these places are essential for oil transportation, the U.S. maintains military control and political influence in and around them, thus holding its status as a core trading nation. Australia, Qatar and Russia owe more abundant resources such as oil and PG, and strengthened their PG trade ties with the U.S. In contrast, Russia is the sole conduit for regional oil and gas exports from Central Asia and the Caspian Sea region. It is the de facto controller of Central Asia's oil and gas flows, and with its abundant domestic oil and gas resources, its trade position cannot be ignored.

Fig. 4. Global PG trade topology network for representative years.
Note: Red and purple represent core and sub-core countries, respectively, other colors represent marginal countries. The thickness of the edge is proportional to trade size, and node shape size is plotted according to degree or outdegree.

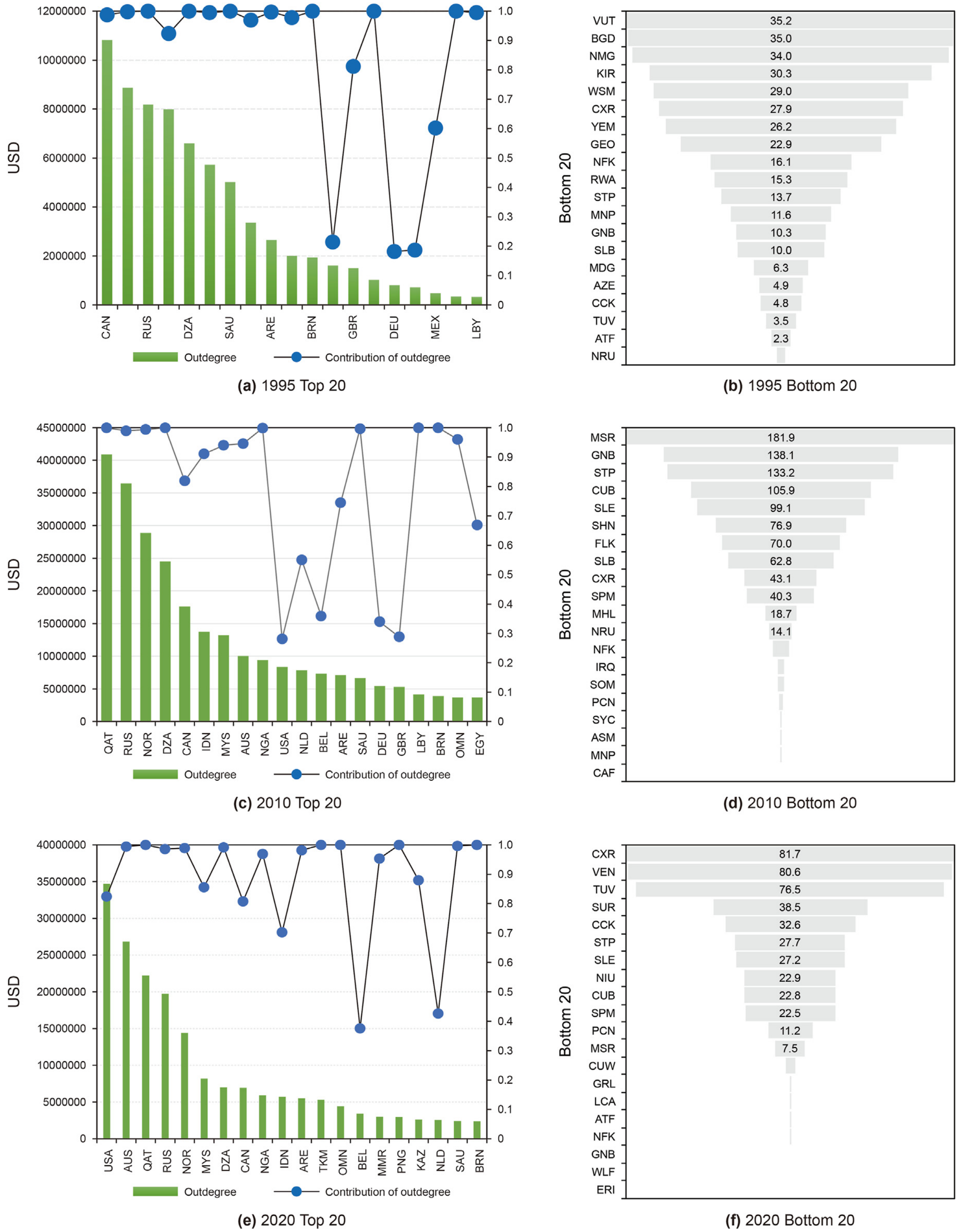


Fig. 5. Distribution of the top 20 in terms of PG trade position and contribution of exports to trade position((**a**)-(**c**)-(**e**), and bottom 20 countries in terms of PG trade position((**b**)-(**d**)-(**f**)) in major years.
Note: The unit of value corresponding to each country in the chart is \$1000, the larger it is, the higher the trade status; The contribution of outdegree is the ratio of degree of outdegree.

3.3. Resilience simulation results

3.3.1. Simulation results of time-varying resilience

According to Eqs. (3) and (4), we measured the change of the resilience of the global PG trade network from 1995 to 2020 by using MATLAB software, and the results are shown in Fig. 6. The global PG trade network resilience shows a fluctuating upward trend, but decreases significantly in recent years. In 1995–2011, the

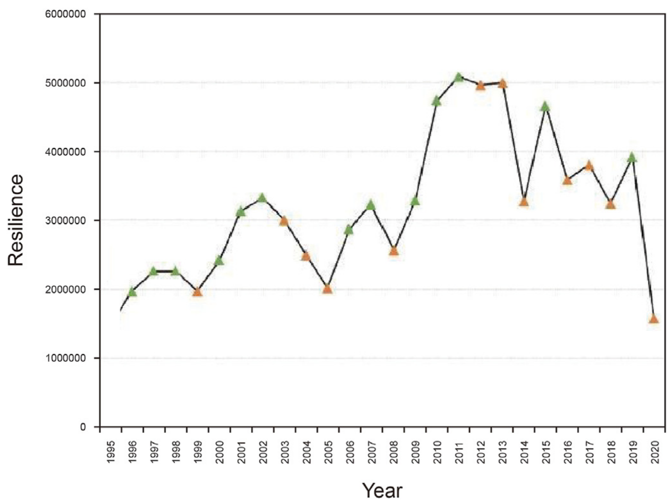


Fig. 6. Change in the resilience of the global PG trade network, 1995–2020.

PG trade network resilience tendency was activated first and then inhibited, and reached the level close to 1995 in 2020. The characteristics indicate that the global PG trade network resilience has its stage. The outbreak of the Libyan civil war in 2011 interrupted Libya's original oil production of 1.6 million barrels per day, and a large number of trade relationships disappeared in 2012. As an oil-rich economy, Libya's war has traumatized its oil industry. Its production in oil and gas fields has been influenced by the war. A large number of oil facilities, caused by supply disruptions and making a short-term impact on world oil supply and demand have been destroyed. The war crisis of Libya has infected some of the major oil-producing economies in the Middle East and North Africa, which may affect their oil and gas exports due to its sensitive location. Not only is natural gas a commodity, but also has some financial attributes. In a situation breaking out the war, market risk aversion is high and international oil prices have risen greatly. These all disrupt the oil market. From the aspect of network structure, the difference of connecting edges among nodes appears with the change of internal structure of network-such as the number of nodes, the number of edges and the centrality of different nodes. Thus, the changes in the resilience of the whole network will be affected directly by other countries' PG trade relations, forming different network linkage areas, and changing the scale and inherent structure of the linkage areas. In this concerned, changing the number of connected areas and their different composition of the network may be an optional way to improve the resilience of the network. On one hand, from Eq. (4), the increase of network size is also beneficial to enhance network resilience, and the expansion of network size can enable nodes to choose other nodes thus establishing trade relationships even in case of shocks. Therefore, the globalization of trade may promote the resilience of the global PG trade network to a certain extent. On the other hand, from Eq. (3), the increase in the number of edges or density of the network is not conducive to the enhancement of resilience. As the node establishes trade relationships with more nodes, the shock of a node will affect the partner countries through import and export trade directly, thus impacting the whole network on a large scale and even causing the collapse of the network.

