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A complex network perspective on interrelations and evolution features of international oil trade, 2002–2013 ☆

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HIGHLIGHTS

- The top 1 network model can well reflect countries' preference in choosing oil trade partners.
- The modified closed-system input-output method can reflect the direct and indirect influences among oil trading countries.
- The interrelation and evolution features of international oil trade network have been discussed.
- The result shows us how to make a rational decision for a country to develop oil trade relations.

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ABSTRACT

In this paper, a directed and weighted world crude oil trade network is constructed. Based on the built network, we apply top network method and modified closed-system input-output method to assess the relative importance of countries in the international oil trade. The top 1 network consisting of top trade relations, can well reflect countries' preference in choosing oil trade partners. As a simplified network model of international oil trade network, the top 1 network has been analyzed the structure and evolution. In order to identify important oil trading countries, the modified closed-system input-output analysis has yielded some promising results, which show countries who play key role in international oil trade, are trading large oil volumes. In addition, by describing the influences of countries on each other, we find major oil importers have a much effect on other countries, including major oil exporters. The evolution analysis obtained by these two methods coincide with each other. To conclude, some suggestions are given according to the results.

1. Introduction

Crude oil is still the principal fuel source in the world, it accounts for nearly 32.9% of global energy consumption in 2015. As a national strategic resource, crude oil plays a pivotal role in economic development and national security. Due to the unbalance distribution of oil production and consumption, international oil trade gives a big push for the cross-border oil flows, which bind the whole world into a global oil trade network. A detailed understanding of oil trading-based network is meaningful for governments because they are eager to understand the global oil trade in order to avoid oil supply risk.

Actually, oil trade flows reflect the relationships among countries, which form a network where the countries are taken as the nodes and the trade relationships as the edges. Thus, the development of "the new science of networks" [1,2] has offered an effective tool when analyzing the trading patterns. The complex network approach has been proved fruitful and shed new light on international oil trade [3–7]. A directed oil trading-based network model was established by An et al. to study the relationship between countries with common trade partners [3]. Wang et al. employed a complex network approach to research the interaction patterns among the crude oil import dependency countries in the global oil trade network [4]. Zhong et al. studied the evolution of communities of the world oil trade network by setting up un-weighted and weighted oil trade network models using data from 2002 to 2011, and analyzed their evolutionary features and

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stabilities over the time [5]. Zhang et al. studied the competition among oil importers using complex network theory, combined with several alternative measures of competition intensity, to analyze the evolution of the pattern and transmission of oil-trading competition [6]. Du et al. studied the overall topological structure properties of global oil trade network, and by applying random matrix theory, explored the complex spatiotemporal dynamic from the country level and fitness evolution of the global oil market from a demand-side analysis [7].

Existing network studies have greatly contributed to our understanding of international oil trade. However some shortages are still existed. First, in the above global oil trade network, a country's trade partners are treated equally. However, not all the trading partners are equally important to a country. A country is concentrated in its trade with a few partners. This concentration is especially notable for developing countries, as most peripheral countries' foreign trade is heavily dependent on particular core countries, according to world system and dependency theories [8–10]. Thus it is necessary to distinguish a country's top trade partners from nonessential ones and to study the specific trade network based on these top trade relations. By introducing the definition of 'export intensity', Ji et al. constructed a global oil trade core network, which is a simplified model of the whole international oil trade, and analyzed the overall features, regional characteristics and stability of the oil trade by using complex network theory [11].

Second, the question of the relative importance of oil trading countries and influences between them has rarely been studied. Even if there existed study of identifying the centrality of nodes, they were often limited to some traditional indicators, such as degree, strength, betweenness, etc. [12–14]. In fact, the actual international oil trade network is both directed and weighted system, and trade relationship between two countries are presented as direct or indirect connections. In the former study, the indirect relation of oil exporters and oil importers has been neglected. For example, if there is an oil importer C, which heavily relies on oil exporter B, which in turn imports oil from another country A, then it is clear that even if there are no direct connections from A to C, A is a major contributor to C. Therefore, it would be significant to have a means of reflecting trade direction, trade volume, direct as well as indirect trade relations.

In light of these gaps, we specifically construct a top 1 import network and a top 1 export network based on top trade relations. The simplified network model can describe countries' preference in choosing trade partners well, and also reflect the positions of oil trading countries and evolution features well. We further develop a modified closed-system input-output analysis method, which not only contains the direction and the intensity of oil trade relations, but also considers the direct and indirect influences among oil trading countries, to discuss the relative importance of these countries and how this evolves. The results of the above two methods are compared. In this paper, Section 2 introduces the model and methodology. Section 3 is empirical analysis for global oil trade network. Section 4 is conclusions and suggestions.

2. Model and methodology

2.1. The global oil trade network modeling

We construct a model of directed and weighted global oil trade network, whose nodes are the nations, and edges are the oil trade relationships between nations. The oil flow out of and into a country can be presented by an edge with direction. The weight of the edge is measured by the trading volumes.

Since the international oil trade includes import and export flows, the network can be divided into oil import network, in which the in-degree and in-strength of nodes are only considered, and oil export network, in which the out-degree and out-strength of nodes are only considered. The in-degree k_{in} of a node (country) measures the number of countries, which export oil to the country. The out-degree k_{out} measures the number of countries, which import oil from the country. The in-strength s_{in} of a country means its total imports, and the out-strength s_{out} is its total exports. Fig. 1 is an example of the directed and weighted network.

Fig. 1 is an example of the directed and weighted network. Suppose there are crude oil trade relationships among four countries named A, B, C and D. Take node B for example, if B imports 5 tons of crude oil from A, the weight of the directed edge, which represents the oil flow from A to B, is 5. Thus, for B, $k_{in} = 1,\ s_{in} = 5$. At the same time, B exports 2 tons of crude oil to D, and exports 1 ton crude oil to C. The weights of the two directed links connecting B to D, and B to C, are 2 and 1 separately. Thus, for B, we have $k_{out} = 2,\ s_{out} = 3$.

