Evolution of International Fossil Fuel Trade Patterns: A Network Analysis Based on Emergy

Weiqiong Zhong[a, b, c] Haizhong An[a,b,c] Xiangyun Gao[a, b, c] Di Dong[a, b, c]*

[a] *School of Humanities and Economic Management, China University of Geosciences, Beijing, China,*
ahz369@163.com

[b] *Key Laboratory of Carrying Capacity Assessment for Resource and Environment, Ministry of Land and Resources, Beijing, China,*

[c] *Lab of Resources and Environmental Management, China University of Geosciences, Beijing, China*

Abstract:

A better understanding of the international fossil fuel trade patterns is crucial to energy security and policy optimization. This study aims to quantitively analyse the international trade patterns of fossil energy. We transform the trade quantity of coal, crude oil and natural gas into emergy by transformity and the sum of the three emergies is the emergy of fossil fuel. Thus the complex network models of them can be built. We analyse on trade partners, trade quantities and hierarchy structure of the networks and find that the main emergy of the world fossil trade is contributed by crude oil, and a smaller number of trade links shoulder most of the trade quantities. The hierarchy structure of fossil trade network is not obvious. USA owns the highest intermediary ability while all of the countries have their specific features of intermediary ability.

Keywords:

Fossil fuel, International trade, Emergy, Complex network.

1. Introduction

Fossil fuel is the most important energy in the modern society. The fossil energy flows between countries by international trade because of the uneven distribution of its production and consumption. A better understanding of the international fossil fuel trade patterns is crucial to energy security and policy optimization [1-3]. This study aims to quantitively analyze the international trade patterns of fossil energy.

The main commodities of fossil energy are coal, crude oil and natural gas with different forms and units. Emergy is a concept of "energy memory" considering the difference of energy quality and the accumulative cost of energy [4]. Emergy analysis is a technique measuring the values of resources, services and commodities in common units of the solar energy it took to make them [5, 6]. Thus, we can transform the trade quantity of coal, crude oil and natural gas into emergy by transformity (in units of seJ/J). The sum of the three emergies can be used to measure the emergy of fossil fuel.

There are numerous countries and complicated relationships in the international trade. The flows of emergy among countries forms a huge and complex system. Complex network modeling has the advantage of analyzing complex systems. It provides a detailed quantitative analysis of the trade patterns. Recently, some researchers studied the regional energy security and global oil trade patterns by complex network analysis [7]. In the international trade network model, the nodes are the countries, and the edges are the trade relationships. The directions of the edges are the trade flows, and the weights of the edges are the trade quantities.

In this study, we built up 4 types of network models of coal, crude oil, natural gas as well as the fossil fuel based on the emergy. Then, the characteristics of the trades can be reflected by network analysis. Section 2 introduces the data and the process of modeling. Section 3 applies network analysis on trade partners, quantities of emergy, hierarchy structure of the networks and intermediary ability of countries. Section 4 is the conclusion remarks.

2. Data and Model

The data of international trade of coal, crude oil and natural gas is downloaded from the website of UN Comtrade, which contains all export and import flows among 226 countries in the world. The trade quantities are measured by the units of kilogram or litre. We selected the annual trade data of all the available countries from 2000 to 2013. The transformity of coal, crude oil and natural gas [6] are shown in table 1. We transformed the trade quantities of the three fuels into emergy and the sum of them is the emergy of fossil fuel.

Table 1. Transformity of coal, crude oil and natural gas

Fuel	Transformity (seJ/J)
Coal	8.17E4
Crude oil	1.48E5
Natural gas	1.71E5

We built up 4 network models based on the transformed data. The nodes are the countries, the edges are the trade relationships, the directions of the edges are the direction of the trade flows, and the weights of the edges are the emergies.