3.3.2. *Resilience simulation cascade effect*

According to Eqs. (3) and (4), we select the global PG trade network matrices in 1995, 2000, 2009 and 2020, using MATLAB software to simulate the change characteristics of the remaining network resilience after the removal of different nodes. This process can be divided into four steps.

In the first step, the PG trade network for a specific year is selected; In the second step, a node is selected arbitrarily to remove it and its connected edges with other nodes together; In the third step, the remaining network resilience is calculated by using Eqs. (3) and (4); In the fourth step, on the basis of the second step, one more node is added each time to remove it together with the corresponding connected edges, and then the third step is executed; In the fifth step, the MATLAB software is used to generate random network graphs with the same number of nodes and edges of the network in 1995, 2000, 2009 and 2020 through simulation. Then, the second, third and fourth steps are executed; Finally, we get the PG trade network and the corresponding stochastic network resilience changes for different years (in Fig. 7).

As seen in Fig. 7(a), the resilience of both networks decreases significantly with the large number of removed nodes. However, under the same initial resilience, when the number of removed nodes increases to 46, the resilience of the network (Sample) will be half of the initial value, while the random network (Random) remains at more than half of the initial resilience; As the number of removed nodes increases from 85 to 103, the resilience of the network declines to about 0 rapidly. The global PG trade network was less resilient in 1995, and the network structure was not stable enough for a small external shock to affect the entire network structure significantly, thus prompting a fundamental change in the global PG trade pattern.

A small external shock can affect the entire network structure significantly and cause a fundamental change in the global PG trade. Similar to the above analysis, the resilience of the network and the stochastic network in Fig. 7(b)–(d) show a clear decreasing trend with the increase of the number of removed nodes. The former shows a rapid nonlinear decline and the latter reflects a small decline relatively. Thus, the stochastic network has better resilience characteristics than the network. It is worth noting that the initial value of the network resilience in 2009 was only about 150,000 which was significantly smaller than the resilience of the random network in other years. This may because the international financial crisis system impacted the global PG trade network in 2008, which made it more unstable and thus less resilient.

In addition, four other phenomena need to be discussed. Firstly, the initial resilience of the network in 2020 is nearly 1,600,000 compared to 1995, which exceeds that of 1995 by about 200,000; Secondly, the resilience of the network in 2020 only drops to half of the initial value when the number of removed nodes increases to 53 (greater than 46 in 1995); Thirdly, the random network resilience appears to be disorderly. For example, the random network resilience appears fluctuating decline and oscillating changes and other signs of irregular changes in 2020, which is very different from the network. The above results mean that the resilience of the global PG trade network increases in 2020 compared with 1995, and the moderate expansion of the network scale can enhance its ability to withstand external shocks. However, the recovery ability of the network is greatly lower than that of the stochastic network in case of shocks. Cooperation has also become closer, and the diversification of trading partners and channels has reduced the dependence of economies on a single organization, as the number of economies in the trading system has increased greatly.

3.3.3. *Country heterogeneity simulation results*

The various degree centrality of different nodes implies a difference in the size of their connections with other nodes. The evidence needed to give that whether such phenomenon imply that different nodes have different resilience to the network. For example, core countries have dense connected edges compared to

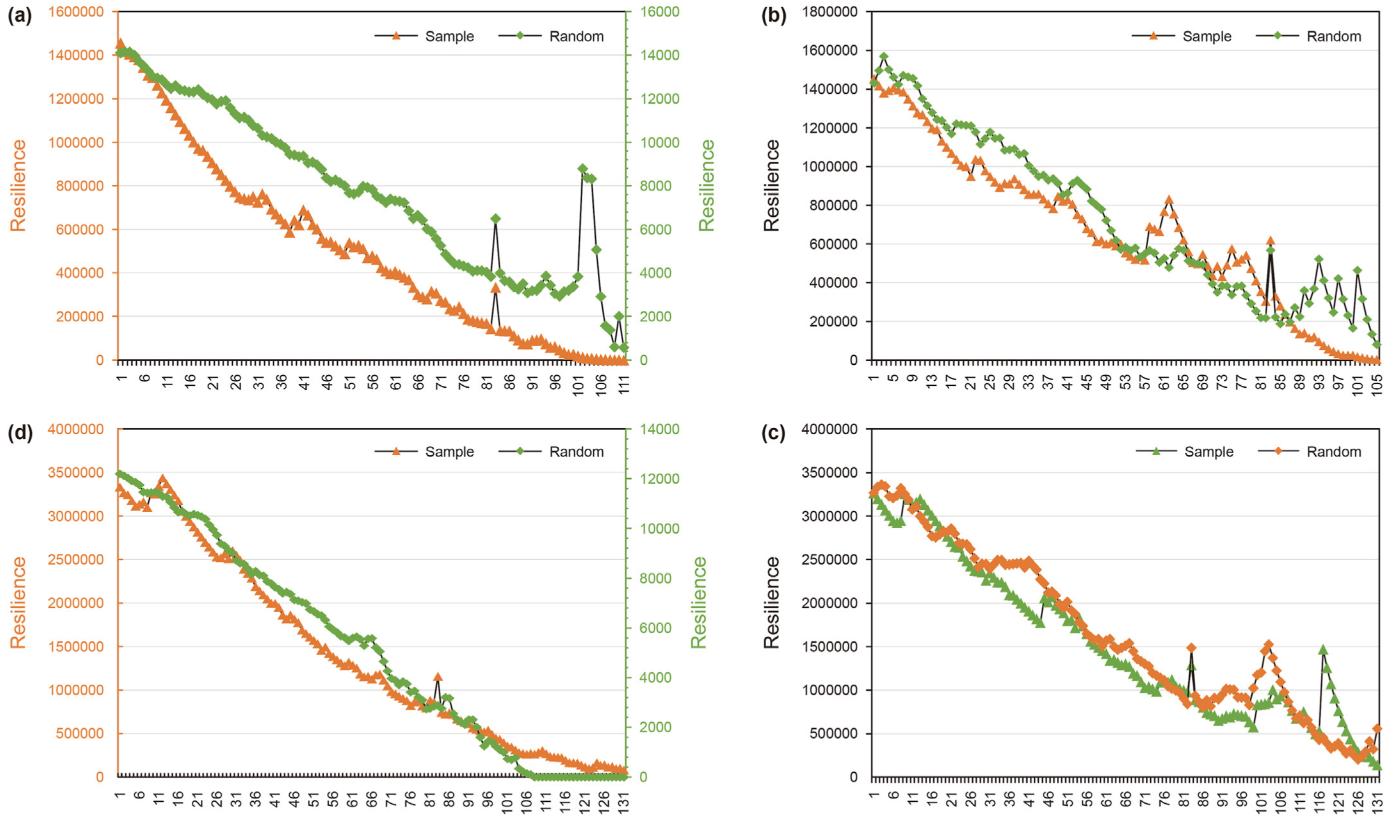


Fig. 7. Simulation results of global PG trade network in different years on stochastic network resilience.
Notes: (**a**) 1995, (**b**) 2000, (**c**) 2009, (**d**) 2020.

non-core countries, whose influence and control over other nodes is stronger. Once the core country is attacked, the number of edges will show a significant decrease, which may enhance the resilience of the remaining network.