2.2. Top network analysis method

Based on the above international oil trade network, we further build a simplified network to capture most important relations in the oil trade by using the core idea of Ref. [10]. The specific simplified network is on the base of top oil trading relations, that is, if country j is country i's top trade partner, country i is linked to country j; otherwise, there is no tie between i and j. Particularly, we consider oil import network. If country i imports oil from j and other countries, we rank the import trade relations of i with other countries by importing volumes. Thus, the top 1 oil import network is constructed by including each country's topmost import trade relation only. In the same way, by ranking the export trade relations of each country with other countries by exporting volumes, the top 1 oil export network is built by including each country's topmost export trade relation only. If each country's top two importing or exporting trade relations are kept, the resultant network is called top 2 import or export network. Further, we can go down the ranking of trade relations and obtain the top networks of the selected standard. One key characteristic of the top import/export network is that all nodes have an in-degree/out-degree not exceeding the selected standard, but the out-degree/in-degree varies across nodes.

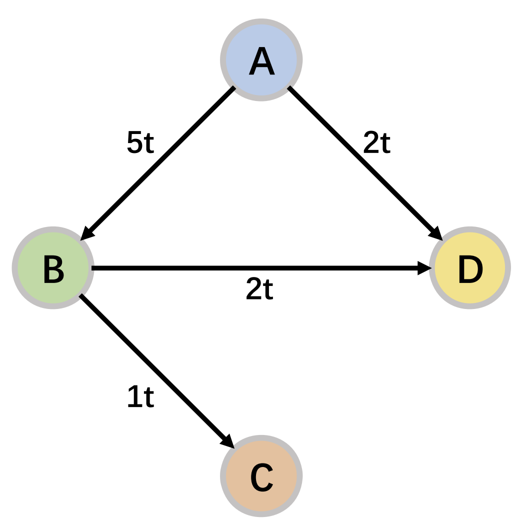

Fig. 1. An example of the directed and weighted network.

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2.3. Modified closed-system input-output analysis method

The input-output theory was first proposed in 1936 by American economist Leontief, and answered two typical questions: first, what happens if the final demand increases? Second, which economic sector is the most important for the whole economy [15]? Tang et al. established an input-output model to calculate oil embodied in the international trade of China [16]. Shen et al. revealed the interrelations among scientific fields and their relative influences by an input-output analysis, in which the element x_j^i of input-output matrices reflected a citation received by paper in field i from paper in field j [17]. Because of including both direct and indirect connections, the relationships among countries can be revealed deeper with the input-output analysis method, than with the traditional measure of complex network by calculating degrees and strengths.

Assume the global oil trade network has N countries. Denote the weighted adjacent matrix as W, which is also called the input-output matrix, whose element x_{ij} represents the volume of oil flowing from country i to country j. Let A be the direct input-output coefficients matrix, the element of which is

$$a_{ij} = \frac{x_{ij}}{x_j}, \quad i,j = 1,2,\ldots,N, \tag{1}$$

where $x_j = \sum_k x_{jk}$. With these elements a_{ij}, we obtain

$$x_i = \sum_j A_{ij} x_j \Rightarrow X = AX. \tag{2}$$

Eq. (2) means that X is an eigenvector of matrix A corresponding to the eigenvalue 1, the largest eigenvalue of matrix A. For simplicity, the eigenvector corresponding to the largest eigenvalue is called the largest eigenvector. $A^{(-j)}$ is what remains of matrix A after its jth row and jth column are removed. Denote the largest eigenvalue of matrix $A^{(-j)}$ by $\lambda^{(-j)}$. If country j has hardly any trading connections to other countries, i.e., the values in the jth row and/or column are very small compared with other elements of A, $\lambda^{(-j)}$ is very close to 1. Otherwise, if country j relates closely to other countries, $\lambda^{(-j)}$ is much smaller than 1. Therefore, the input-output factor on the input side (In-IOF) is given [17]

$$S_{IO}^j = 1 - \lambda^{(-j)} \tag{3}$$

to calculate the relative importance of country j. The practical interpretation of the largest eigenvector is: the vector X can be regarded as the specific combination of oil from different countries, that results in well operating of oil trading system. The kth element of X, denoted as $\langle k|X\rangle$, can be interpreted as the supplying of the kth

