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Structure and patterns of the international rare earths trade: A complex network analysis

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ABSTRACT

The international rare earths trade pattern has become increasingly complex during the past few years. It attracted wide attention and affected rare earths resources strategies of many countries. This study constructs an international rare earths trade network based on complex network theory to analyze the distribution of trading countries, the overall structure of trade, and the major countries and communities of the network. The results indicate that the international rare earths network displays a scale-free characteristic from 1996 to 2015, which implies that a few trade relationships always exist and that countries play critical roles in the international rare earths trade. The distribution of the kernel density is significantly right-skewed, which indicates that most countries have approximately three trade partners, while only a few countries have a large number of trade partners. Moreover, the world's rare earths trade shows a tendency towards integration. The number of communities in the network has varied from eight to four during the past twenty years.

1. Introduction

As a non-renewable strategic resource, rare earths are widely used and are key elements in the high-tech and defense-related industries (Mclellan et al., 2013), arousing heightened concerns of international community. According to the US Geological Service (USGS) Mineral Commodity Summaries in 2016, the reserves of rare earths worldwide are estimated to be 130 million tons. China and Brazil hold the largest shares of these reserves with corresponding shares of 42.3% and 16.9%, followed by Australia, India, and the United States with corresponding shares of 2.5%, 2.4%, and 1.4%.

Since the global rare earths trade is a complex system with numerous countries and complicated relations (Li et al., 2013; Ge et al., 2016; Wang et al., 2016), its development is affected by many factors, such as the structure of supply and demand (Gschneidner, 2011), reserves, national policy (Müller et al., 2015), and geopolitics (Mancheri et al., 2013). In recent years, most of the previous studies regarding the international rare earths trade are focused on export prices, tariffs, markets (Klossek et al., 2016), exporting restrictions (Tukker, 2014), management policy comparisons or policy adjustments (Mancheri, 2015; Wübbeke, 2013), trade strategies (Morrison and Tang, 2012), supply and demand (Barteková and Kemp, 2016), environmental and development concerns (Wübbeke, 2013), production forecasts (Wang et al., 2015; Earths, 2015), recycling potential (Sprecher et al., 2014; Schulze and Buchert, 2016; Machacek, 2015), sustainability (Bailey et al., 2016; Mclellan et al., 2014; Atwood, 2013), etc. These studies have made significant achievements that have practical significance. However, because of Chinese dominance in global rare earths reserves and production, most of the existing literature primarily analyzes the rare earths trade patterns and policies or optimal partners, etc., in the context of China. Schlinkert and van den Boogaart (2015) develop a four-stage model to understand the transformation of the rare earths elements market from China's monopoly to a polypoly (Schlinkert and Gerald, 2015). He et al. (2014) and Ge et al. (2016) apply the decision analytic approach to select the ideal trading partners for China in the international rare earths elements market and analyze competing and complementary relationships between major rare earths elements trading countries (Ge et al., 2016; He et al., 2014). Mancheri (2015) evaluated China's export restrictions policy and China's position in international trade in terms of both volume and value (Mancheri, 2015). In addition, Mancheri and Marukawa, (2016) conducted a comprehensive study of the rare earths elements industry from mining to final products, the role of China and Japan regarding rare earths elements supply and demand, and the price mechanism and its impact on the Japanese manufacturing sector (Mancheri and Marukawa, 2016).

Currently, one popular method used to analyze the international trade problem is the complex network theory (Zhang et al., 2014, 2007; Smith and White, 1992; Kim and Shin, 2002; Mahutga, 2006; Li et al.,

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2003; Geng et al., 2014; Zhong et al., 2014; Vidmer et al., 2015). Using the complex network method can reveal the relationship between countries and divide trading countries into several communities. By conducting an analysis of degree centrality, strength centrality, closeness centrality and other indices, we can explore the role that each country plays and the status of trading countries (Fan et al., 2014; Chen et al., 2016; Nuss et al., 2016). Tokito, (2016) analyzed the complexity of the international trade network for platinum primary products (Tokito et al., 2016). Ge et al. (2016) adopted complex network method to analyze the competing and complementary relationships between rare earth trading countries based on the trading data of 2011–2015 and they used category of rare earths compounds and oxides (HS 2846) (Ge et al., 2016). Wang et al. (2016) used the complex network method to discuss the spatial dynamics of trade communities and the role of major countries in the global rare earths trade from 2002 to 2014 (Wang et al., 2016). In addition, An et al. (2014) discussed the features and evolution of international crude oil trade relationships using the complex network method (An et al., 2014).

Previous studies have made significant achievements and are a good reference for understanding the international trade of rare earths. However, these studies primarily focused on the trade problems of major countries, such as China, the United States or Japan. Although some of the literature analyzed international rare earth trade using quantitative method, most of the studies are limited to explaining the reasons of the trade patterns in each time period. Besides, the majority of the studies discussed the trade relationships in 5 or 10 years, and also limited to analyzing the trade in a long time period, the role of main countries and the reasons for the variation of patterns in each time period.