Based on the analysis above, we take the top 15 and bottom 15 countries in the degree centrality as the sample of PG trade matrix in 2020, and then spills these countries out of the network respectively, then calculating the network resilience using Eqs. (3) and (4). The results are shown in Fig. 8. It can be seen that the U.S., South Africa and India are more resilient to the network than other countries significantly, where the edge countries ranked in the bottom 15 have lower resilience. If the core countries are attacked, the network density and the weighted average trade volume of countries will decrease together. But this shock can only build transmission with the whole network through more sparse trade relations, so recovering to the previous average level is nearly impossible. When the edge countries could be hit, the network density would not decrease much, the weighted average trade volume of countries is relatively stable, and network shocks could be transmitted to the whole network through more dense trade relations. Then, the trade network is more likely to recover back. The different impact of disruptions on resilience in core and peripheral countries suggests that countries with high trade status have a greater impact on the influence and resilience of the entire network. From the perspective of sustainability, once a core country is attacked and disappears from the network, it will no longer be the PG trade country for many countries, then these countries can find other countries and consider these countries as the largest trade partner countries easily. So, if it goes off the higher network resilience, it will be more important to the network structure. And, once these countries form a path dependence on the PG resources of the core countries, it will be very difficult to shift from the old trade intensive margins to other countries. Once a partner country stops exporting PG, that country will face a huge issue of national energy security.

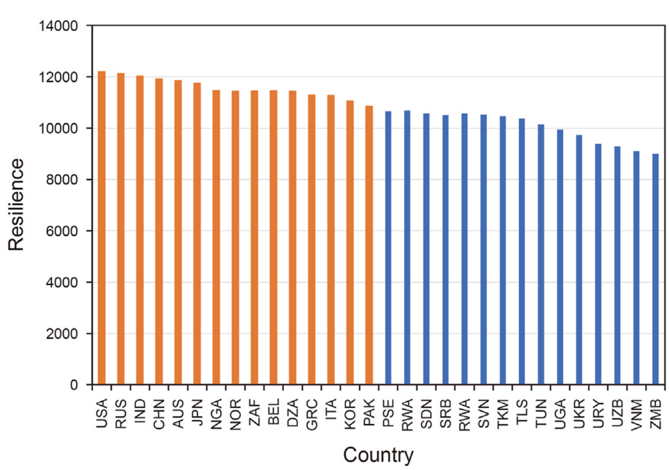


Fig. 8. Simulation results of the top 15 and bottom 15 country resilience simulations for 2020 annual count center degree.

3.4. Discussions

3.4.1. The evolution of trade network structure and global governance

The global PG trade network is changing from a “demand-led” to a “supply-demand coexistence” pattern. The rapid rise of the trade status of emerging economies and the weakening of the trade status of the U.S. are accelerating the process of shaping global trade governance. With the rapid expansion of global energy demand and the sudden emergence of resource shortage, the change in the PG trade pattern will require the future global governance body to shift from big power governance to global shared governance inevitably. It means that major energy-producing countries and emerging economies will have a higher voice in global energy trade, thus changing or even breaking the “core-sub-core-fringe” hierarchy in the traditional energy trade network to a certain extent as a crucial force.

The variation in the network structure of PG trade will result in the improvement and reconstruction of global economic and trade governance rules, and the direction of change of the latter should be in line with the evolution trend of the former. The transformation of the governance framework indicates a change in the structure of global energy power players, which is no longer manifested in the unilateral game of interests dominated by Japan and the U.S. and their allies but is shifting to the joint participation of energy. Instead, it has shifted to a complex network of joint governance with the participation of multiple actors of interest, such as energy-producing countries, consuming countries, international organizations, and multinational energy companies. It is necessary to consider the synergy between energy trade patterns and economic and trade rules from global governance and systemic thinking. Among them, the resource endowment advantages of the major energy resource countries will be more prominent, and the competition among energy-demand countries on energy resources will be more intense. As a result, global energy governance will present a network with multiple objectives, decentralized themes, layered structures, and fragmented mechanisms.

3.4.2. *PG trades relationships reflect the importance of transport corridor security*

Once the transport corridor is cut off or attacked, the PG supply and demand relationship between countries will be disrupted, then affecting the global energy trade pattern directly. The outbreak of the Libyan civil war in 2011 interrupted Libya's original oil production of 1.6 million barrels per day, and a large number of trade relationships disappeared in 2012. Therefore, the security of transportation corridors is susceptible to the global energy trade pattern. It can even be considered that transportation corridor security is a genuine guarantee to ensure a stable energy supply and international energy security. Due to more than 60% of China's annual crude oil coming from the Middle East and Africa, crossing the Indian Ocean, Malacca Strait, and the South China Sea, such long-distance transportation is vulnerable to regional unrest and pirate attacks, which requires military forces to escort the transported cargo.

3.5. *Practical implications of the impact of the international financial crisis*

Using the 2011 war in Libya as an example, we analyze the impact of contingencies on the trade position of countries in the global PG trade network, especially the war participants and major OPEC countries. On February 16, 2011, protests began in several Libyan cities calling for the government to step down, and then spread to the capital city of Tripoli, where demonstrators clashed with security forces. On February 26, 2011, the U.N. Security Council unanimously adopted Resolution 1970, in which it decided to impose an arms embargo on Libya, prohibit the Libyan leader, Gaddafi, and key members of his family from traveling abroad. On March 18, 2011, Libyan Foreign Minister Moussa Koussa announced that Libya accepted the UNSC resolution on the establishment of a no-fly zone in Libya, and that it would immediately cease fire and halt all military operations.

French warplanes carried out four military strikes in Libya on the same day, destroying several Gaddafi army armored vehicles. On March 19, U.S. President Barack Obama authorized the U.S. military to take “limited military action” against Libya, the Mediterranean Sea, U.S. and British warships and submarines launched 110 to 112 Tomahawks and Tomahawks into Libya on the same day. Tomahawk cruise missiles, attacked more than 20 air defense facilities in Libya. The military operation, called “Odyssey Dawn”, involved France, Canada and Italy, in addition to the U.S. and Britain.

Table 1 reports the changes in the distribution of the top 41 countries in terms of PG trade position before and after the 2011 war in Libya.[2] The main conclusion is that the war in Libya has led to a differentiation in the trade position of the war participants and major OPEC countries. On the one hand, the war has led to different declines in the trade position of Libya, the U.S. and Canada PGs, while Italy and France have increased their trade position and the United Kingdom has remained unchanged. The largest declines were recorded by Canada, which fell from 8th to 20th place, with trade falling from $215.2 trillion to $145.7 trillion, followed by Libya, which fell from 31st to 41st place. The outbreak of the Libyan civil war in 2011 interrupted Libya's original oil production of 1.6 million barrels per day, and a large number of trade relationships disappeared in 2012. As an oil-rich economy, Libya's war has traumatized its oil industry. A large number of oil facilities, caused by supply disruptions and making a short-term impact on world oil supply and demand have been destroyed. On the other hand, the war has led to a divergence in the trade position of different major OPEC countries, mainly in the form of a decline of Saudi Arabia and Iran, and an increase of Kuwait, among others. The above results show that unexpected events, such as war, can directly disrupt the international division of labor and trade linkages in PG, and seriously even cause disruption and structural damage to the global trade network, which makes it a practical necessity to consider the issue of the resilience.

In addition, a noteworthy phenomenon is that Japan's top ranking was not affected by the war in Libya, which may be related to the neutrality that Japan holds. Japanese Foreign Minister Tsuyaki Matsumoto said on 20 March that the Japanese government, based on its position of demanding the Libyan authorities to immediately stop exercising violence, supports the measures taken by UN member states against Libya in accordance with UN Security Council resolutions.

4. Analysis of the causes of the evolution of PG trade networks

4.1. *Model construction*

The edges of PG trade network are relational data and there are correlations among them, the traditional econometric model cannot obtain unbiased and consistent estimates. We adopted the exponential random graph model (ERGM) method to examine the formation mechanism of global PG trade networks. The ERGM assumes that the probability of the emergence of node-linked edges depends on the emergence of other relationships, emphasizing the dependence between relationships. On this basis, the model first generates multiple stochastic simulation networks by Markov chain Monte Carlo maximum likelihood estimation (MCMC-MLE),

[2] Libya ranked 41st in degree centrality in the PG trade network in 2012, so the top 41 countries were selected for analysis.

