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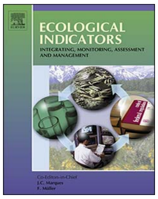

Original Articles

Identify sectors' role on the embedded CO_2 transfer networks through China's regional trade

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ABSTRACT

This study developed a framework for combining multi-regional input-output analysis and network indicators to assess the interregional CO_2 flows in China. The interregional CO_2 flows of eight regions were calculated and visualized based on a multiregional input-output (MRIO) model for China. The focus of the research was intermediate use. The results of the network indicators showed that refined petroleum, coke, nuclear fuel and chemical products (07), and basic metals and fabricated metal sectors (09) played key roles in the complex networks. and these sectors in most regions controlled a large share of CO_2 transfer by functioning as key hubs and authorities. They along with commerce, transport, storage, and post (16) acted as agents that brokered the CO_2 flows within and between regions. The roles of some other industrial sectors were also identified, e.g., construction (15) functioned as the largest authority. The results demonstrated the importance and effectiveness of network indicators for identifying the characteristics of CO_2 emissions embedded in the domestic supply chain, and provided new information relevant to policy implementation.

1. Introduction

The vast and diverse consumption of fossil energy over many years has produced a huge amount of greenhouse gas (GHG) emissions. As the largest fossil fuel energy consumer in the world, China, sourcing mainly from coal, emits as much CO_2 as the total amount released by the US and the EU combined. Effectively managing GHG emissions is crucial for achieving the goal of United Nations Framework Convention on Climate Change (UNFCC), as well as China's international pledge that national CO_2 emissions will peak before 2030. In addition, the Chinese government has pledged to reduce its carbon intensity by 40–45% relative to the 2005 level by the end of the 13th Five Year Plan (2016–2020) (Guan et al., 2014). The emission reduction targets are usually decomposed into a mandatory allowance and allocated to each province (Wang et al., 2013), which takes responsibility for the policy implementation of the central government. However, increasingly complex products and dynamic supply chains have complicated the allocation because the energy and embedded CO_2 flows through interregional trade are difficult to track. Understanding these flows is vital for allocating a CO_2 allowance for each province based on specific criteria, such as consumer responsibility. Input-output analysis (IOA) provides an estimation of intersectional and/or interregional flows of products and services through monetary data (Miller and Blair, 2009). It has been widely used to assess the flows of embodied energy (Liu et al., 2010) or CO_2 flows (Xu et al., 2011, 2010). More recently, IOA has been combined with trade data in multiregional input-output (MRIO) models to follow material, water (Zhang and Anadon, 2014), energy (Zhang et al., 2015) and CO_2 flows (Feng et al., 2014). Furthermore, understanding the characteristics and topology of the flows in a common scientific language has become an important task. Network analysis, which uses visual and mathematic descriptions to facilitate understanding, is such a language. In the past two decades, it has become a widely used framework for analyzing and understanding complex systems through insights to a system's topology, functioning, and dynamics. Basically, an input-output table can be viewed as a network in which sectors can be recognized as nodes, and the monetary transactions are weighted arcs between nodes (Nuss et al., 2016; Zhang et al., 2015a). Thus, IOA fundamentally supports network analysis, and it can be used to measure the structural features of flows among sectors and regions.

In this study, we combined the MRIO model with network analysis to evaluate the regional CO_2 flows embedded in interregional trade. To our best knowledge, there is no study focusing on the industrial sectors' role in the CO_2 transfer networks. We are the first to identify the key

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sectors and their roles by using various network indicators. The sections are organized as follows. Section 2 provides a literature review of MRIO studies, specifically on CO_2 emissions in China, as well as network analysis. Section 3 introduces the methods and data used in this study. Sections 4 gives the results of the application of CO_2 flow networks through China's regional trade, followed by a discussion in Section 5. Finally, Section 6 presents the conclusions of the study.

2. Literature review

The MRIO model can reveal not only the complex connections among sectors but also the economic links between regions (Guo et al., 2012). Thus, MRIO analyses have been widely applied to a range of human-induced resource and environmental issues, specifically on large economies (Kucukvar et al., 2016). China has received special attentions with regard to energy consumption and CO_2 emissions at both the interregional and international scale. For example, Hong et al. (Hong et al., 2016) used the MRIO model to investigate the embedded energy of China's construction industry and identified provincial energy flows from the central part of the country to the eastern coast. Feng et al. (Feng et al., 2013) tracked CO_2 emissions embedded in products traded among provinces and internationally, and found that 57% of China's emissions were relocated, with around 80% of the emissions derived from goods consumed in the coastal provinces. Guo et al. (2012) also reported that the eastern area accounted for the largest proportion of embodied CO_2 emissions, and energy-intensive sectors were the main contributors. Wiebe et al. (2012) confirmed that developed countries had improved their CO_2 emission performance by transferring their emissions to emerging economies such as Brazil, Russia, India, China, South Africa, and Argentina. Liang et al. (2007) used the MRIO model to investigate China's interregional energy requirements and CO_2 emissions, and used a scenario analysis for forecasting. These studies identified carbon leakage through interregional or international trade and revealed its impact on China's emissions at relatively high resolution and precision compared to the traditional IOA. The above studies have proved that MRIO analysis could enable better policy implementation for CO_2 emission control in China.