3. Analysis and Results

3.1. Trade partners

Trade partners of a country can be reflected by degree in the network. The out-degree is the number of export links a country has with others, and the in-degree is the number of import links. The values of out-degree and in-degree can reflect a node's importance in the network. The higher the value is, the more importance the node is. These values are computed by [8]

$$k_i^{out}(t) = \sum_{j=1}^{n} d_{ij}(t) \quad (1)$$

$$k_i^{in}(t) = \sum_{j=1}^{n} d_{ji}(t) \quad (2)$$

where n is the total number of nodes in the network. If country i exports oil to country j during the year t, then a link from i to j is drawn, and $d_{ij}(t) = 1$. Otherwise, no link is drawn, and $d_{ij}(t) = 0$. The out-degree $k_i^{out}(t)$ of country i in the year t is the sum of $d_{ij}(t)$, and the in-degree $k_i^{in}(t)$ of country i in the year t is the sum of $d_{ji}(t)$. The average degrees of the 4 types of models from 2000 to 2013 are shown in Fig. 1. We can see that countries in the international coal trade own the most trade partners and gas own the least. All of them show ascending tendency. The average degree of the integrated fossil network is much higher than the single commodity network, which means the trade relations are various between the three fuels.

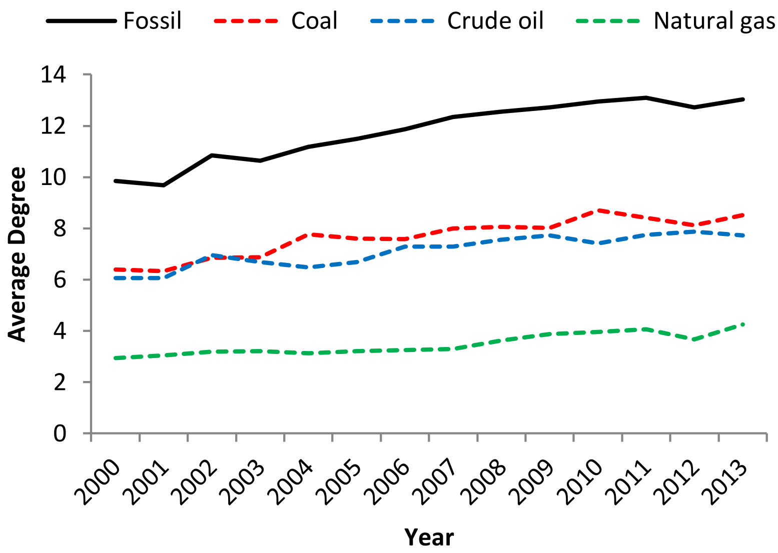

Fig. 1. Average number of trade partners

The trade relationships in the 4 networks each year follow power law distribution which means a small number of countries own many trade partners and most of the countries own a few trade partners (the figures of 2002,2006 and 2013 are shown in Fig. 2).

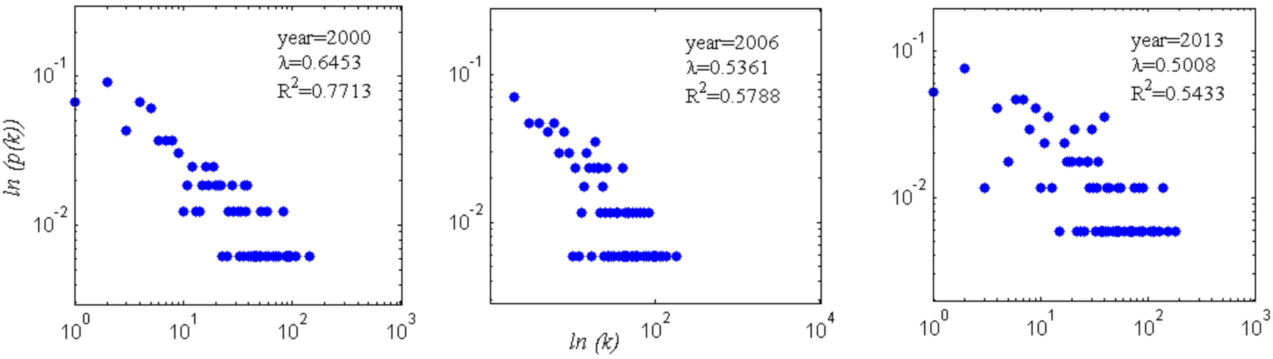

Fig. 2. Distribution of the number of trade partners

3.2. Trade quantities of emergy

Trade quantities of emergy of a country can be measured by weighted degree in the network. The weighted out-degree $s_i^{out}(t)$ and weighted in-degree $s_i^{in}(t)$ of country i reflect a node's importance in the network considering both relationships and quantities of emergy. The higher the value, the more importance. $s_i^{out}(t)$ and $s_i^{in}(t)$ are computed by

$$s_i^{out}(t) = \sum_{j=1}^{n} d_{ij}(t) * w_{ij}(t) \qquad (3)$$

$$s_i^{in}(t) = \sum_{j=1}^{n} d_{ji}(t) * w_{ji}(t) \qquad (4)$$

where $w_{i,j}(t)$ is the weight of $d_{ij}(t)$, which is the total amount of emergy that country i exports to country j during the year t. The average weighted degree of the 4 types of models from 2000 to 2013 are shown in Fig. 3. We can see that the main emergy of the world fossil trade is contributed by crude oil.