Table 1
Changes in the distribution of the top 41 countries in terms of PG trade position before and after the war in Libya in 2011.

	2010						2012				
1	JPN	48559965.0	22	CHN	8006589.2	1	JPN	77465244.3	22	IND	12583011.1
2	QAT	40922133.9	23	SAU	6689782.8	2	QAT	52560578.3	23	ARE	11848051.9
3	RUS	36860729.0	24	IND	6242208.4	3	NOR	45084144.6	24	SAU	8317522.9
4	USA	29782609.7	25	TUR	6075233.4	4	RUS	44886226.3	25	TKM	7553107.6
5	NOR	29039731.0	26	EGY	5468690.0	5	ITA	31450773.4	26	BRA	6333377.2
6	ITA	24932142.6	27	CZE	4531054.6	6	KOR	30666738.8	27	TUR	6230626.7
7	DZA	24540359.2	28	THA	4514762.9	7	DZA	29182726.4	28	SGP	6213716.6
8	CAN	21523668.9	29	SGP	4473572.1	8	FRA	26713027.1	29	OMN	6036918.2
9	KOR	21249505.9	30	BRA	4255780.6	9	BEL	25991920.9	30	BRN	5704050.1
10	BEL	20412025.9	31	**LBY**	4140587.2	10	USA	25286714.2	31	CZE	5570974.8
11	GBR	18469994.4	32	BLR	4067394.6	11	GBR	24541901.7	32	BOL	5491329.9
12	FRA	17531155.1	33	BRN	3882700.2	12	IDN	22047778.0	33	THA	5369308.5
13	DEU	16095368.3	34	OMN	3808389.3	13	DEU	21230821.3	34	EGY	4830069.0
14	IDN	15087161.8	35	IRN	3611488.0	14	MYS	20126181.6	35	KAZ	4391190.2
15	NLD	14348144.8	36	MEX	3449553.2	15	CHN	19409715.1	36	HUN	3832169.6
16	MYS	14042540.0	37	HUN	3078820.9	16	NLD	19344602.9	37	ARG	3749408.6
17	ESP	12529557.8	38	BOL	2804505.9	17	NGA	18796149.4	38	KWT	3726401.2
18	AUS	10621931.2	39	SVK	2789297.2	18	ESP	15347419.0	39	BLR	3562898.4
19	ARE	9548738.6	40	KWT	2449587.8	19	AUS	14810247.3	40	MMR	3405975.7
20	NGA	9417969.3	41	MMR	2410794.9	20	CAN	14578585.0	41	**LBY**	3264609.1
21	UKR	8981072.8				21	UKR	14303013.1			

Note: The green background indicates countries involved in the 2011 war in Libya (LBY) and the red color indicates OPEC members.

and then combines the endogenous structure of the observed network, node characteristic attributes, and exogenous network covariates to perform estimation, diagnosis, simulation, and improvement steps to finally obtain simulation networks that are very close to the observed network and the corresponding model parameters. According to Cranmer & Desmariais (2011) and Lusher et al. (2013), ERGM denotes the probability of occurrence of a particular network g:

$$\mathrm{Prob}(\boldsymbol{G}=g|\theta)=\frac{\exp\left(\sum_i \theta_i z_i(g)\right)}{k(\theta)} \tag{5}$$

Prob ($\boldsymbol{G} = g|\theta$) denotes the probability of occurring in given θ. $\boldsymbol{G}$ and g are the actual observed and the simulated network θ. $k(\theta) = \sum_i \exp\left\{\sum_i \theta_i z_i(g)\right\}$ is a normalized constant, denoting the number of numerators of Eq. (5) summed over all possible networks (usually restricted to all networks with the same set of nodes as y), used to ensure that the probability always remains between 0 and 1, and that the probability of all possible networks sums to 1. $z_i(g)$ denotes a set of variables related to network structure, node attributes and exogenous networks, θ_i is the parameter to be estimated for different variables, a positive value indicates that the structure or node attributes or the presence of an exogenous network will facilitate network formation more than a random situation, a negative value indicates that the probability of such a positive direction is relatively small. z mainly includes chart density (*EDGES*), weighted sharing partnerships (*GWESP*); node attribute variable assortativity (*Homophily*: Both countries are members of the WTO or not), tariff rate (*TARIFF*), trade facilitation (*TF*), level of economic development (*GDP*) and institutional quality (*INSTITUTION*); Exogenous network covariates as a common language (*LANGUAGE*), common boundaries (*BORDER*), network of colonial relations (*COLONY*), religious affiliation networks (*COMRGN*), regional trade agreement network (*RTA*) and so on.

When N is large, the denominator of Eq. (5) will produce $2^{\frac{N(N-1)}{2}}$ simulated graphs, which will make the calculation very difficult. Referring to Frank and Strauss (1986) and Lusher et al. (2013), we assumed that:

(1) the occurrence of edges obeys the Markov condition that the occurrence of an edge depends on other edges, independent of the presence or absence of past edges

$$\mathrm{Prob}(w_{ij}) = \mathrm{Prob}\left(w_{ij}\middle|w_{ij}^{\mathrm{other}}\right) \tag{6}$$

Deformate Eq. (5)

$$\ln\frac{\mathrm{Prob}\left(w_{ij}=1|w_{ij}^{\mathrm{other}}\right)}{\mathrm{Prob}\left(w_{ij}=0|w_{ij}^{\mathrm{other}}\right)}=\theta'\left[z\left(g_{+ij}\right)-z\left(g_{-ij}\right)\right] \tag{7}$$

g_{+ij}、g_{-ij} are increase in diagram (g), decrease in continuous edges (w_{ij}).

(2) a random initial graph (g^0). The *PR* is compared by increasing and decreasing the number of consecutive edges according to Eq. (6).

$$PR=\min\{1,\frac{\mathrm{Prob}_\theta(g^*)}{\mathrm{Prob}_\theta(g^{n-1})}\} \tag{8}$$

If $PR > 1$, the current network graph can fit the observed network with greater probability than the previous network, then increase the number of edges, otherwise decrease the number of edges

Then, we using the maximum likelihood method (MLE), the expected values of the various statistics of all the generated graph distributions are calculated separately to see if they are the same as the values of the statistical indicators of the observed network. If there are deviations, the initial parameter values are corrected until convergence, and finally the model parameter θ corresponding to the simulated network that is closest to the observed network is obtained. If the coefficient is positive (or negative), it means that the variable contributes to the formation of network trade relations.

In model fitting, we refer to the common practice of first building a zero model (NULL) incorporating only *EDGES* as the evaluation benchmark for constructing complex models (Harris, 2014). Then, we added variables in the order of endogenous structural variables, node attribute variables, and network covariates, and finally determine whether the model is optimized according to the AIC and BIC criteria (the smaller the two, the better). In addition, considering the sensitivity of the model parameters to the algorithm, we also use the stepwise MCMC-PLE method for robustness testing in the later section.

4.2. Network variable and data

According to complex network theory, network formation may be influenced by a combination of endogenous structural factors, node attributes, and exogenous covariate networks (Frank and Strauss, 1986; Harris, 2014), so we selected explanatory variables from the above three aspects.

