Study on the Transfer of Embodied Sulfur Dioxide Footprints in Inter-provincial Trade in China Based on Complex Networks

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Abstract. With the acceleration of China's economic growth and the deepening of regional trade integration, inter-provincial trade has become a crucial component of the national economy. However, it has inadvertently posed environmental challenges, particularly in terms of sulfur dioxide (SO2) emissions, which pose significant threats to air quality, ecosystems, and human health. Nevertheless, existing research lacks an in-depth analysis of the spatiotemporal evolution characteristics of implied SO2 in China's inter-provincial trade. Analyzing these characteristics can identify key provinces involved in SO2 emissions, providing a solid foundation for formulating energy-saving and emission-reduction policies at the provincial level. Therefore, in this study, we combine an environmentally extended multi-regional input-output model with complex network analysis to investigate the characteristics of implied SO2 footprint transfer within China's inter-provincial trade networks. Our method quantifies the temporal variation of SO2 transfer paths between provinces. The research results indicate that the accessibility of China's inter-provincial SO2 footprint transfer network has been improving annually. However, there is still room for enhancement in terms of the synergistic SO2 relationships among provinces. By implementing energy-saving and emission-reduction policies on key provinces with high SO2 emissions, the policy impact will efficiently propagate through the SO2 footprint transfer network to other provinces, thereby enhancing China's overall energy-saving and emission-reduction efficiency.

Keywords: Trade Implies Sulfur Dioxide Emissions; Environmentally Extended Multiregional Input-Output; Complex Network

1 Introduction

In recent years, China has been in a crucial phase of rapid urbanization and industrialization. While this process has driven economic growth and enhanced human well-being, it has also led to a significant increase in energy consumption [1]. The rapid industrialization has resulted in a marked rise in emissions of various atmospheric pollutants, particularly sulfur dioxide (SO2), nitrogen oxides, and carbon monoxide

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[2]. Among these pollutants, SO2 has emerged as a key target for environmental governance in China due to its prominent role in air pollution. To effectively reduce SO2 emissions in China, it is crucial to have a comprehensive understanding of their sources and driving factors [3]. Previous studies have made significant contributions in this regard. For instance, Yang et al. employed structural path analysis to explore the dynamic changes in SO2 emissions embedded within China's domestic value chain, finding that the utilization of fossil fuels is the primary source of SO2 emissions [4]. Chen et al. further estimated the hidden SO2 emissions across different regions in China from 2007 to 2012 using environmentally extended input-output analysis and structural decomposition analysis, identifying coal pollution intensity, energy intensity, governance intensity, and economic scale as key factors influencing SO2 emissions [5]. Wang et al. adopted a hybrid method combining bilateral trade and multi-regional input-output analysis to further investigate the transfer of SO2 emissions among 31 provinces in China in 2015 [6]. However, these studies primarily focused on the driving factors and transfer pathways of embodied SO2 emissions in China's inter-provincial trade, neglecting the temporal and spatial correlation characteristics of embodied SO2 footprint transfer, which is crucial for fostering coordinated development between trade activities and environmental protection among provinces.

Complex network analysis provides a holistic approach to studying the spatio-temporal evolution of systems, vividly portraying the dynamic changes in complex systems over time and space. This study applies this method to investigate the transfer of embodied SO2 in China's inter-provincial trade. Based on the theory of Environmentally Extended Multiregional Input-Output (EE-MRIO) and complex network theory, we constructed a network for the transfer of embodied SO2 footprints in China's inter-provincial trade. By analyzing this network, we can obtain insights into the temporal and spatial transfer characteristics of embodied SO2 footprints in trade among Chinese provinces.

The paper is organized as follows: Section 2 introduces EE-MRIO, complex network theory, and data sources. Section 3 presents the network for the transfer of embodied SO2 footprints in China's inter-provincial trade and analyzes the temporal and spatial evolution characteristics of embodied SO2 emissions depicted by this network. Finally, Section 4 summarizes the main conclusions of this paper and provides relevant recommendations.

2 Research Methodology

This section introduces the data sources and methods used to analyze the characteristics of embodied SO2 footprint transfer in inter-provincial trade in China. This paper employs the SO2 emission data for each Chinese province in 2017 and 2020 provided by the Multi-resolution Emission Inventory for China (MEIC) V1.4 database from Tsinghua University, along with China's multi-regional input-output data, for qualitative analysis, to obtain the spatio-temporal characteristics of embodied SO2 footprint transfer in China's inter-provincial trade. Firstly, the EE-MRIO model is utilized to calculate the embodied SO2 emissions in the trade of each Chinese province. Secondly, a network model for embodied SO2 footprint transfer in China's inter-provincial trade is established, with each Chinese province as a node and the embodied SO2 emission relationships among provinces as edges.

2.1 Environmentally Extended Multiregional Input-Output

The EE-MRIO model is used to quantify the impact of economic activities on the environmental system [7]. For constructing the EE-MRIO model in this paper, two types of data are required: China's multi-regional input-output data and SO2 emission data. Based on the SO2 emission intensity (i.e., the amount of SO2 emitted per unit of economic output), the formula for calculating the total SO2 footprint is as follows:

$$S = E \bullet (I - A)^{-1} \bullet Y \tag{1}$$

Where, S represents the total embodied SO2 emissions matrix in China's inter-provincial trade; E is the diagonal matrix of SO2 emission intensities for the five sectors of electricity, industry, residential use, transportation, and agriculture across all provinces in China, with the diagonal elements e_i denoting the SO2 emission intensity vector for the $i-th$ province; I is the identity matrix; A is the direct consumption coefficient matrix, where the elements a_{ij}^{rs} represent monetary flows from sector r in province i to sector s in province j; and Y is the diagonal matrix of China's inter-provincial trade demand, with the diagonal elements y_{ij}^{r} being the final demand vector from province i to province j.