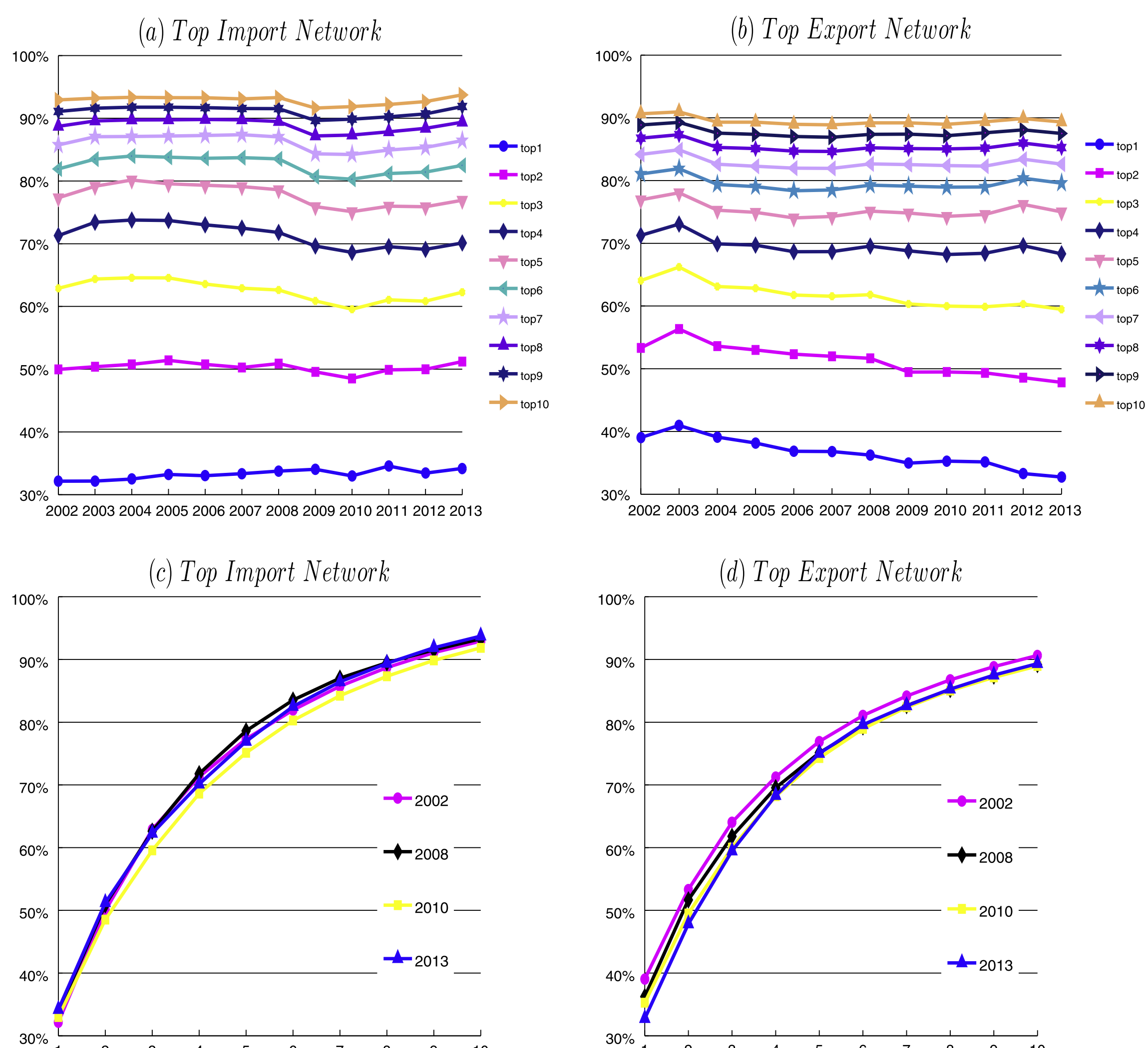

Fig. 2. Percentages of top import and export oil trade networks in overall international oil trade. Note: (a) and (b) show the percentages of the top 1–top 10 import and export oil networks in overall international oil trade from 2002 through 2013, respectively. (c) and (d) show how loosening the selection standard (from top 1 to top 10) increases the percentage of the top network in overall international oil trade in the years 2002, 2008, 2010 and 2013.

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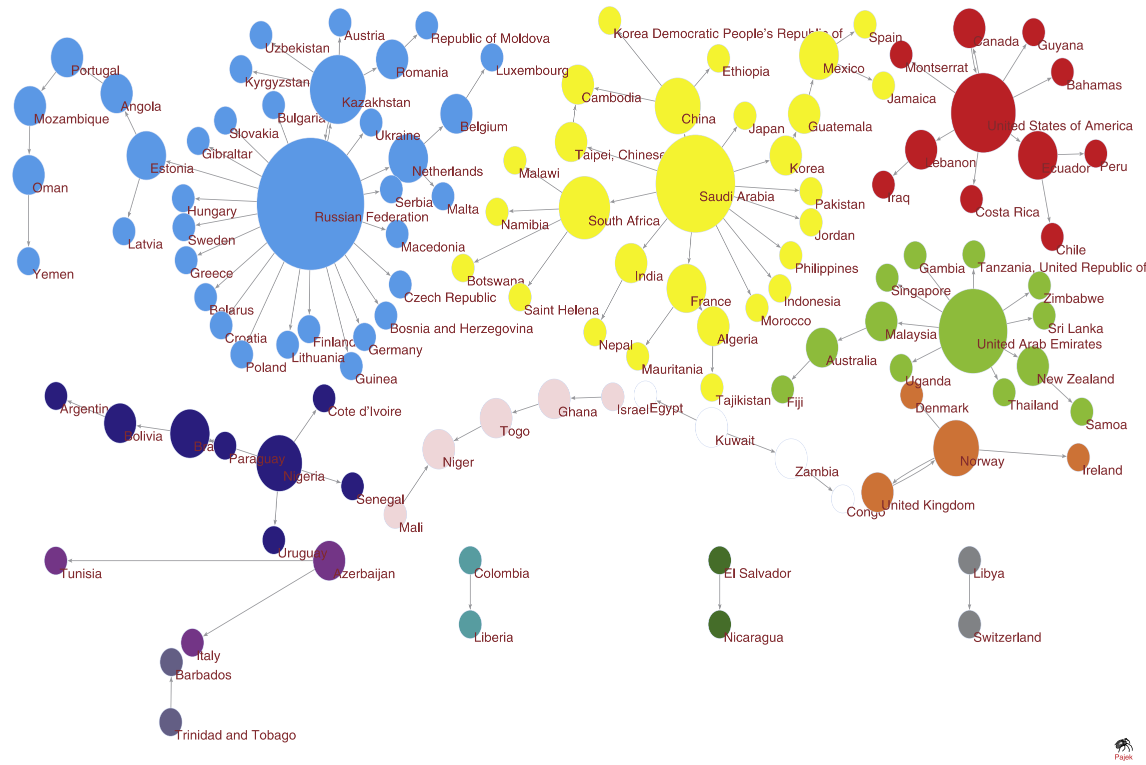

Fig. 3. Top 1 oil import network in 2013.