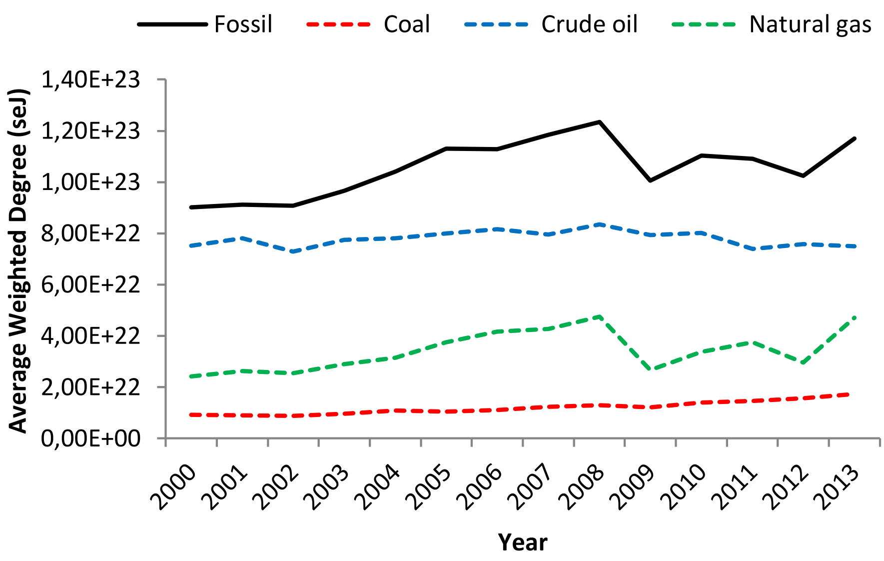

Fig. 3. Average trade quantities of emergy

The trade quantities of emergy are carried by the trade links (edges), thus we analysed the accumulative distributions of the weights in the 4 networks each year. The results of 3 years (2000, 2006, 2013) are shown in Fig. 4. We can see that except natural gas, the international trade of coal, crude oil and fossil are becoming more and more concentrated. Fig. 5 shows the proportion of edges shouldering 80% of the trade quantities. A smaller number of trade links shoulder most of the trade quantities. This phenomenon is less obvious in the network of crude oil, and most obvious in the network of natural gas. Additionally, the gaps of the curves are moving towards up left corner, which means the energy patterns (coal, crude oil and fossil) are more centralized from 2000 to 2013.

