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Global embodied mineral flow between industrial sectors: A network perspective

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ABSTRACT

Embodied resource accounting and flow tracking are drawing increasing attention in the economy and environment issues. Differing from previous studies, this paper focus on embodied minerals, including non-metallic minerals and metals. This article proposes a systemic framework to estimate the global embodied mineral flows between sectors using multi-regional input-output analysis. Then, a global embodied mineral flow network is established, based on complex network theory, to explore the structure characteristics of embodied mineral flows. The results firstly show there is significant small-world property in the global embodied mineral flow network. Most sectors can have indirect connection with other sectors via a few sectors. Secondly, the network topology shows that a few important sectors play different roles. For example, *Other Non-Metallic Mineral* in China is the most important consumer of embodied minerals. The sectors' roles can be used to find the key points in the global embodied mineral flows. Thirdly, the results indicate that the embodied mineral flows have strong directionality. It includes: (1) Embodied minerals mainly flows within countries. China, the USA and India are important embodied mineral consumers. (2) Embodied mineral flows commonly follow fixed connections between sectors, such as *Construction*→ *Other Non-Metallic Mineral*, which helps locate the target of resource adjusting. Finally, the policy implications for different countries are proposed.

1. Introduction

Embodied resource accounting and tracking embodied resource flows in the economic system have been hot topics on qualifying the impact of economy on environment (Chen and Chen, 2013; Chen et al., 2012; Gasim, 2015; Giljum et al., 2015; Hao et al., 2017; Wiedmann et al., 2015). Previous studies mainly focus on the embodied analysis on energy, water and some specific metals. However, as the requisite materials in the production process, the importance of minerals should not be neglected. Almost all products are made of minerals directly or indirectly. Embodied minerals are defined as the total marginal mineral input to produce or acquire a product (Odum, 2006). For example, a computer embodies the minerals used for producing the components, including shell, motherboard, drive and screen. The same case can be expanded to all products flowing in the economic system. When industrial sectors require the input of products, they generate the need for minerals. Embodied mineral accounting can be helpful to find the potential and essential mineral consumption drivers. Hence, it is imperative to estimate embodied mineral flows between industrial sectors and study the structure features of the global embodied mineral flow network.

Some researches on minerals have been well established, such as the trade in mineral products, mineral supply, mineral consumption and mineral market risks (Adibi and Ataee-pour, 2015; Dong et al., 2017; Ebner, 2015; Tiess, 2010). However, the majority of existing studies focus on direct mineral input on economy activities. Direct minerals are defined as the mineral input that producers consume in their current production process. It can only reflect the on-site immediate mineral consumption by users when tracking the flows of minerals in the economic system. Different from direct minerals, embodied minerals contain all historical and off-site information of products in the process of production, transportation and consumption. This means that embodied minerals can not only record the mineral consumption in the production period, but also track the movement of minerals in the products that are already been out of the current production cycle, including consumption goods by households and governments or investment goods by enterprises. Therefore, embodied minerals can be used to supplement direct minerals and provide a more systematical perspective to investigate mineral issues. Moreover, globalization makes it more common to produce a product in one country and export it to

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others (Tang et al., 2013b; Zhao et al., 2010, 2016). The global economy is becoming an increasingly integrated network, with each component directly or indirectly connected to the others. This interweaving economic network dramatically increases the complexity to fully recognize the influence of mineral input on an economic output. However, embodied minerals allow exploration of the mineral flows beyond the production cycle, which means it can break the limitation of geographic location. Hence, embodied mineral analysis also provides an opportunity to identify all connections between mineral input and economic output.

As for research approach, the input-output analysis has become an effective tool to simulate embodied mineral flows between all sectors globally (Beylot et al., 2016; Beylot and Villeneuve, 2015; Dietzenbacher et al., 2013; Lei et al., 2013; Zheng et al., 2017b). Input-output analysis was originated by Wassily Leontief. In recent decades, many scholars have witnessed the success of input-output analysis in the simulation of economic system at different scales. Some researches have estimated embodied energy in the industrial sectors in China and other countries (Nguyen and Ishihara, 2006; Owen et al., 2017; Tang et al., 2013a; Zhang et al., 2016a). Virtual water flow or water footprints also have been studied combining the input-output table with other methods, such as life cycle approach (Yin et al., 2016; Zhang et al., 2016b; Zhao et al., 2010). Furthermore, multi-regional input–output analysis (MRIO) makes it possible to study the interactions between countries. The global energy flow and water flow have been well simulated using the MRIO model (Alsamawi et al., 2017; Chen and Chen, 2013; Chen et al., 2012; Yu et al., 2010; Zhang et al., 2015; Zheng et al., 2017a). These researches provide a strong foundation for this paper. Thus, the MRIO model and embodied analysis have been applied to estimate the global embodied mineral flow.