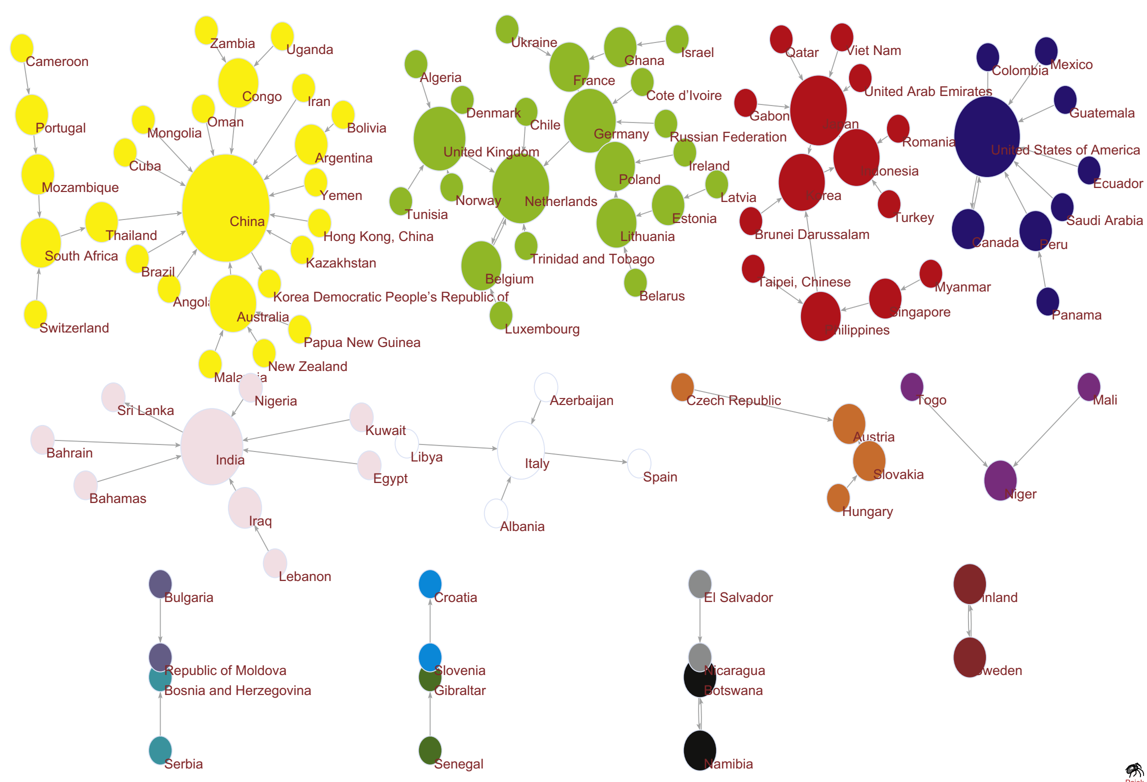

Fig. 4. Top 1 oil export network in 2013.

country to the global oil trade network. $\langle k|\lambda^{(-j)}\rangle$, the kth element of the largest eigenvector of matrix $A^{(-j)}$, can be understood as the contribution of country k for the oil trade system without country j.

Thus, to reflect the influence of country j to country k, we propose the input-output influence on the input side (In-IOI) defined by

$$\Delta_k^j = 1 - \frac{\langle k|\lambda^{(-j)}\rangle}{\langle k|X\rangle}, \tag{4}$$

Obviously, for a given country j, Δ_k^j describes if j is removed from the global oil trading network, how much the oil imports/exports of country k changes, directly and indirectly. When $\Delta_k^j \ll 0$, country k relies strongly on country j, and when $\Delta_k^j \gg 0$, country k can be regarded as a competitor of country j.

The above analysis are applicable to the import side. For the same reason, when we transpose the input-output matrices $(x_{ij})_{N\times N}$, by using the above two equations, we can get the input-output factor (Out-IOF) and input-output influence (Out-IOI) on the export side. The modified closed-system input-output analysis method can show the characteristics of the real oil trade, since it is based on the weighted adjacent matrix of global oil trade network, which not only mirrors the direction of oil flow, but also reflects the quantity of oil trade.

3. Empirical analysis for global oil trade network

3.1. Data

We employ bilateral trade flows data from the United Nations Commodity Trade Database (UN Comtrade; http://comtrade.un.org). We build a balanced panel of $N = 183$ countries and regions for which we have commodity-specific imports and exports flows from 2002 to 2013 ($T = 12$ years). The used code is HS 270900: crude petroleum oils.

3.2. Top 1 oil trade network: revealing the structure and evolution

The top oil trade networks extract the most important relationships from the global oil trade network. Fig. 2 shows the trade volume percentages of various import and export top networks in the overall international oil trade. According to Fig. 2(a) and (b), oil flows in the top 1 import and export networks make up more than 30% of total imports and exports, respectively. The top 2, top 6 and top 10 networks account for approximately 50%, 80% and 90% of total global oil trade. These percentages have almost been stable over time. This illustrates top trade relations can indeed reflect the global oil trade network well. Fig. 2(c) and (d) further shows the relationship between top networks and their percentages in total oil trade in the years 2002, 2008, 2010 and 2013. All curves start above 30%, then rise up and approach 100% as more trade relations are brought into the top networks. However, the trend of the percentages appears a convex increasing parabolic curve, thus the growth rate is decreasing. Since top 1 relations are included by all types of top networks, and the top 1 network alone accounts for more than 30% of the overall oil trade, in this study we analyze the structure and evolution of top 1 import and export networks.

Fig. 3 visualizes the top 1 oil import and export networks in 2013. In the top 1 oil import network, each major oil exporter, Russia, Saudi Arabia, United Arab Emirates, United States of America, etc., leads a large cluster. Although the total exports of United States of America are not much, but the number of countries USA exporting oil to are relative larger, and many of these countries have USA as their largest import source. Russia, Saudi Arabia, United Arab Emirates are countries with larger exports, and are the top sources of many oil importers. In the top 1 oil export network, each major oil importer, China, United States of America, India, Japan, etc. leads a large cluster. Besides the big clusters, there also exist some small clusters surrounding around some local centers.

In order to better understand the hierarchical structure of the top 1 oil trade networks, we apply the degrees to reflect the status of countries. In the top 1 oil import network, all countries have in-degree 1 or 0, but have different out-degrees. The out-degree can determine the status of countries in the network. Similarly, in the top 1 oil export network, all countries have out-degree 1 or 0, but different in-degrees, which can reflect the position of countries in the network. Table 1 shows the top 10 countries in the top 1 oil import network between 2002 and 2013. From Table 1, the ten countries can be roughly divided into three levels. The central Status of Russia and Saudi Arabia have been stable over time. They can be regarded as the first level. The second level consists of four members: United Arab Emirates, Nigeria, South Africa and United States of America. The average out-degree of each member is

Table 1
Out-degree for major countries in top 1 oil import network, 2002–2013.

Country	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Russia	20	20	23	25	20	23	22	22	22	23	22	21
Saudi Arabia	12	13	12	13	16	13	15	15	13	14	11	12
United Arab Emirates	5	5	9	5	7	10	11	9	7	12	8	9
Nigeria	8	6	6	5	6	5	6	8	7	5	6	4
South Africa	7	6	5	7	6	7	7	8	6	3	6	4
USA	5	3	4	4	3	7	6	3	4	5	4	7
Norway	6	5	5	5	6	3	3	3	3	2	3	3
Kazakhstan	3	1	4	2	3	3	4	4	4	4	6	5
Libya	3	3	3	3	3	4	3	3	2	0	2	1
Iran	2	3	3	3	4	3	2	1	4	3	1	0

Table 2
In-degree for major countries in top 1 oil export network, 2002–2013.