This study introduces the complex network theory into the study of the evolution of the international rare earths trade over the past 20 years. And we concentrate on rare earths metals (HS 280530) in our analysis for a longer term, which is different from some of the previous literatures. The study discusses the overall structure of the network and the role and status of the main countries; and explains the reasons for the trade patterns during each period. In addition, we use an algorithm to detect the rare earths communities in the international rare earths trade network based on the concept of modularity (Blondel et al., 2008). Then, we analyze the evolution of these communities by considering community scale and modularity. Therefore, this study makes three contributions. First, the study includes all the countries that participate in the rare earths trade and ranks the top 6 countries for both imports and exports to determine the status of each country and their advantages in the rare earths trade, which differs from previous studies regarding general trade patterns. Second, we studied the evolution of the international rare earths trade patterns for 20 years rather than considering a shorter period, which helps us understand the variety of trade communities and trends of the international rare earths trade. Third, this study applied the degree distribution and kernel density estimation to evaluate the distribution of trading countries, which can reveal the closeness between participating countries.

2. Data and methodology

2.1. Data

The data are obtained from the UN COMTRADE database for the commodity “Rare-earth metals, scandium and yttrium” (the HS code is 280530). This database includes information regarding all the import flows and export flows among the trade participating countries or regions in the world. We defined each country or region as a node and trade relations between countries as an edge. In the trade network, we used trade value to define the weight of edges. Because for bilateral trade relations, each country calculates its trading data independently, it results in difference of trade value in bilateral trade. Generally, export data cannot fully reveal the true value of the rare earths trade because of smuggling and other reasons.[1] After a comparison, import trade value of most countries are much large than export trade value, so we selected the annual import value data of the rare earths trade for countries from 1996 to 2015.

2.2. Method

2.2.1. Construction of the rare earths network

In this study, the international rare earths trade network can be abstracted as a connected network $G = (N, W)$ by N and W, where N is the number of nodes and W is the number of edges. The nodes represent the countries, and the edges represent the relationships between each of the countries. The direction of the edges corresponds to the direction of the rare earths flow.

2.2.2. The indicators for analyzing the rare earths network

2.2.2.1. The degree and degree distribution. The degree of a trade node is defined as the number of the node's adjacent edges in the network, which demonstrates the characteristics of the basic network. A directed network, includes two types of degrees: in-degree and out-degree. The out-degree represents the number of outgoing edges, while the in-degree represents the number of incoming edges. By analyzing the degrees of all the nodes, we can further explore the relationship between countries, the trade status of countries and the changes in the trade pattern over time. These terms are defined by Eqs. (1) and (2) (Freeman, 1978):

$$k_i^{out} = \sum_{j=1}^{n} a_{ij} \tag{1}$$

$$k_i^{in} = \sum_{j=1}^{n} a_{ji} \tag{2}$$

where k_i^{out} and k_i^{in} denote the out-degree and in-degree of a country for the number of countries that import from and export to that country. The element $a_{ij} = 1$ when a trade flow exists from i to j and $a_{ij} = 0$ otherwise.

If n_k nodes have the same degree k, the degree distribution p(k) is defined as $p(k) = n_k/n$. If the degree distribution can be fit with the power law as described in Eq. (3), the network is a scale-free network (Watts and Strogatz, 1998a). Scale-free networks have severe heterogeneity, whereby a few nodes have very major connections; however, most nodes have only small connections. The minority hub point in a scale-free network plays a leading role. We used the least square method to estimate the power law exponent of the degree distribution.

$$p(k) \sim k^{-\gamma} \tag{3}$$

where γ is the power-law index and k is the degree of nodes.

2.2.2.2. Kernel density estimation. Kernel density estimation is a statistical process used for spatial smoothing and/or spatial interpolation. The kernel density estimation approach was first provided by Rosenblatt (Rosenblatt, 1956) and Parzen (Parzen, 1962a), it is a nonparametric statistical method used to estimate the unknown probability distribution.

Let $(x_1, x_2, \ldots, x_n)$ be a univariate independent and identically distributed sample drawn from some distribution with an unknown density f. We are interested in estimating the shape of this function f. Its

[1] According to China Business News, about 20,000 t of rare earths were smuggled from China in 2008, which was estimated to have accounted for one third of the total volume of rare earths leaving China that year, but countries involved in the smuggling trade of rare earth changed over time. It cannot be represented in the network model. Therefore, we use official data to calculate.
(Xinhua, “China mulls plans to curb rare earth smuggling,” Sept. 14, 2009. The Chinese Customs' data showed that 39,500 t of rare earth oxides were exported from China in 2008.).