1. Explained variables. The explanatory variable is the edge w_{ij} corresponding to the PG trade network $\boldsymbol{G}$. We first construct a symmetric PG trade network matrix between countries based on the countries and their connected edge weights $\boldsymbol{W}$. Then, referring to Cranmer and Desmarais (2011), we arrange the elements in $\boldsymbol{W}$ in descending order and select the top 10% (corresponding to a threshold value of US$68.69 million) as the threshold to build an undirected symmetric bivariate PG trade network matrix $\boldsymbol{W}_{1\le i,j\le G}$.[3] If there is a connected edge between network nodes, $w_{ij}=1$, otherwise it is taken as 0.
2. Endogenous structural variables. Since the network is undirected, we refer to the main consideration of network density, network transmissibility characteristics, and set the following endogenous structural variables: (1) graph density *EDGES*. It is the weight between the actual number of edges and the maximum possible number of edges, representing that all countries trade with equal probability. This variable is equivalent to the model constant term and is used to control the network structure. (2) Geometric weighted edge sharing partner *GWESP*. It is based on ternary transferability and explains the clustering characteristics in the observed network. $\nu(g;\alpha)=e^{\alpha}\sum_{i=1}^{n-2}\{1-(1-e^{-\alpha})^{i}\}ESP_i(g)$. $ESP_i(g)$ is the number of edges with one shared partner, α generally being between 0–1. *GWESP* reflects the fact that two countries are more likely to trade if they have one or more shared trading partners, thus explaining the structural characteristics from a trade agglomeration perspective. Since different values of α affect the number of edges of shared partner countries and thus indirectly affect network formation, we also make them 0.25, 0.75 and 1 for robustness tests in the latter part.
3. Nodal variables. We selected the following variables as nodal attribute variables. These include: (1) tariff rate *TARIFF*. It is taken as the simple arithmetic average MFN rate expressed for all products in each country; (2) trade facilitation *TF*. It refers to Otsuki et al. (2003), mainly from the perspective of customs environment, and takes the number of documents required to import in each country after standardization and forwarding as a metric. The reduction of customs import documents helps to simplify customs clearance procedures, reduce import costs, and improve trade efficiency, thus accelerating the cross-border flow of products, and thus may affect the formation and evolution of PG trade networks. (3) Logarithmic GDP ln *GDP*. GDP per capita in current dollars and expressed as logarithmic ln *GDP*. Kali and Reyes (2007) emphasize that GDP is closely related to a country's trade and its network degree. (4) Institutional quality *INSTITUTION*. It is taken as a simple arithmetic average of six subscales of corruption control, voice and accountability, political stability, government efficiency, regulatory quality and rule of law across countries. The higher the institutional quality, the more favorable it is to carry out value chain division of labor and trade, because countries with high institutional quality can both provide a stable, transparent and predictable institutional environment for value chain division of labor, reduce the risk of outsourcing links and cross-border transactions, and also provide a stable and predictable market environment for home countries. (5) Common *WTO*: If a country is a member of WTO, the element takes 1, otherwise it takes 0. WTO provides member countries with institutional frameworks such as tariff concessions and unified trade dispute settlement mechanism, and thus may influence network trade relations through multilateral rules coordination mechanisms.
4. Network covariates. Network covariates refer to whether other network relationships are more trade oriented, thus causing changes in trade network relationships. It reflects the global influence of other exogenous networks on network formation. We select:

(1) A common border network *BORDER*, the corresponding element is taken as 1 if adjacent, otherwise it is taken as 0. Having a common border is beneficial to both reduce transportation, cross-border and coordination costs and promote bilateral trade (Chaney, 2014), as well as to induce the signing of trade agreements such as customs integration between the two countries, thus enhancing bilateral trade.
(2) Common language network *LANGUAGE*. Elements take the same value as the border-adjacent network. Having a common language among countries can both promote bilateral trade by reducing communication barriers and communication costs and enhancing cultural identity, and strengthen trade ties by promoting cultural exchange and diffusion and establishing competitive advantages in trade (Feng et al., 2020).
(3) Colonial relationship network *COLONY*. The element takes 1 if there is a colonial relationship between two countries in history, otherwise it takes 0.
(4) Religious relationship network *COMRGN*. If more than 9% of the population of two countries have the same religious belief, the element is taken as 1, otherwise it is taken as 0.
(5) Regional trade agreement *RTA*. Regional trade agreements are selected as the factors affecting the evolution of trade networks. The signing of RTAs between countries can promote bilateral trade by reducing tariff and non-tariff barriers, and also reduce trade between member and non-member countries through trade diversion. Therefore, RTAs can influence the evolution of global trade networks. The data of each variable are mainly obtained from UNCTAD-Eora database, Doing Business Report, Global Competitiveness Report, IMF, WTO, World Bank, Transparency International, CEPII database and Google Earth.

4.3. Analysis of simulation results

The results of ERGM model fitting are shown in Table 2. As seen from column (1), when only *EDGES* is included, the corresponding AIC and BIC values are as high as 7380 and 7387, indicating that it is difficult to achieve an effective fit by considering only the network fundamentals and the inclusion of the remaining variables is required. In fact, the Bernoulli model that only includes *EDGES* assumes that the network nodes are randomly connected to each

[3] Diagonal elements $w_{ii}=0$.

Table 2
ERGM simulation results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
EDGES	−1.716***	−6.219***	−3.737***	−0.527	−67.164***	−82.449***	−70.914***	−74.030***	−77.513***	−80.939***
	(0.030)	(0.721)	(00.540)	(0.513)	(5.141)	(5.978)	(4.642)	(4.982)	(5.042)	(9.276)
GWESP		3.473***	2.850***	1.727***	−0.631	−1.235	−0.592	−0.198	−0.416	−0.044
		(0.636)	(0.454)	(0.352)	(0.673)	(0.635)	(0.755)	(0.580)	(0.849)	(0.665)
TARIFF			−0.082***	−0.032***	−0.097***	−0.032	0.001 (0.042)	−0.008	−0.007	−0.020
			(0.005)	(0.008)	(0.021)	(0.022)		(0.036)	(0.043)	(0.032)
TF				−5.351***	−1.234	−0.166	−0.235	−0.377	−0.785	0.381 (1.096)
				(0.574)	(0.090)	(0.604)	(1.063)	(1.005)	(1.132)	
ln*GDP*					1.320***	1.588***	1.354***	1.431***	1.497***	1.522***
					(0.103)	(0.116)	(0.091)	(0.109)	(0.096)	(0.166)
INSTITUTION						0.861***	0.687***	0.835***	0.638***	0.598***
						(0.180)	(0.135)	(0.147)	(0.122)	(0.222)
WTO							−0.322	−0.518	−0.250	−0.037
							(0.252)	(0.375)	(0.410)	(0.437)
LANGUAGE								−0.584**	−0.799**	−0.417
								(0.197)	(0.269)	(0.265)
BORDER									3.571***	3.023**
									(0.713)	(1.118)
COLONY										0.573 (1.113)
COMRGN										0.046 (0.333)
RTA										1.276***
										(0.376)
AIC	7380	7267	6957	6368	2951	2773	2761	2711	2515	2392
BIC	7387	7281	6979	6396	2987	2815	2811	2767	2578	2477
Log-likelihood value	-−3689	−3631	−3475	−3180	−1470	−1380	−1373	−1347	−1248	−1184
Observations	5462	5462	5462	5462	5462	5462	5462	5462	5462	5462

Note: All columns are simulated using the MCMC-MPLE method, coefficients are standard deviations in parentheses, and the *GWESP* decay parameter is taken as 0.1. ***, ** and * indicate significant at the 1%, 5% and 10% levels, respectively. Observations are N*(N−1) and network diagonal elements are not counted. Same as below.

other with a certain probability, and its global PG trade network pattern formed by global value chains (GVC) is not compatible with it. Column (2) is significant for both variables after the inclusion of *GWESP*, and the AIC and BIC values are reduced but still high, indicating that the inclusion of *GWESP* improves the model fit. Further, by gradually including node attributes and network covariates, the corresponding AIC and BIC values in column (10) are reduced to 2392 and 2477, respectively, which are more than half compared to column (1), and comparing columns (1)–(10), we find that the variables significant in column (10) are also largely significant in the remaining columns with roughly the same sign, which indicates that the model fits better and has good robustness after including all variables. This indicates that the model fits better and is more robust when all variables are included. Therefore, the following analysis is mainly based on column (10). The *EDGES* coefficient is −80.939 and significant, which indicates that the endogenous structure of the network is the basic motivation for the formation of the PG trade network relationship. When the network increases by one connected edge, the probability of another connected edge of the observable network increases accordingly. ln*GDP* and *INSTITUTION* coefficients are 1.522 and 0.598, both of which pass the 1% significant level test, indicating that the economic size and institutional quality of each country are important forces driving the formation of global PG trade network relationships. For each unit increase and improvement in ln*GDP* and institutional quality of each country, the probability of forming world PG trade network relationships increase by 82.1% and 64.5% accordingly. The higher the economic scale, the stronger the market demand and supply capacity, the larger and more diversified the PG trade, and thus the more conducive to the formation of trade networks. Institutional quality can influence the degree and scope of division of labor in GVC through the provision of effective institutional supply, thus indirectly affecting the formation and evolution of world PG trade networks. The coefficients of *BORDER* and *RTA* are 3.023 and 1.276 and significant, indicating that having common borders and signing RTAs among countries significantly contribute to the formation of global PG trade network relationships, and having common borders and RTA networks increase the probability of forming inter-country trade network relationships by 96.1% and 78.2%, respectively, compared with countries without common borders and RTA relationships.