Social network analysis is a useful tool to portray the structural properties of a system by analyzing its components and linkages (Wasserman and Faust, 1994). It provides a versatile and visible analytical framework to examine the internal structure, functioning, and dynamics of networks ranging from molecular to economic-environmental systems (Leoncini and Montresor, 2000; Luscombe et al., 2004; Nuss et al., 2016). Furthermore, both direct and indirect mutual interactions can be identified and quantified through network analysis (Guo et al., 2016; Zhang et al., 2010). The technique has therefore been widely applied to determine the complexity and integrity of the metabolic processes of both natural and economic systems (An et al., 2015; Fath, 2007). The embedded CO_2 flows through trade could form a complex CO_2 transfer networks. It would be very beneficial to investigate such networks to formulate regional or global climate policies effectively. Because no actual CO_2 monitoring data supports the construction of direct transfer networks. Scientists usually combine IOA and network analysis together to construct and assess the CO_2 networks. Although the combination has already been used in various fields, including raw material accounting (Chen et al., 2016; Nuss et al., 2016; Ohno et al., 2016), energy consumption (Chen and Bin Chen, 2015; Zhang et al., 2015b; Zhang et al., 2016), virtual water flows (Fang and Chen, 2015), and energy-water nexus (Chen and Chen, 2016a, 2016b; Duan and Chen, 2016; Wang and Chen, 2016), only a small number of studies have been reported on the embedded CO_2 transfer. For example, Kagawa et al. (2015) identified supply-chain clusters with high CO_2 emissions by focusing on the global supply-chain networks. Chen and Chen (2016b) quantified the carbon flow and focused on the controlled emissions of the Jing-Jin-Ji area in China. Zheng et al. (2016) also focused on the Jing-jin-ji area, and traced the carbon footprint and the indirect energy efficiency of five sectors in this area. Chen et al. (2015) established dynamic metabolic networks for assessing the effectiveness of carbon emission mitigation. Prell and Feng (2015) tracked United States' consumption triggered carbon inequalities, especially focused on electronics, motor vehicles and wearing apparel. These studies have already demonstrated the power of network analysis for complex CO_2 transfer networks. But in most cases, network analysis is only treated as a supplement of the MRIO analysis. No study focused on the position and role playing of industrial sectors in the networks, except limited attempts from Chen and Chen (2016b). One reason is that traditional indicators (e.g., degree centrality, betweenness, and closeness) do not function well in IOA-derived networks, which often have high density (close to 1). Therefore, much work needs to be done to develop suitable methods and reveal the systematic properties of CO_2 transfer networks.

3. Methods and data

3.1. Calculation of embedded CO_2 flows

Embedded CO_2 emission flows through interregional trade were calculated based on the monetary MRIO table and direct regional CO_2 emissions. The interregional supply and demand relation could be expressed as Eq. (1):

$$X^R = A^{RS}X^R + F^{RS} + E^R - M^R \tag{1}$$

where X^R is the output vector of region R; A^{RS} is the interregional direct input coefficient matrix from region R to region S; F^{RS} is the final demand vector from region R to region S; E^R is region R's export vector; and M^R is region R's import vector.

To calculate the CO_2 embodied in domestic production, we introduced an import coefficient matrix $\hat{M}$ to exclude the influence of an import on direct use and final demand. $\hat{M}$ was estimated by using the share of an import within the total domestic demand.

$$M^{RS} = \hat{M}(A^{RS}X^R + F^{RS}) = \hat{M}A^{RS}X^R + \hat{M}F^{RS} \tag{2}$$

Then, Eq. (1) could be rewritten as follows:

$$X^R = [I - (I - \hat{M})A^{RS}]^{-1}[(I - \hat{M})F^{RS}] \tag{3}$$

where, I is the unit vector, and $L = [I - (I - \hat{M})A^{RS}]^{-1}$ is the import-excluded Leontief inverse Matrix. $[(I - \hat{M})F^{RS}]$ denotes the domestic final use. The interregional CO_2 transfer T^{RS} through domestic trade was calculated using Eq. (4):

$$T^{RS} = D^{RS}[I - (I - \hat{M})A^{RS}]^{-1}[(I - \hat{M})F^{RS}] \tag{4}$$

where, D^{RS} is a diagonal matrix of the direct CO_2 emission coefficient for each sector.

3.2. Network analysis

Each industry in each region was represented as a node, and the embedded CO_2 flow between two industries was represented as an arc weighted by the CO_2 flux. Connecting all of the industries by their pairwise embedded CO_2 flows formed a network. The network characteristics were analyzed using the following methods.

3.2.1. Control and dependence

The control index (CI) and dependence index (DI) were first proposed by Chen and Chen (2015; Chen and Chen, 2015. The regional control matrix $\hat{L}$ is the difference in pairwise integral flows between sector i and j:

$$\hat{L} = [\hat{b}_{ij}], \begin{cases} \hat{b}_{ij} = b_{ij} - b'_{ij}, \; b_{ij} - b'_{ij} > 0 \\ \hat{b}_{ij} = 0, \; b_{ij} - b'_{ij} < 0 \end{cases} \tag{5}$$

where b_{ij} is the element of the Leontief inverse matrix, and b'_{ij} is the