Country	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
USA	17	14	16	15	16	16	14	14	14	16	12	7
China	1	5	5	4	8	8	6	6	7	8	10	13
Japan	9	7	6	5	6	6	5	5	5	4	5	5
Germany	3	3	4	3	5	6	6	5	5	5	7	4
Australia	4	5	5	5	4	4	5	5	4	4	5	3
Italy	6	5	5	4	4	4	5	3	3	4	6	3
India	0	0	0	0	2	2	4	8	3	7	9	6
Korea	7	1	3	1	2	2	3	4	4	4	3	3
Sweden	4	5	2	5	3	1	2	2	2	4	3	1
Canada	1	0	4	5	7	2	5	1	1	2	0	1

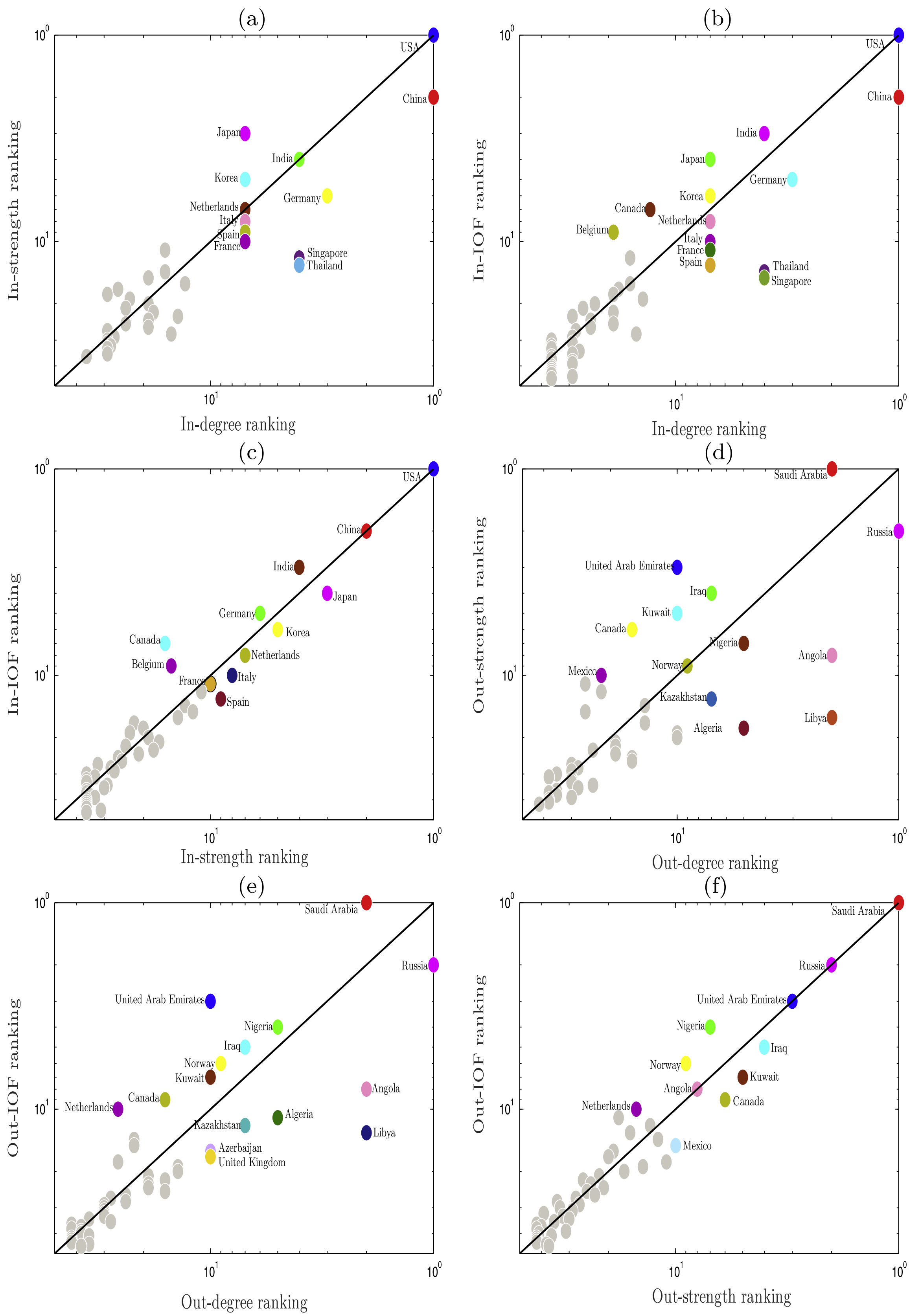

Fig. 5. (a)-(c) Comparisons of degree, strength and IOF rankings on the import side. (a) Correlation between in-strength ranking and in-degree ranking in 2013. In the region above the diagonal line along which the two rankings are equal. (b) The relation of in-IOF ranking and in-degree ranking in 2013. (c) In-IOF ranking versus in-strength ranking in 2013. (d)-(f) Comparisons of degree, strength and IOF rankings on the output side. (d) Correlation between out-strength ranking and out-degree ranking in 2013. (e) The relation of out-IOF ranking and out-degree ranking in 2013. (f) Out-IOF ranking versus out-strength ranking in 2013.