Having a common border can both facilitate bilateral trade by reducing interstate transport, cross-border and coordination costs and can also enhance bilateral trade by prompting two countries to sign trade agreements such as customs integration. Signing or upgrading regional trade agreements can facilitate and strengthen trade relations by lowering tariff and non-tariff barriers, while also reducing trade between member and non-member countries through trade diversion, thus influencing the evolution of global PG trade network patterns.

4.4. Fitting effect analysis

The above research did not compare whether there is a significant difference between the simulated and observed networks. If there is no significant difference, the fit is good. We next used GOF test and MCMC diagnosis to test the fitting effect and whether degradation occurs in the fitted model. Based on column (9) of Table 2, Fig. 9 plots the box and line blends of 100 simulated network characteristics indicators for degree distribution, geodesic distance, binary shared partner number distribution, and ternary shared partner number. Where the blue color is the median of the observed network, the black line is the corresponding indicator of the simulated network, and the gray color corresponds to the 95% confidence interval corresponding to the simulated network indicator. As can be seen, the four types of network indicators are basically located around the blue observation network indicators, and the latter are also in the gray area corresponding to the 95% confidence interval, indicating that the model in this paper has a good simulation effect on the observation network. We further

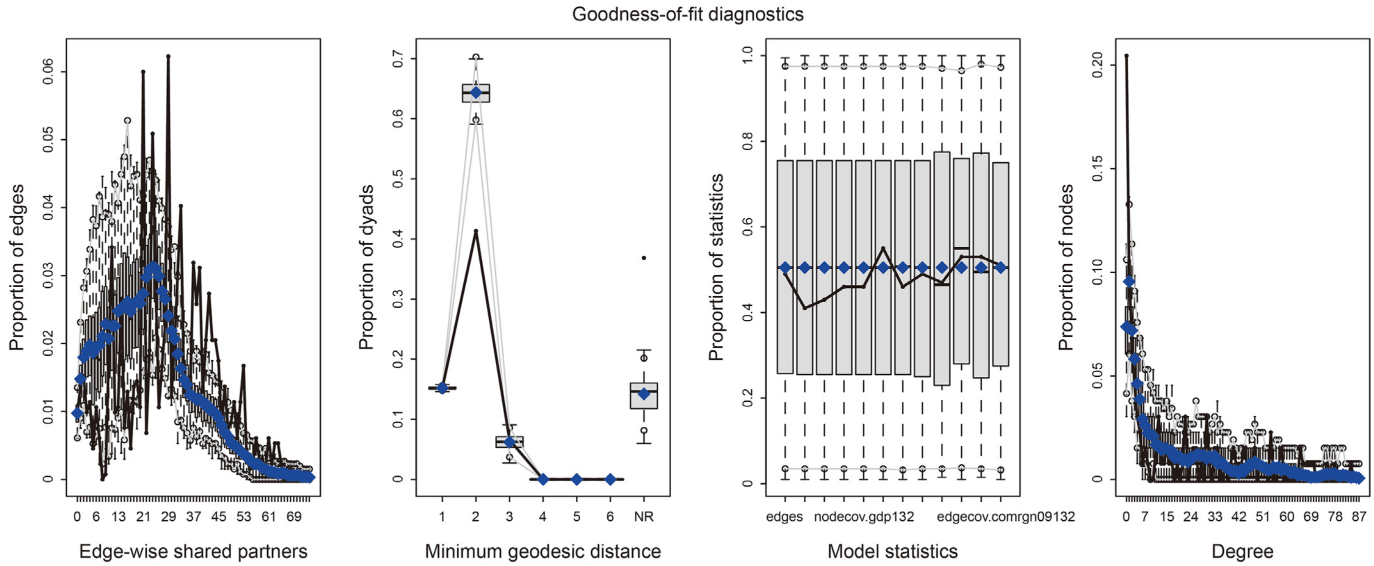


Fig. 9. GOF test.
Note: The black solid lines in each figure are the statistical characteristics of the observed network, the box line plots and blue dots are the corresponding statistical characteristics of the simulated network and their medians, and the gray color represents the 95% confidence interval corresponding to the simulated network. If the median of the box line plot is close to the black solid line of the observation network and the black solid line is located in the region of the gray line, it means that the simulation fits well.

used the MCMC test to examine whether the inclusion of each network variable would degrade the model, and the diagnostic results for each variable are shown in Appendix A. Both network variables, no matter which network variables, are basically located in the random fluctuations above and below the observed network, and no serious deviation occurs, indicating that the inclusion of these network variables in the previous model does not cause degradation problems.[4] In summary, the model fits well and the previous benchmark conclusion is more reliable.

4.5. Analysis of heterogenous results and robustness test

4.5.1. Time period heterogeneity

The global PG trade network evolved dynamically during the period under examination, and the network structure differed significantly at different stages. To further analyze the differences, we use the 2008 financial crisis and the 2013 “Belt and Road” initiative as the cut-off points, and re-estimate them respectively, and the results are shown in columns (1)–(3) of Table 3. The coefficients of *BORDER* are significant in each stage, except for 2014–2020, and the magnitude of the coefficients shows an overall “rise and fall”. The coefficients of *INSTITUTION* and *RTA* tend to increase at different stages, which indicates that the role of institutional quality and signing of RTAs in network formation tends to strengthen in each country. In particular, the coefficients of *INSTITUTION* and *RTA* increase significantly in 2009–2013 and 2014–2020, while the coefficients of ln*GDP* and *BORDER* tend to decrease, indicating that the influence of economic size and geographical bordering of each country has weakened. The 2008 financial crisis not only impacted the division of labor in GVC, hindered the process of global economic and trade cooperation, and even caused the interruption of trade exchanges between some countries, reducing the probability of increasing the formation of trade relations among countries, but also prompted countries to pay more attention to the huge impact of factors such as post-border institutional risks when conducting trade. In 2013, China proposed the “Belt and Road” initiative provides a consultative platform for regional economic and trade cooperation, and as the initiative and as more economies continue to join, China signs or upgrades regional trade agreements with more geographically non-bordering countries, the initiative's impact has gradually broken through the constraints of geographical distance.

4.5.2. Network status heterogeneity

Considering the differences in resource control and utilization capabilities of countries with different network positions, countries with high network positions have relatively stronger control capabilities and usually occupy the core position in the division of labor in GVC, and it may be easier for these countries to form close value chain division of labor and trade relations with each other. In fact, the previous paper also found that there is a “rich club” phenomenon in the PG trade network. Therefore, we first construct the node attribute variable *NP* based on the average degree of 1650 millions from 1995 to 2020, and if the node degree is higher than 1650 millions, *NP* takes 1, otherwise it takes 0. Then, we re-estimate the results as shown in column (4). We find that the *NP* coefficient is 2.358 and significant, and the four types of variables are basically significant, indicating that the PG trade relationships are more likely to form among countries with high network status, and the four types of factors remain important. The ease of forming the PG trade relationships among countries with high network status is not only consistent with the homogeneity in social networks, but also with the regional nature of the division of labor in GVC. The regional value chain (RVC) division of labor and trade system in Europe, America and Asia, mainly Germany, the U.S. and China, has been formed in GVC. Compared with non-center and peripheral countries, both the scale of the PG trade and the depth of value chain division of labor are relatively higher among the center countries, so these countries tend to form trade relations with countries of similar network status, and eventually form a relatively close PG trade relationship Network.

