DSI DATA SCIENCE AND INFORMETRICS
VOL.3, NO.1, FEB. 2023

RESEARCH ARTICLE

Interprovincial transfer of embodied air pollution in China

Yuhuan Sun*, Bingcheng Zhu, Yuqing Han

School of Statistics, Dongbei University of Finance and Economics, Dalian, China

ABSTRACT

This study uses a multi-regional input-output model to measure the consumption-based transfer of embodied air pollution across provinces in China. Revised direct exhaust emissions are compared under regional and industrial standards to reveal the static volume distribution and dynamic transfer paths. The results show that China is characterized by a net inflow of atmospheric pollution pressure. The amount of interprovincial transfer exhibits a two-level divergence. The distribution of net outflow areas exhibits a certain degree of dispersion and uniformity, whereas net inflow areas exhibit local agglomeration. The main transfer paths are from east to west and south to north. Eastern coastal areas are the primary source of embodied pollution transfer, whereas northern coastal areas and the middle reaches of the Yellow River account for the primary concentrations of pollution inflows. The proportion of major industry contributions approximately conforms to the Pareto principle; different resource endowments may provide comparative advantages and thus distinct distributions.

KEYWORDS

Consumption-based transfer; Multi-regional input-output Model; Direct emissions; Regional Distribution

1 Introduction

Recently, smog has occurred frequently throughout China, which not only decreases visibility but also contains many harmful substances which endanger human health (Lelieveld et al., 2015; Wang et al., 2016). Smog also causes both explicit and implicit economic losses. Air pollutants have the characteristics of mobility and diffusivity. The emission of local pollution sources may cause regional environmental damage in related areas, as well as significant cross-border transmission phenomena and regional spillover effects. In addition, the process of regional economic integration and marketization in China is accelerating. Therefore, inter-regional trade has gradually increased, resulting in the passive separation of the production and consumption of products. The trading party transfers the resource consumption, pollution discharge, and environmental pressure generated by various economic production activities to the other party to bear; that is known as embodied pollution transfer. Thus, areas, where pollution-intensive industries are more concentrated can achieve economic benefits and social welfare in the trade process but also receive a large amount of embodied pol-

* Corresponding Author: yhsun602@126.com

lution (Xin et al., 2022). Xue et al. (2014) found that the annual average PM2.5 concentrations of the Yangtze River Delta, Pearl River Delta, Beijing-Tianjin-Hebei, and Chengdu-Chongqing City Group agglomerations affected by outside regions accounted for 37%, 28%, 22%, and 14%, respectively. Embodied pollution reflects the environmental impact of a country or region's final use and provides an important reference for countries to formulate environmental policies and implement pollutant management (Li et al., 2013).

Scholars usually conduct research on embodied resources and embodied pollution by establishing input-output models, including virtual water (Wang, 2016; Zhang et al., 2014), environmental element footprints (Wiedmann et al., 2010; Zhu et al., 2019), embodied pollution transfer (Liu & Wang, 2015; Pang et al., 2017), and other aspects. Two mainstream methods are used to estimate embodied pollution emissions from international or inter-regional trade: the Emissions Embodied in Bilateral Trade (EEBT) method based on the single-region input-output model (Lenzen, 1998; Pan et al., 2013) and the Multi-Region Input-Output (MRIO) model based on final consumption trade (Meng et al., 2013; Shi et al., 2012). The main difference between the two is whether the intermediate input and final use of regional trade transfer are to be decomposed and distinguished. Specifically, the EEBT method is oriented toward modeling the total amount of bilateral direct trade and cannot trace the embodied pollution transfer of imported and exported products. Conversely, the MRIO method is based on information and data and characterizes the upstream intermediate consumption, local final use, and spillover feedback effects through a complete production chain (Liu & Wang, 2016). Therefore, some scholars believe that the calculation results of the MRIO model are more accurate. For example, Wyckoff and Roop (1994), Brizga et al. (2017), and Veiga et al. (2018) used the MRIO model to measure the transfer of embodied pollution in OECD (Organization for Economic Cooperation and Development) countries, the European Union, and Brazil, respectively.

Based on different research scopes and measurement angles, empirical research on the transfer of trade-embodied pollution mainly conducts unilateral or multilateral trade analysis from different spatial scales, such as multiple regions worldwide, a single region in a country, or multiple regions in a country. At the international trade level, the research conclusions will differ for different trading parties. For example, Muradian et al. (2002) showed that highly developed countries such as the United States, Japan, and Western Europe shifted some of their air pollutant emission pressure to other countries. Moreover, Ackerman et al. (2007) expanded the Japan-US input-output model to calculate carbon emission factors in various sectors and found that the carbon emission intensity patterns of the two countries' sectors are closely related but have little impact on cross-border transfer. Furthermore, Li et al. (2019) coupled four types of air pollutant emission inventories to measure the embodied emission transfer volume of China's trade with other countries; the results showed that China is the emission output place of embodied sulfur dioxide, nitrogen oxides, and inhalable particulate matter, and the emission input place of embodied non-methane volatile particulate matter. Other scholars have focused on the embodied transfer of pollution by trading parties such as China and the United States (Du et al., 2011), China and Japan (Chen et al., 2016), and China and Australia (Petrovits et al., 2010).

In single-country input-output analysis, the domestic input-output table and emission coefficient are typically used to calculate the embodied pollution of imported products from other countries (Ni et al., 2012). For example, Walter (1973) used US input-output data to estimate direct and indirect trade pollution emissions, and Shen (2007) analyzed the impact of China's import and export trade on energy consumption, which revealed that the energy consumed by Chinese exports is lower than the energy saved by imported products. Moreover, Zhang (2010) estimated the carbon content of China's foreign trade based on a non-competitive input-output table and decomposed the influencing factors. The results showed that China has become a net carbon exporter since 2005, and its rapid growth is mainly due to the expansion of the trade scale.