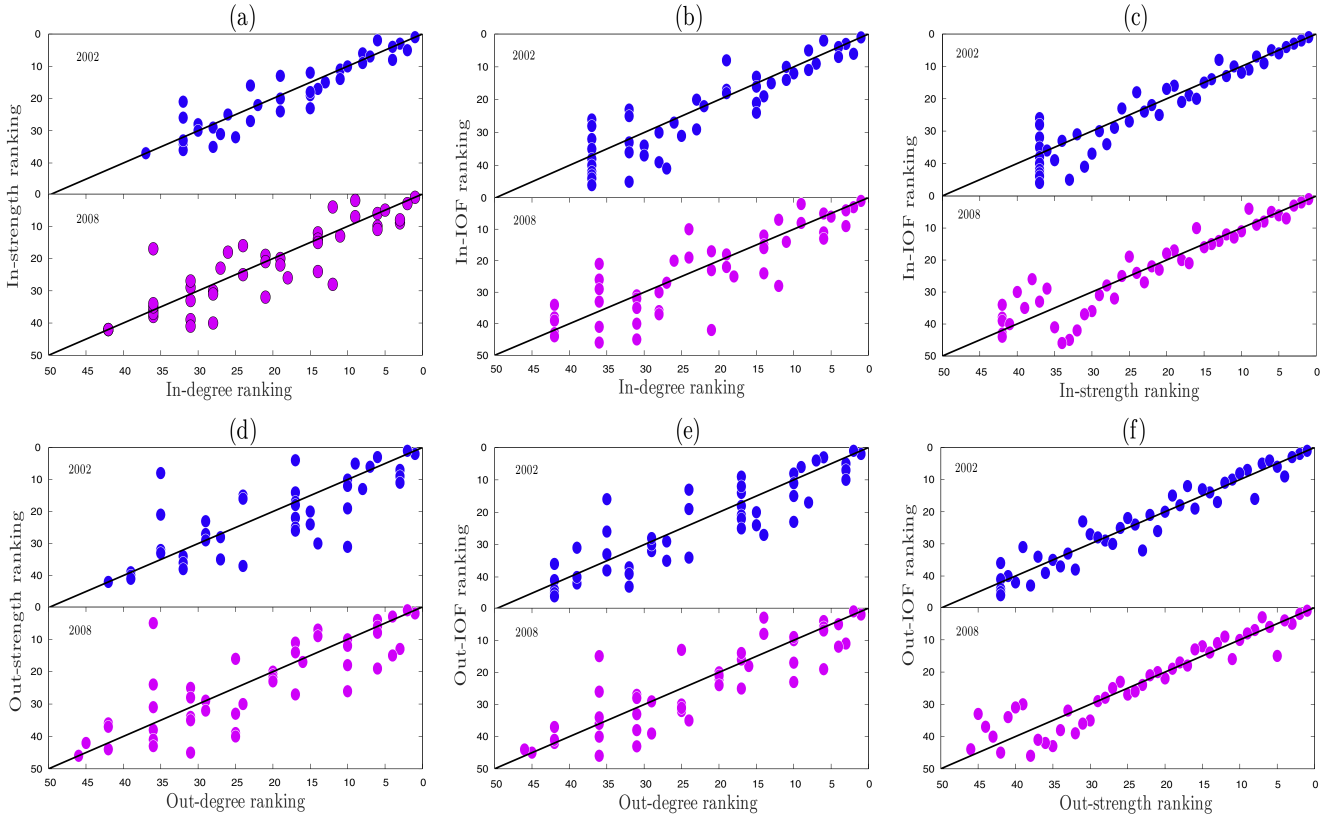

Fig. 6. (a)-(c) Comparisons of degree, strength and IOF rankings on the import side. (a) Correlation between in-strength ranking and in-degree ranking in 2002 and 2008. (b) The relation of in-IOF ranking and in-degree ranking in 2002 and 2008. (c) In-IOF ranking versus in-strength ranking in 2002 and 2008. (d)-(f) Comparisons of degree, strength and IOF rankings on the export side. (d) Correlation between out-strength ranking and out-degree ranking in 2002 and 2008. (e) The relation of out-IOF ranking and out-degree ranking in 2002 and 2008. (f) Out-IOF ranking versus out-strength ranking in 2002 and 2008.

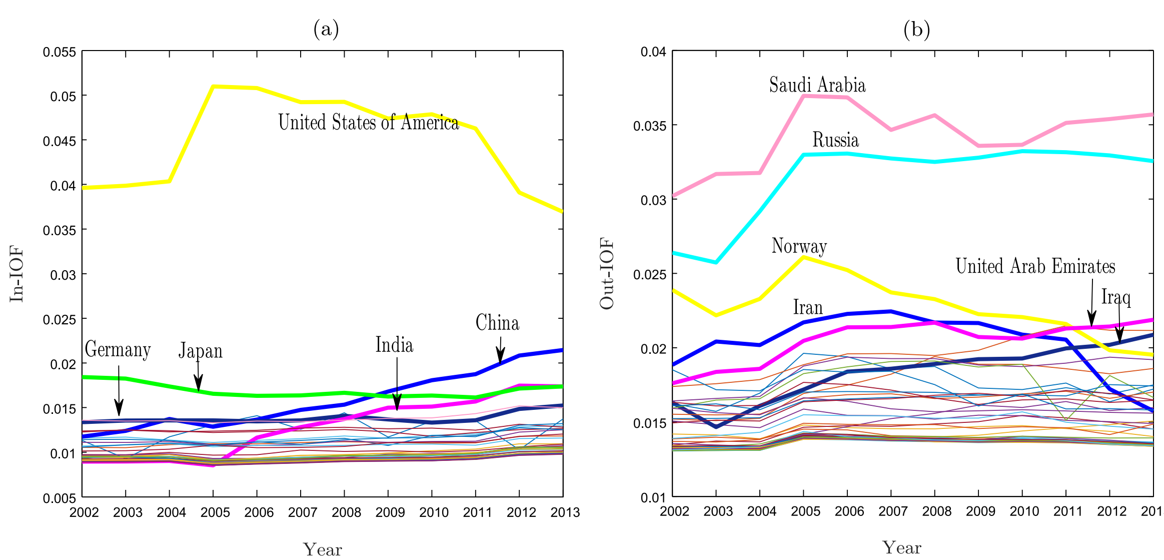

Fig. 7. (a) Evolution of In-IOF. (b) Evolution of Out-IOF.

between 5 and 8, and their out-degrees are all above 3 in the whole time period. Positions of Norway and Iran decrease gradually. It means many countries who before had the two countries as their top oil import sources have shifted to other countries. In contrast, the position of United Arab Emirates increases obviously. The third level includes four members: Norway, Kazakhstan, Libya and Iran. The average out-degree of each member is between 2 and 4.