2.2 Model of the Embodied Sulfur Dioxide Footprint Transfer Network in China's Inter-provincial Trade

In Section 2.1, a data matrix containing SO2 emissions among various provinces and their five industrial sectors in China has been obtained. Based on this, combined with the complex network theory in system science, a modeling analysis of the spatio-temporal characteristics of SO2 transfer between provinces is conducted, thereby overcoming the deficiencies of existing research in terms of temporal continuity and spatial variability. This provides a powerful research tool for clarifying the SO2 emission responsibilities of each province and achieving SO2 reduction in China.

In this paper, each province is regarded as a node, the embodied SO2 emission relationships between them as edges, and the corresponding SO2 emission data in S as edge weights. With the number of network nodes (number of provinces) being $N = 30$, the set of network nodes is denoted as $V = \{v_1, v_2, \cdots, v_{30}\}$, the set of edges as $E = \{e_{11}, e_{12}, \cdots, e_{NN}\}$, and the set of weights as $W = \{w_{11}, w_{12}, \cdots, w_{NN}\}$. Ultimately, a graph $G = (V, E, W)$ is used to depict the sources and destinations of embodied SO2 emissions from trade activities among various provinces in China from 2017 to 2020.

By analyzing the overall structural indicators of the network and individual correlation characteristic index, the spatio-temporal characteristics of SO2 footprint transfer among provinces embodied within the network can be explored. In this study, six indicators—average path length [8], weighted clustering coefficient [9], network density [10], degree centrality [11], intermediate centrality [12], and proximity centrality [13] are used.

3 Empirical Analysis

This section constructs the embodied SO2 footprint transfer networks in China's inter-provincial trade for the years 2017 and 2020 using the data and methods described in Section 2, as shown in Fig. 1 and Fig. 2 respectively. The size of each provincial node is rendered based on its node degree. The overall structural characteristics of the networks are presented in Table 1.

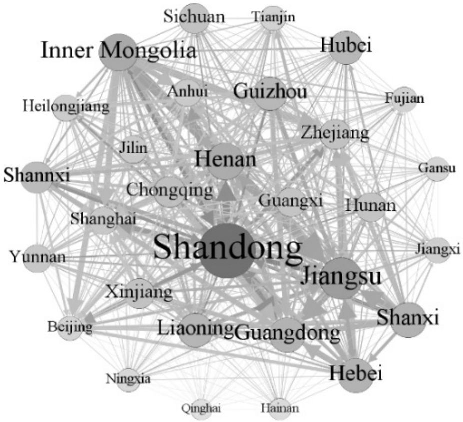

Fig. 1. The embodied sulfur dioxide footprint transfer network in China's inter-provincial trade in 2017.

Fig. 2. The embodied sulfur dioxide footprint transfer network in China's inter-provincial trade in 2020.

Table 1. Overall network structure indicators.

Indicators	2017	2020
Average path length	1.872	1.833
Weighted clustering coefficient	0.313	0.335
Network density	0.0913	0.0901

As shown in Table 1, the average path length of the network has been shortening from 2017 to 2020, indicating that the SO2 footprint flows between provinces require passing through fewer than two provinces on average, which suggests an annual improvement in network accessibility. The weighted clustering coefficient of the network has been increasing consistently during this period, implying a rapid enhancement in network grouping. In 2020, the network exhibited a small average path length and a large weighted clustering coefficient, characteristics indicative of a small-world network. Small-world networks are sensitive, meaning that perturbations applied to key network nodes can exert considerable influence on the network as a whole. Therefore, for the 2020 network, if energy-saving strategies such as cleaner production and energy efficiency improvements are implemented in sectors of provinces that are major emitters of embodied SO2 in trade, these policy impacts will efficiently propagate through the network to other provinces, thereby radiatively enhancing the efficiency of coordinated SO2 emission reduction in China's inter-provincial trade. However, the decline in network density from 2017 to 2020 suggests that there is still room for improvement in the exercise of coordinated SO2 relationships among provinces.

Table 2 presents the top three provinces in terms of node degree centrality in China's inter-provincial trade SO2 footprint transfer network for the years 2017 and 2020.

Table 2. Network node degree centrality.

Year	Province	2020
2017	Jiangsu	0.343
	Henan	0.315
	Shandong	0.311
2020	Guangdong	0.361
	Henan	0.349
	Jiangsu	0.338

As can be seen from Table 2, the degree centrality of the top three provinces in 2017 and 2020 exhibits dynamic changes. Jiangsu Province and Henan Province ranked among the top three both in 2017 and 2020, indicating that from 2017 to 2020, Jiangsu and Guangdong had more connections with other provinces in the network, making them the nodes with the strongest carbon radiation power. The main reason is that Guangdong Province and Henan Province are important manufacturing bases in China, and manufacturing activities typically require significant energy consumption.

Therefore, they generate relatively large volumes of trade-related implied SO2 emissions.

4 Conclusion and Recommendation

This paper reveals the spatiotemporal characteristics of embodied SO2 emissions in inter-provincial trade by constructing an EE-MRIO model and utilizing complex network analysis. The results indicate that the embodied SO2 emissions in inter-provincial trade dynamically change over time, with eastern coastal regions and central provinces such as Henan, Shandong, Jiangsu, and Guangdong remaining as key emission sources. The embodied SO2 emission network exhibits small-world characteristics, and pollution prevention policies in key provinces have a significant impact on the entire network. Based on these findings, policy recommendations include: prioritizing the reduction of SO2 emissions, formulating emission reduction plans for each province based on their roles in the network, implementing coordinated inter-provincial emission reduction strategies, and increasing the proportion of clean and renewable energy.

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