[4] See Appendix A.

Table 3
Heterogeneous ERGM simulation results.

Variables	1995–2008	2009–2013	2014–2020	Different network status
	(1)	(2)	(3)	(4)
EDGES	−90.870*** (2.506)	−83.982*** (10.339)	−79.485*** (1.972)	−62.434*** (5.553)
ln*GDP*	1.743*** (0.059)	1.560*** (0.192)	1.460*** (0.047)	1.078*** (0.103)
INSTITUTION	0.560* (0.268)	1.068*** (0.233)	0.747*** (0.190)	0.548* (0.259)
BORDER	3.665*** (1.527)	4.406*** (0.858)	2.696 (1.401)	4.744*** (1.296)
RTA	1.270*** (0.341)	1.179* (0.517)	1.371*** (0.394)	1.226* (0.484)
NP				2.185*** (0.470)
AIC	2399	2335	2525	2072
BIC	2484	2420	2609	2163
Log-likelihood value	−1187	−1155	−1250	−1023
Observations	2911	1095	1456	5462

Note: Due to space limitations, only the estimated coefficients of significant variables are reported in Table 3, the rest are not reported for the claim. Same below.

4.5.3. Different methods

To examine the robustness of the previous network fitting and model estimation results, we re-fit and estimate using different sampling sizes, different decay parameters and different threshold ways, and the results are shown in Table 4. Different estimation methods can directly affect the model parameters and thus the main conclusions in the previous section.

(1) Different sampling sizes. The previous paper used MCMC for random sampling 100 times to simulate the network, and then for model estimation, the different number of sampling times will also have some influence on the simulation results. For this reason, we expand the sampling times to 1000 and 5000 times, respectively, and then re-estimate the results as shown in columns (1)–(2), respectively. It is easy to see that the four types of variables are still significant and the values are relatively close, which indicates that the previous fitting results are not sensitive to the sampling size.

(2) Different decay parameters. In the model setting, we take the decay parameter α in *GWESP* as 0.1 to portray the endogenous structure of the network from the perspective of how many shared partnerships in the triangular transfer structure of the network, and in fact the different values of the decay parameter reflect the variability of the endogenous structure of the network. For this reason, we make α take 0.25, 0.75 and 1, respectively, and re-estimate the results as shown in columns (3)–(5). It can be seen that the coefficients of the four core variables are significant and relatively close, which indicates that the previous fitting results are basically robust and insensitive to the form of endogenous structure setting of the network.

5. Conclusions

The unequal distribution of PG in different geographical regions and countries' contradictory supply and demand to meet their domestic energy needs have accelerated its trade process. Besides, the increased uncertainties such as the Russia-Ukraine conflict have disrupted global energy trade patterns, threatening the sustainability of global energy trade and national energy security directly. Therefore, it is significant to identify the evolution pattern of global PG trade, characterize the strength of different countries and discourse over this strategic resource, model how energy supply and demand disruptions affect the PG trade network and analyze the causes of the evolution of it. Based on the HS2711 four-digit code data in UN COMTRADE from 1995 to 2020, we evaluate of the global PG trade network in a complex network approach based on the HS2711 four-digit code data in UN COMTRADE from 1995 to 2020. The results illustrate that the scale of the global PG trade network tends to expand, and the connection is gradually tightened, experiencing a change from a "supply-oriented" to a "supply-and-demand" pattern, in which the U.S., Russia, Qatar, and Australia have gradually replaced Canada, Japan, and Russia to become the core trade status, while OPEC countries such as Qatar, Algeria, and Kuwait mainly rely on PG exports to occupy the core of the global supply, and the trade status of other countries has been dynamically alternating and evolving. Resilience simulation reveals that the resilience of the global PG trade network is lower than that of the random network and decreases non-linearly with more disrupted countries. Moreover, the impact of the U.S. is more significant than the rest of countries. Further network simulation using ERGM model finds that national GDP, institutional quality, common border and RTA network are the determinants of world value-added trade network formation, and the positive impact of the

Table 4
Robust test.

Variables	(1)	(2)	(3)	(4)	(5)
EDGES	−81.157*** (2.574)	−81.228*** (2.615)	−86.371*** (9.586)	−85.774*** (2.475)	−67.992*** (5.437)
ln*GDP*	1.535*** (0.047)	1.537*** (0.048)	1.633*** (0.197)	1.610*** (0.056)	1.264*** (0.100)
INSTITUTION	0.743*** (0.066)	0.741*** (0.067)	0.733** (0.216)	0.785*** (0.293)	0.852** (0.268)
BORDER	3.262*** (0.307)	3.274*** (0.301)	2.210** (0.730)	4.312*** (1.299)	3.019** (1.142)
RTA	1.306*** (0.121)	1.283*** (0.126)	1.504** (0.478)	1.231** (0.426)	0.945*** (0.392)
AIC	2393	2393	2385	2391	2395
BIC	2478	2478	2470	2476	2479
γ					
Log-likelihood value	−1184	−1184	−1180	−1183	−1185
Observations	5462	5462	5462	5462	5462

Note: Columns (1)–(2) are the results of 1000 and 5000 times of MCMC sampling, (3)–(5) are the simulation results of *GWESP* decay parameters taken as 0.25, 0.75 and 1.

four factors on network formation not only varies significantly across regions and stages, but also increases with national network status.

We propose some development implications.

Firstly, adhere to the multilateral trading system, strengthen regional trade cooperation, and promote the reconfiguration of global governance rules. Constructing the multilateral trading system is the most likely approach to deliver benefits to producers and consumers by far. Key energy demand and supply countries like the U.S., China, Japan, Australia and Russia play a major influence in driving the global energy trade landscape. On the contrast, the International Energy Agency, the World Bank, the United Nations Framework Convention on Climate Change and the World Trade Organization play coordinating roles in the evolution of global trade governance rules. In line with this, global rules governance shifts from U.S. led to multipolar governance gradually, do regionalism become a means of geopolitical competition among major powers? Is the role of international organizations diminishing or becoming a tool for power distribution among major powers? These questions all point to the theme of global energy rule governance.

Secondly, enhance the right to speak on economic and trade rules, and promote the restructuring of the global economic and trade pattern. A few countries occupied and controlled the global resources and international trade benefits are not unequal for the periphery countries. It is difficult to change the low trade status of most developing countries in the short term because of the inherent hierarchical characteristics and relative stability of the global PG trade structure. Most countries face “vertical oppression” in trade interests and “comparative weakness” in trade rules. Therefore, most developing countries are more urgent to gradually change such unequal trade relations by upgrading the status and enhancing the appeal of international economic and trade rules.

Third, the strengthening of the degree of dependence of the world PG trade network may prompt a country to form excessive dependence on foreign imports and lock in that path, which will increase its external risks and amplify the impact of systemic shocks. For a given country, an increase in its degree centrality means that it trades with more countries, i.e., imports or exports tend to diversify, thus ensuring a stable source of supply. Shocks in peripheral countries will not have a large impact on network stability, while in core countries may be transmitted to the entire network, thus triggering a systemic crisis. The close trade ties among high-centered countries accelerated the rapid spread of the financial crisis within them. Therefore, it is important to analyze the distribution pattern of global PG trade network structure and its evolution to strengthen global and regional cooperation, prevent global systemic shocks and risk response. Meanwhile, diversify the sources of PG imports and accelerate the process of domestic extraction are necessary. Compared with Australia, Canada, Iran and other countries that have developed PG earlier, most countries PG development and exploration technology is relatively weak, and its large domestic oil and gas reserves still need to be fully developed. Therefore, they should promote commercialization to reduce its dependence on imports fundamentally and promote the security of energy trade. Economies with large import trade relationships should concentrate on diversification and cross-regionalization in selecting trading partners, which are also significant measures to inhibit energy shortages and unexpected shocks.