Table 2 shows the in-degree for major countries in the top 1 oil export network from 2002 to 2013. The 10 countries can be roughly divided into four levels. The first level only has United States of America, whose average in-degree is above 14. This illustrates the United States of America is the biggest oil export market for many countries. The second level consists of two members: China and Japan. The average in-degree of each member is between

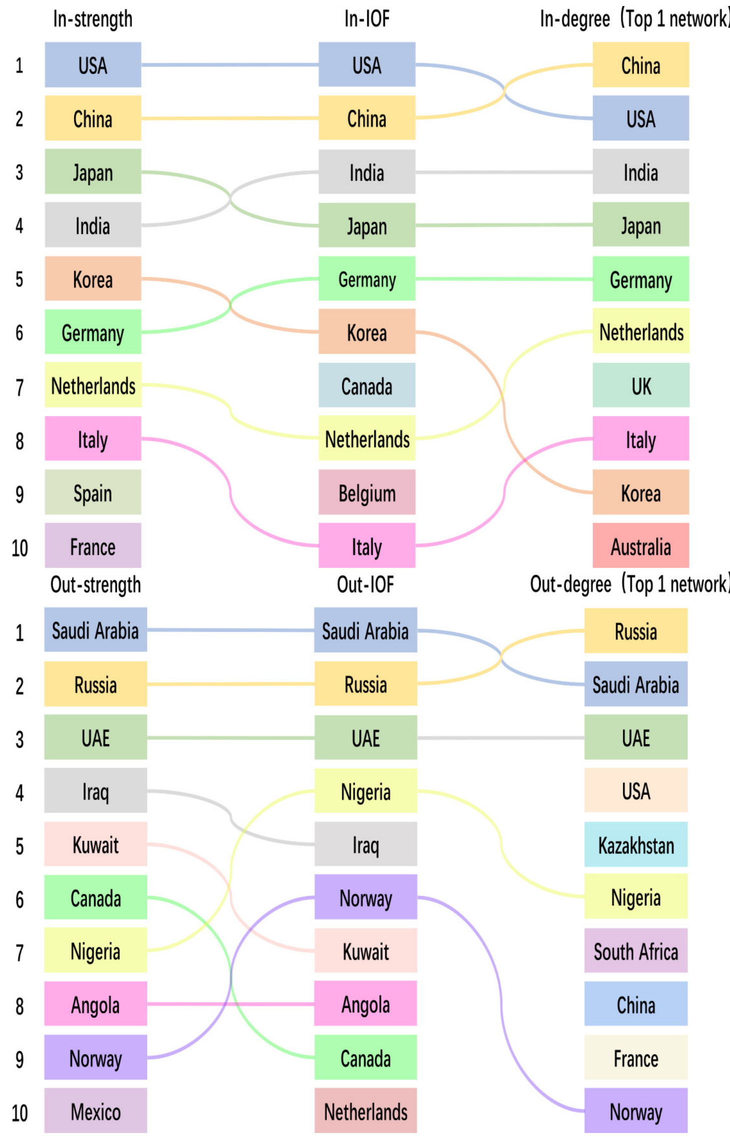

Fig. 8. A comparison of different methods to measure the countries who play more important role in global oil trade.

5 and 7. The third level includes five members: Germany, Australia, Italy, India and Korea. The average in-degree of each member is between 3 and 5. The fourth level contains countries as Sweden and Canada. The central position of the United States of America has remained stable during the 12 years. The status of Japan has shown a gradual decline over the 12 years. This means many countries who before had Japan as their export market have shifted to other countries. On the contrary, the trends of China and India's positions have been on the rise year by year. It shows an increasing diversity of their import sources.

3.3. Modified closed-system input-output analysis: revealing the interrelation and evolution

We construct the input-output network (matrices) from 2002 to 2013 by extracting 46 major oil trading countries (the crude oil trading volume of each country is above 100 million tons in 2013). They are Algeria, Angola, Australia, Azerbaijan, Belarus, Belgium, Brazil, Canada, China, Colombia, Congo, Ecuador, Finland, France, Germany, Greece, India, Indonesia, Iran, Iraq, Italy, Japan, Kazakhstan, Korea, Kuwait, Libya, Malaysia, Mexico, Netherlands, Nigeria, Norway, Oman, Poland, Portugal, Qatar, Russia, Singapore, South Africa, Spain, Sweden, Chinese Taipei, Thailand, United Kingdom, United States of America, Saudi Arabia, United Arab Emirates. The closed-system input-output method is applied to analyze the relative importance of and influences among these major oil trading countries.

First, we examine the correlation of the relative importance, as measured by IOF, degree and strength. Fig. 5(a) shows the in-degree and in-strength rankings of USA, India, Netherlands, etc. are the same. There also exist countries of which the two rankings are different obviously. For example, the in-degree rankings of Singapore and Thailand are in the top, while the in-strength rankings are a little lower. Their imports are nearly 0.12 billion tons less than that of Japan, but their importing countries are more than Japan's. This effectively spreads the imports risk, and reduces the dependency on exporters. Fig. 5(b) shows the correlation of in-IOF ranking with in-degree ranking is very similar with Fig. 5(a). We examine the correlation between in-IOF and in-strength. The countries are almost on the diagonal line in Fig. 5(c). From Fig. 5 (d), we find countries like Libya, Angola, Algeria, etc., whose exports are about 0.3 billion tons less than Saudi Arabia, but the out-degrees of which are very close to that of Saudi Arabia. It means that Libya, Algeria, etc. have a wider export market. Fig. 5 (e) shows the correlation of out-IOF ranking and out-degree ranking is very similar with Fig. 5(d). From Fig. 5(f), we find the out-IOF