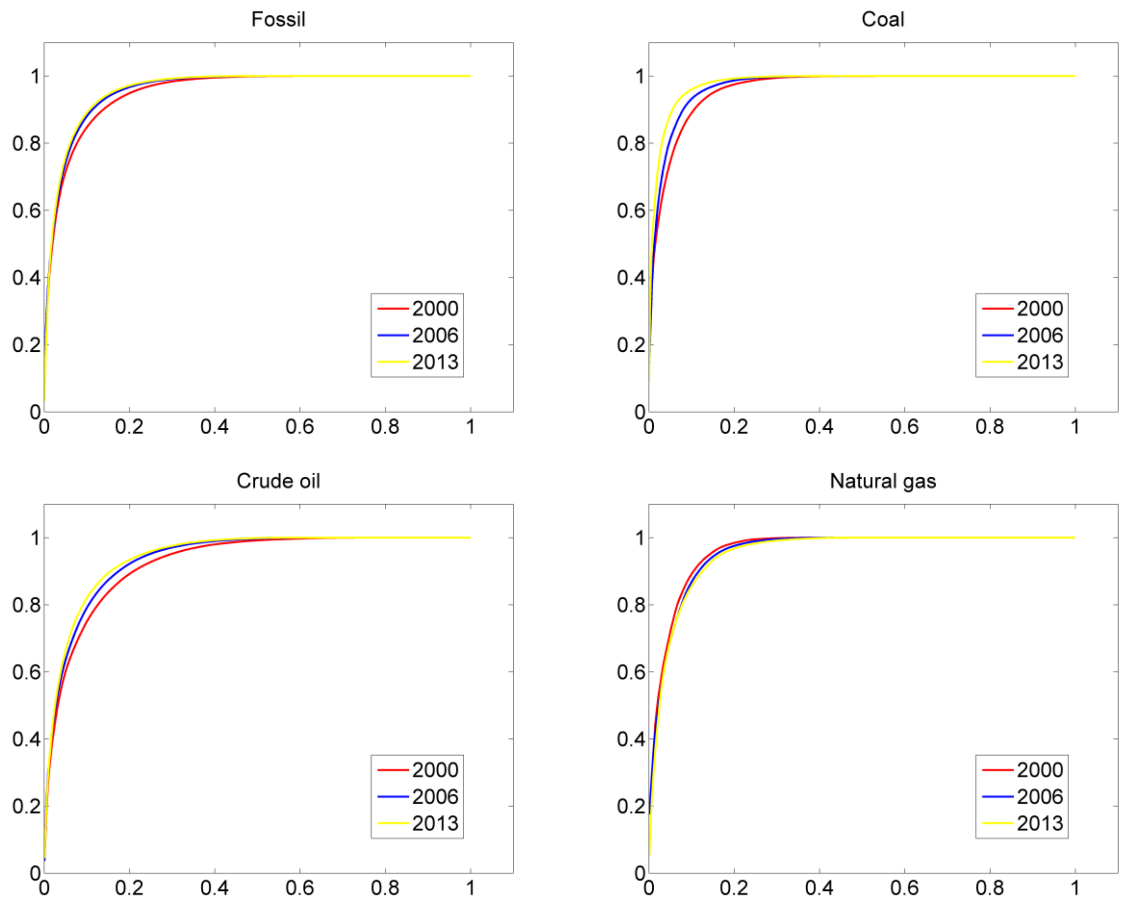

Fig. 4. Accumulative distribution of the weights (emergy)

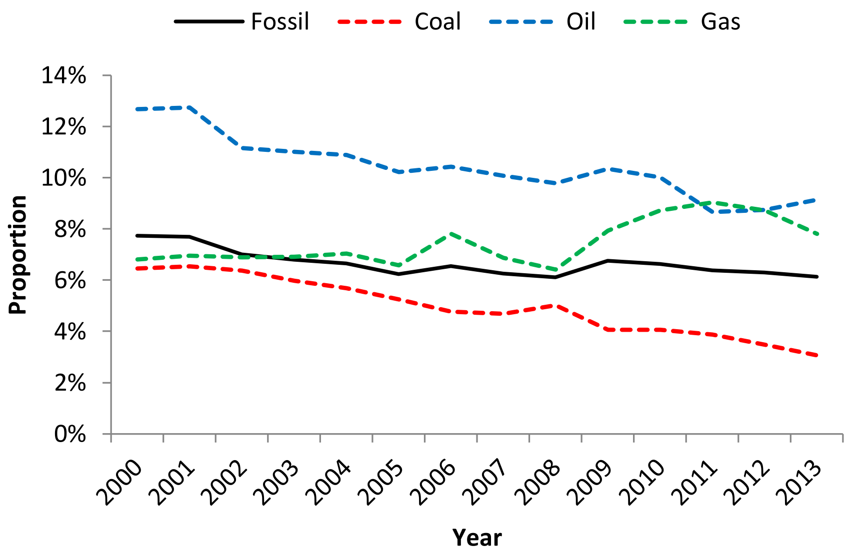

Fig. 5. Proportion of edges shouldering 80% of emergy

3.3. Hierarchy structure

Degree is an index measuring how many countries have trading-based relationships with a given country. It is the number of edges of a node in the network. It indicates the direct impact of a country. Countries with higher degrees possess important roles, because they directly affect more countries.

Clustering coefficient of a country is the probability of trading-based relationships existing between the countries connecting to this country in the network. It reflects the closeness of these countries. If a country's neighbours are closely related, the country has a higher clustering coefficient; on the contrary, if a country's neighbours are loosely related, the clustering coefficient of this country is lower. Countries with higher clustering coefficient have higher influence in the network, because the better connections between the countries, the faster the influences spread.