Finally, take advantage of geographical proximity, accelerate the signing or upgrading of regional trade agreements, and build value chains in neighboring regions. Geographical proximity is a natural advantage for three core countries. Germany, the U.S. and China could follow the principle of “from near to far” and provide institutional supply for the construction of RVC by signing or upgrading regional trade agreements. For example, by expanding the export of production capacity and transferring low-end industries to the neighboring regions to build an inclusive neighboring RVC that is “dominated by us and complemented by other countries”. In fact, against the backdrop of the severe impact of the new epidemic, the production of GVC is becoming increasingly regionalized and localized, which further highlights the importance and urgency to build RVC in the periphery and ensure the safety and reliability of supply chains.

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Data availability statement

The data presented in this study are available on request from the corresponding author.

CRediT authorship contribution statement

Na Li: Writing – original draft. **Yi-Ran Song:** Data curation, Investigation. **Ying Wang:** Conceptualization, Validation. **Chun-Bao Ge:** Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

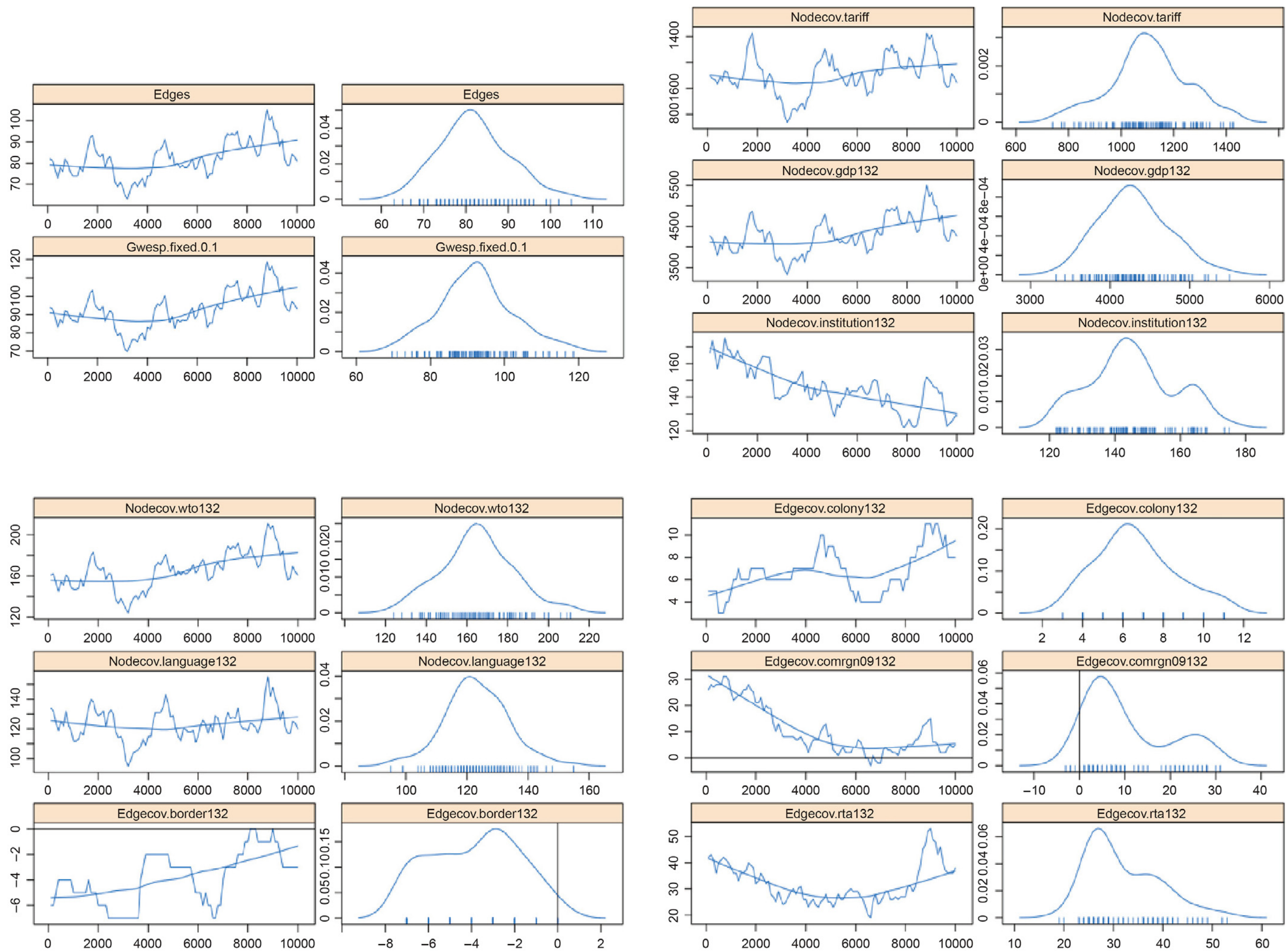
Declaration of competing interest

The authors declare no conflict of interest.

Appendix A. 236 Country or region (ISO3)

ABW	BLM	CUW	GHA	JOR	MKD	OMN	SLV	TUR
AFG	BLR	CXR	GIB	JPN	MLI	PAK	SMR	TUV
AGO	BLZ	CYM	GIN	KAZ	MLT	PAN	SOM	TZA
AIA	BMU	CYP	GMB	KEN	MMR	PCN	SPM	UGA
ALB	BOL	CZE	GNB	KGZ	MNE	PER	SRB	UKR
AND	BRA	DDR	GNQ	KHM	MNG	PHL	SSD	URY
ANT	BRB	DEU	GRC	KIR	MNP	PLW	STP	USA
ARE	BRN	DEU	GRD	KNA	MOZ	PNG	SUN	UZB
ARG	BTN	DJI	GRL	KOR	MRT	POL	SUR	VCT
ARM	BWA	DMA	GTM	KWT	MSR	PRK	SVK	VEN
ASM	CAF	DNK	GUM	LAO	MUS	PRT	SVN	VGB
ATF	CAN	DOM	GUY	LBN	MWI	PRY	SWE	VNM
ATG	CCK	DZA	HKG	LBR	MYS	PSE	SWZ	VUT
AUS	CHE	ECU	HND	LBY	MYT	PYF	SXM	WLF
AUT	CHL	EGY	HRV	LCA	N/A	QAT	SYC	WSM
AZE	CHN	ERI	HTI	LKA	NAM	ROU	SYR	YEM
BDI	CIV	ESP	HUN	LSO	NCL	RUS	TCA	ZAF
BEL	CMR	EST	IDN	LTU	NER	RWA	TCD	ZAF
BEL	COD	ETH	IND	LUX	NFK	SAU	TGO	ZMB
BEN	COG	FIN	IOT	LVA	NGA	SCG	THA	ZWE
BES	COK	FJI	IRL	MAC	NIC	SDN	TJK	
BFA	COL	FLK	IRN	MAR	NIU	SDN	TKL	
BGD	COM	FRA	IRQ	MDA	NLD	SEN	TKM	
BGR	CPV	FSM	ISL	MDG	NOR	SGP	TLS	
BHR	CRI	GAB	ISR	MDV	NPL	SHN	TON	
BHS	CSK	GBR	ITA	MEX	NRU	SLB	TTO	
BIH	CUB	GEO	JAM	MHL	NZL	SLE	TUN	

Appendix B. MCMC degeneration diagnostic test



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