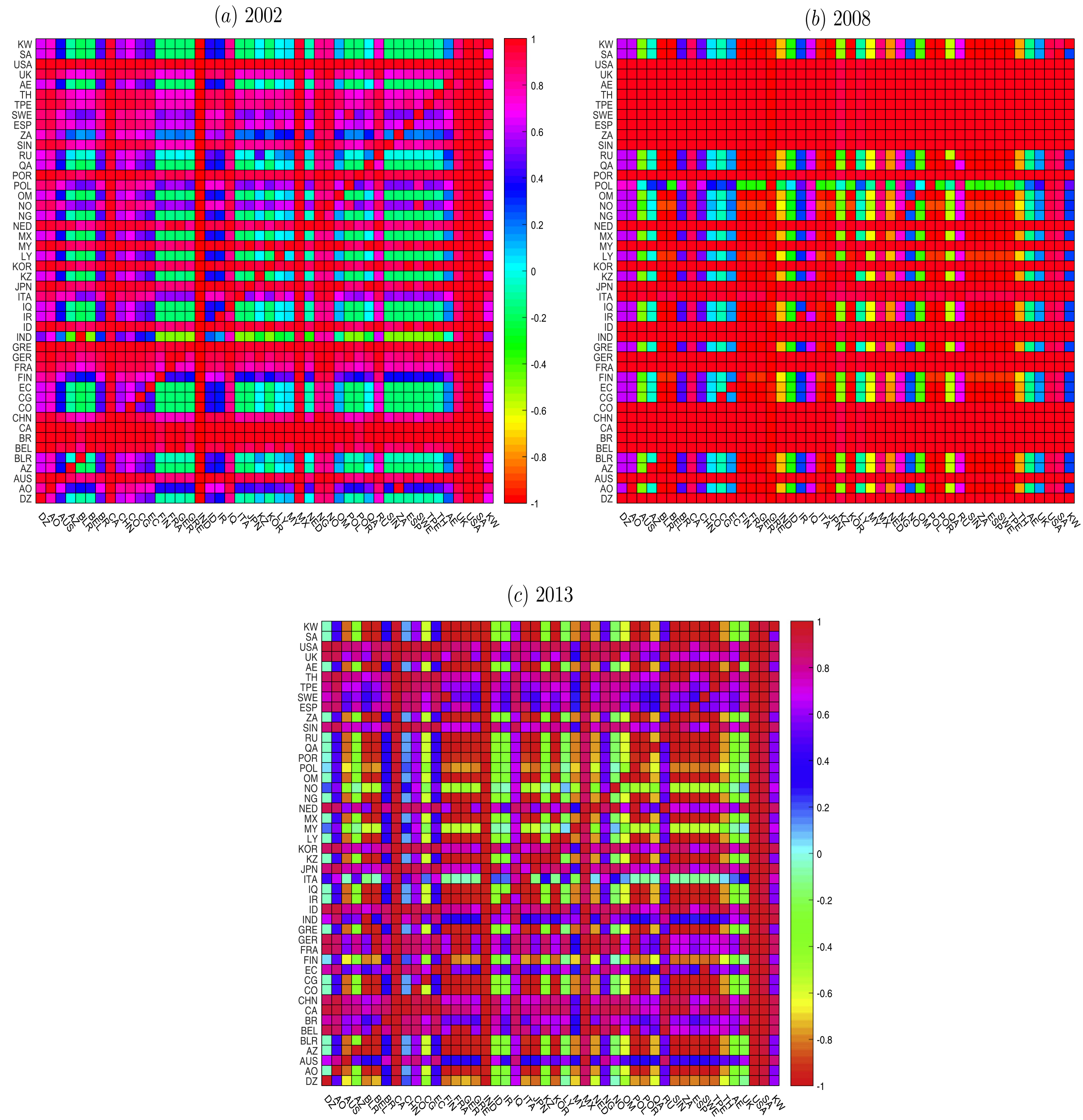

Fig. 9. Input-output influence on the input side in 2002, 2008 and 2013.

and out-strength rankings of top ten countries are almost the same. Almost all the countries are distributed around the diagonal line.

Besides, we perform comparisons of degree, strength and IOF rankings on the input and output sides in 2002 and 2008 separately, as shown in Fig. 6. These all illustrate that countries with large influences, whatever on the input side or on the output side, are with large strengths, that are large importers or exporters.

Fig. 7 shows the evolution of In-IOF and Out-IOF. In Fig. 7(a), we find the United States of America played the most important role on the import side over a period of 12 years, from 2002 to 2013. It's worth mentioning that China and India played increasingly important roles in international oil trade. However, the importance of Japan was decreasing gradually. In Fig. 7(b), Saudi Arabia and Russia lied in essential positions on the export side during the whole sample period. The importances of United Arab Emirates and Iraq have strengthened from 2002 through 2013. But Norway and Iran became continually less important. This result coincides with that of Top network analysis.

Besides comparing the evolution trend, the following Fig. 8 performs a comparison about the relative importance of countries in 2013 based on the above metrics methods. The result shows that the measurement results obtained by the three indicators: strength, IOF and degree of top network, are very close, especially by strength and IOF.

Pursuing stable oil supply has been a great concern for both policy makers of most industrialized nations and scholars especially since the break of two global oil crises of the 1970s. It is generally known that oil-exporting countries have played an essential role in international oil-trading network. OPEC (Organization of the Petroleum Exporting Countries) has played a dominant role in the global oil sector by coordinating and unifying petroleum policies among its member countries. As of 2015, the 14 member countries accounted for an estimated 43% of global oil production and 73% of the world's "proven" oil reserves. Sudden change in oil-exporting countries will cause fluctuation of oil supply. Much work has been done on the supply side [18–21]. In Fig. 9, we report influences among major oil importers and exporters by using a heatmap, in which the color corresponds to the IOI from the row to the column countries. From Fig. 9, we find that the major importers, such as United States of America (USA), China (CHN), Japan (JPN), United Kingdom (UK), Singapore (SIN), Netherlands (NED), Korea (KOR), Germany (GER), France (FRA), Spain (ESP), and Australia (AUS), etc. have great influence on other countries, including major oil exporters. Therefore, while special attention is paid to the oil supply side, the demand side of the international oil trade should also be concerned with by policy makers and scholars.

4. Conclusions and suggestions

In this paper, we tried to answer the question: how important is the country in the international crude oil trade? The global crude oil trade network model is built from crude petroleum data from 2002 to 2013. We applied the modified closed-system input-output analysis method and top network analysis method to reveal the structural features and evolution of the global oil trade system.

Not all relations in the international oil trade network are of the same importance. Although the top 1 network is a simplified model, which only consists of countries' topmost trade relations, but it can well reflect countries' preference in choosing oil trade partners. By the structural analysis of top 1 oil import or export network, we find the whole network is separated by clusters, most of the countries in which are surrounding around global or local centers, that is, major oil exporters, such as Russia, Saudi Arabia, United Arab Emirates, etc., or major oil importers, such as China, United States of America, India and Japan, etc. These global and local centers are regarded as the main oil importing sources or exporting destinations. Further, the evolution features of major countries in top networks are analyzed. The result offers a way to make a rational decision for a country to develop oil trade relations.

The modified closed-system input-output analysis method has considered both direct and indirect effects in measuring which country contributes more in the global oil trade and thus may be traded preferentially. We find that a country with greater influence, is also with larger oil trading volume. The evolution of IOF analysis follows the same trend with that of top network analysis. Moreover, the heatmap of IOI describes the influences of countries on each other. Particularly, we find major oil importing countries have great influence upon not only the marginal countries, but also major oil exporting countries. Therefore, when people are paying continual attentions to the issues related to major oil exporting countries, they also should concern the series of problems brought by oil importing countries.

In addition, the above two methods are applicable to more energy systems that have input-output relations among their elements. When combined with time-series data, the methods can also be adopted to track the evolution of the elements.

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