The clustering coefficient of node i with degree k_i is computed by:

$$C_i = 2n_i/k_i(k_i - 1) \qquad (5)$$

where n_i is the number of the edges among the neighbours of node i.

To study the correlation between roles and influences, we calculated the average clustering coefficient $C(k)$ of nodes with the same degree[9]:

$$C(k) = \frac{1}{NP(k)} \sum_{k_i=k} C(i) \qquad (6)$$

If nodes with the same degree have similar clustering coefficient, the hierarchy structure of the network is more ordered because similar roles have similar influences. We plotted k and $C(k)$ of fossil network in 2000, 2006 and 2013 in Fig. 6. The centrality of the points in Fig. 6 reflects the hierarchy structure of the network. We can see that the hierarchy structure of fossil trade network is not obvious.

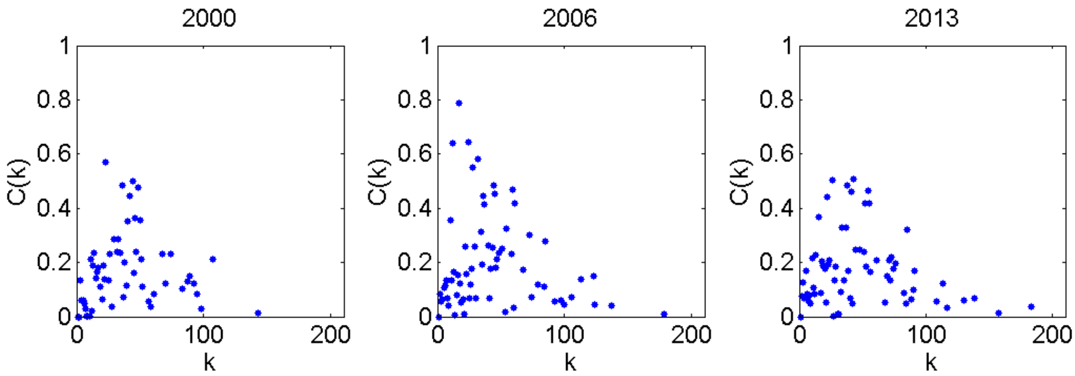

Fig. 6. Average clustering coefficient of countries with the same degree

3.4. Intermediary ability

Betweenness centrality measures the intermediary ability of the nodes as mediums in the network. It can also be explained as the extent to which a country controls the emergy flow. In the international crude oil trade network, betweenness centrality is the frequency a country stands on the shortest path between two other countries. The betweenness centrality of node i is given by [10, 11]

$$\mathrm{BC}(i) = \sum_{s \neq i \neq t} \frac{\sigma_{st}(i)}{\sigma_{st}} \quad (7)$$

where σ_{st} is the total number of shortest paths from node s to node t and $\frac{\sigma_{st}(i)}{\sigma_{st}}$ is the number of these paths that pass through node i.

The betweenness centralities of five countries are shown in Fig. 7. USA is the main energy consuming and producing country in North America and it is the world's biggest economy; China is the main energy consuming and producing country in Asia with rapid economic development; UK is the main energy consuming and producing country in Europe; Russia is the main energy producing country; and Netherlands is a historic trade center.

In the perspective of total emergy of the fossil fuel trade, we can see that USA owns the strongest intermediary ability, however its intermediary ability is slightly descending, especially in 2009. The intermediary ability of China is ascending and since 2002 China ranked second among these 5 countries. The intermediary ability of UK ranked second in 2001, it is fluctuating around a certain level and ranked third during 2002 ~ 2011. The third place of UK is replaced by Netherlands since 2012. The intermediary ability of Netherlands and Russia are similar. The difference of the two countries are in 2000, 2012 and 2013; in 2000 Russia ranked second and in 2012 and 2013 Netherlands ranked third. The trend of Netherlands is ascending while the trend of Russia is descending.

It is worth mentioning that in the model of integrated fossil fuel trade network, the betweenness centralities of the countries are not simply the sum of betweenness centralities in the single fuel trade network. It is recalculated based on the sum of the three emergies and all the relationships. That is why we can see quite different results in the networks of single fuel trade. The intermediary ability of USA in the international trade of coal is much weaker than the other two fuels, and it is more sharply fluctuated in the international trade of natural gas. Due to the huge consumption of coal, China's intermediary ability in the coal trade is the strongest. At the same time, due to the production of natural gas, the intermediary abilities of Russia and UK are strong in the international trade network of natural gas. The transportation restriction also limits the intermediary ability of Netherlands in the trade of natural gas.