These studies showed that input-output models can be well applied to embodied mineral accounting. However, the existing researches mostly focused on the energy consumption intensity or water-use efficiency of sectors in the economic system (Chung et al., 2009; Deng et al., 2015; Liu et al., 2015; Shi and Zhan, 2015), ignoring the interactions between industrial sectors and the topology characteristics of the embodied resource flow network. However, as a complicated economic system that contains hundreds and thousands of industrial sectors, there are both direct and indirect connections between different industrial sectors. To underlying the hidden information in the complicated economic system, complex network theory provides a good solution, which has been widely applied to many fields, such as economy, finance and international trading (Gao et al., 2014, 2017; Hao et al., 2016; Jiang et al., 2017a, 2017b; Zhong et al., 2016). Using complex network analytical approach can help us to better understand the essence of the embodied resource flow structure. The study on the indirect energy flow network showed the indirect energy flow in China has the small-world property (Sun et al., 2016). The same property has also been found in the embodied rare earths flow network (Wang et al., 2017). Moreover, scholars found that the structure of global embodied energy flow network has significant evolutionary features (Shi et al., 2017).

The studies above provide valuable references for us to investigate the global embodied mineral flows. The gap within the existing body of knowledge is lacking of consideration of embodied minerals and the global structure characteristics of embodied mineral flow network. The main purpose of this paper is to build the global embodied mineral flow network and explore its structure features through the combination of multi-regional input-output analysis and complex network. The roles of industrial sectors, which can be recognized by network topology, and the flow paths between industrial sectors are relevant to reshaping the industrial structure of one country. It can also help to find the essential drivers of mineral consumption. Moreover, we analyze the embodied mineral flows at country level and industry level to study the roles of counties and industries respectively in the embodied mineral trading. Finally, we propose some recommended policies based on the results.

2. Data and method

2.1. Data

This paper selects the world input-output table in 2009 (the 2013 released edition) from the World Input-Output Database (WIOD) and the 2009 mineral consumption data from the Environmental Accounts of WIOD. According to the document named Environmental Source that WIOD provides, WIOD differentiates between used and unused minerals (Genty et al., 2012). Only used minerals finally enter the economic system for further processing or direct consumption. Therefore, we choose used minerals as mineral consumption data. Used minerals are divided into three categories: Minerals_construction_Used, Minerals_industrial_Used and Minerals_metals_Used. Minerals_construction_Used represents non-metallic minerals for construction, Minerals_industrial_Used represents other non-metallic minerals, and Minerals_metals_Used represents metals. Considering WIOD only records the minerals extracted from nature by one sector, *Mining and Quarrying*, from a practical perspective, we reallocate the minerals to the sectors receiving specific mineral inputs at the first stage of processing (Schoer, 2006): Minerals_construction_Used to *Construction*, Minerals_industrial_Used to *Other Non-Metallic Mineral* and Minerals_metals_Used to *Basic Metals and Fabricated Metal*. By preparing these three sectors as starting points, this paper tracks the flows of minerals in the economic system. The latest world input-output data is 2014 edition; however, the latest mineral use data just updates to 2009. To ensure the consistency of data, we choose both the input-output data and the mineral consumption data in 2009. The unit of monetary world input output table is millions of US$. The unit of mineral consumption data is 1000 t.

2.2. Embodied mineral flow accounting

The embodied mineral flow accounting method is introduced in detail in Ref (Chen and Chen, 2013). In the monetary input-output table, the simple extension of balance is: $\sum_{i=1}^{N} \varepsilon_i \times x_{i,j} = \varepsilon_i \times X_i$. $x_{i,j}$ represents the intermediate input to other sectors from sector i. X_i represents the total output of sector i. However, it has been criticized for not considering additional resource inputs in the system (Casler and Wilbur, 1984; Miller and Blair, 2009). Thus, we add m_i as the direct mineral input from the outside environment to the physical balance in terms of the embodied mineral flow of a sector (Fig. 1).

For sector i, the balance of embodied minerals is as follows:

$$m_i + \sum_{j=1}^{N} \varepsilon_j \times x_{j,i} = \varepsilon_i \times \left(\sum_{j=1}^{N} x_{i,j} + f_i \right) \tag{1}$$

where N denotes the number of total sectors. ε_j (ε_i) represents the embodied mineral intensity of output from sector j (i). $x_{j,i}$ represents the intermediate input to sector i from sector j. Sector i connects to the outside environment via importing direct minerals m_i and importing embodied minerals $\sum_{j=1}^{N} \varepsilon_j \times x_{j,i}$ through purchasing goods and service from other sectors. f_i denotes the final demand of sector i. $\sum_{j=1}^{N} x_{i,j}$ represents the intermediate output from sector i to other sectors. Thus, $\varepsilon_i \times (\sum_{j=1}^{N} x_{i,j} + f_i)$ denotes the total embodied mineral output from sector i.

For the whole economy network that has N sectors, we have

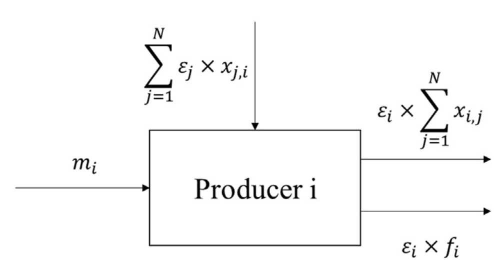

Fig. 1. Embodied mineral balance of producer i.