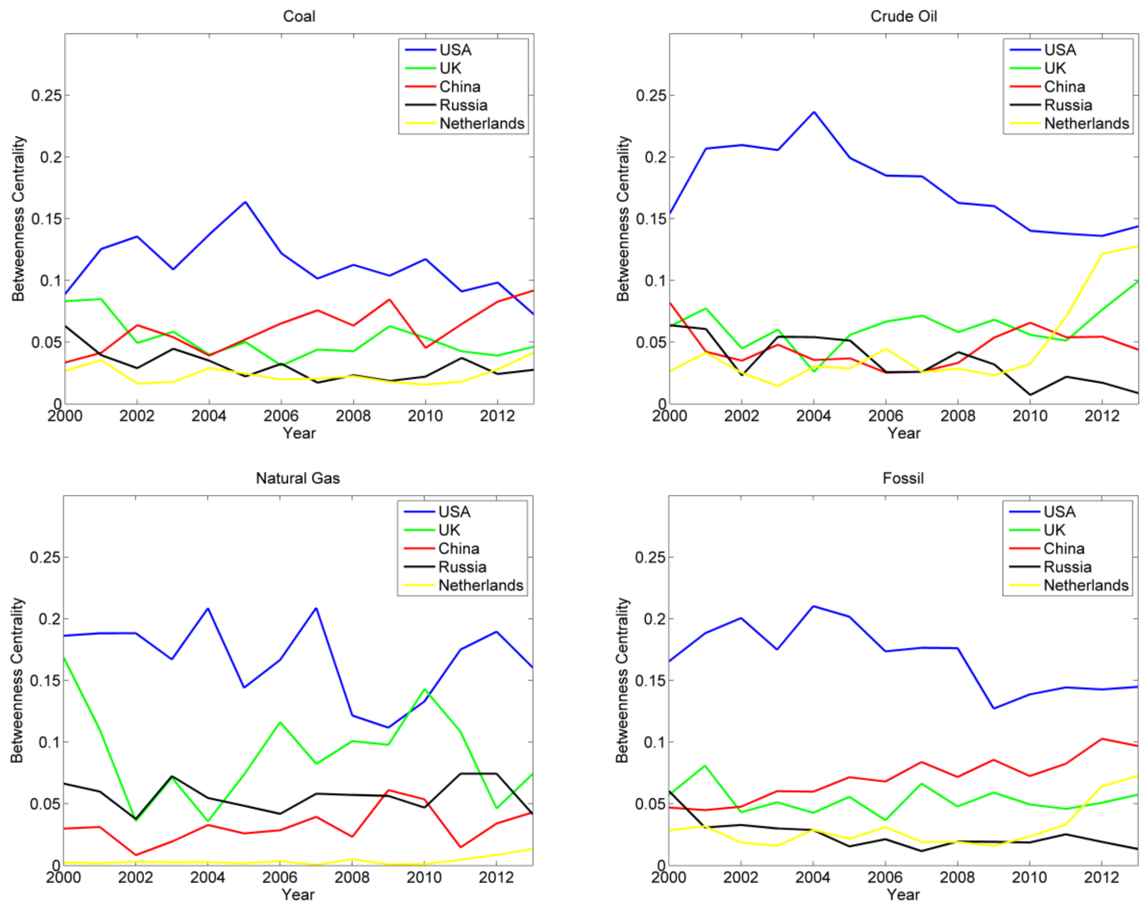

Fig. 7. Intermediary ability of 5 countries

4. Conclusion

In this paper, we set up single commodity network of coal, crude oil and natural gas, as well as the integrated trade network of fossil fuel based on emergy. We found that the average degree of the integrated fossil network is much higher than the single commodity network, which means the trade relations are various between the three fuels. The trade relationships in the 4 types of networks each year follow power law distribution which means a small number of countries own many trade partners and most of the countries own a few trade partners. The main emergy of the world fossil trade is contributed by crude oil, and a smaller number of trade links shoulder most of the trade quantities. The hierarchy structure of fossil trade network is not obvious. We also discussed the evolution of international fossil trade pattern based on the intermediary ability of 5 major countries in the network and found that USA owns the highest intermediary ability while all of the countries have their specific features of intermediary ability.

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