However, research conducted with a single country as the unit ignores the imbalance of internal regional development and cannot reflect regional differences. Therefore, some scholars have divided China into multiple regions and used the MRIO model to study the relationship between trade and the environment. For example, Wang (2016) quantified the amount of virtual water transfer between China's eight major regions based on industry-wide standards and analyzed the dynamic regional net outflow trend and flow path. Pang et al. (2017) compiled an inter-regional input-output table for China in 2007 with Beijing-Tianjin-Hebei as the core of the research, selected six major pollutants to measure the embodied transfer of trade, and found that Hebei was the biggest loser and Beijing was the biggest beneficiary. In related research on the province scale, Wu et al. (2017) calculated the transfer of embodied PM2.5 in trade between 30 provinces of China and distinguished the interprovincial transfer caused by intermediate input and final consumption. Their dynamic analysis found that the economic crisis had reduced the amount of embodied PM2.5 transfer. Cui et al. (2018) measured the embodied carbon emissions of urban residents in 30 provinces and regions in China and showed differences in the temporal and spatial evolution characteristics and driving mechanisms of embodied carbon emissions in various provinces.

Existing research can be summarized as follows: 1) Regarding the selection of the calculation index, a single pollutant is typically used to assess trade diversion, with carbon emissions being the most popular pollutant. In recent years, research has tended to employ a comprehensive index of the Three Wastes—industrial wastewater, waste gases, and residues. 2) In terms of the spatial scope, studies are generally concentrated on a global or regional scale. This, coupled with the continuous publication of regional input-output tables under China's regional division standards, has ensured that research on emissions from international and interprovincial trade with China as the main body has gradually increased. 3) Research methods have gradually expanded from single-region (country) input-output models to multi-region (country) input-output models. Some scholars have analyzed environmental unfairness by coupling environmental health factors, economic welfare transfer, and other issues; however, few have compared it with the distribution of direct pollution emissions.

Therefore, this study is based on the input-output table of industry-wide inter-regional emissions for 31 provincial units in China in 2012. Industrial waste gas emissions are used as an index to calculate and revise pollution emission coefficients, and the embodied transfer volume of trade is calculated through multi-regional input-output models. From the perspectives of regions and industries, combined with the Pareto principle, factor endowments, comparative advantages, ecological compensation, and other theoretical foundations, the approximate distributions of direct provincial emissions are compared with the embodied pollution transfer. Then, the static characteristics of air pollution emission transfer and dynamic paths are analyzed. Finally, this study explains the contributions and limitations, and raises some suggestions for future research.

2. Methods and Data

2.1 Data source and index selection

This article uses the 2012 inter-regional input-output table jointly compiled by the Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences and the Department of National Accounts, National Bureau of Statistics (Liu et al., 2018). The table covers 31 provincial units and 42 sectors in China and is based on the non-competitive input-output form that lists imported products separately and does not participate in the calculation of domestic intermediate use and final use.

As industrial emissions account for a relatively large proportion of air pollution sources, this article focuses on the transfer of air pollution embodied by interprovincial trade; thus, industrial waste gas emissions (100 million m^3) are selected to comprehensively evaluate air pollution emissions. This index includes both provinces and industries. Both dimensions are derived from the "2013 China Environmental Statistics Yearbook."

2.2 Regional division and industry integration

Regarding the division of geographical regions involved in the follow-up analysis, all refer to the eight comprehensive economic zone[1] division standards proposed by the Development Research Center of the State Council. The inter-regional input-output table and the industry classification of industrial waste gas emissions in the "China Environmental Statistical Yearbook" both include 42 sectors; however, the specific classifications are different. For a unified calculation method, the sectors are integrated into 27 sectors, of which 15, including accommodation and catering, wholesale and retail, and finance, are not reflected in the "China Environmental Statistics Yearbook," so they are not included in the scope of analysis. The specific merging and classification results are shown in Supplementary Table 1. The department numbers cited below refer to this table.

2.3 Pollution emission coefficient calculation and correction

Under normal circumstances, the direct emission coefficient of pollutants is calculated using formula (1):

$$d_{ij} = w_{ij} \;/\; x_{ij} \tag{1}$$

where d_{ij} represents the direct industrial waste gas emission coefficient of sector j in region i, w_{ij} represents the corresponding direct industrial waste gas emissions, and x_{ij} is the total output of sector j in region i.

The limitations of relevant statistical data make it impossible to directly calculate the pollutant emission coefficient d_{ij}. Considering that there are certain differences in the industrial structure and technological level of various regions, the total output of each sector in each region and the total direct emissions of industrial waste gas from various regions and sectors are used. This article draws on the method of Li et al. (2013) and adopts the rank balance method at the national level. As shown in Table 1, it is assumed that the total industrial waste gas emissions in the region are $U_1, U_2, \ldots, U_{31}$ and the total sectoral emissions are $Q_1, Q_2,$

1 Northeast region (Liaoning, Jilin, Heilongjiang), northern coastal areas (Beijing, Tianjin, Hebei, Shandong), eastern coastal areas (Shanghai, Jiangsu, Zhejiang), southern coastal areas (Fujian, Guangdong, Hainan), middle reaches of the Yellow River areas (Shaanxi, Shanxi, Henan, Inner Mongolia), middle reaches of the Yangtze River areas (Hubei, Hunan, Jiangxi, Anhui), southwest region (Yunnan, Guizhou, Sichuan, Chongqing, Guangxi) and great northwest region (Gansu, Qinghai, Ningxia, Tibet, Xinjiang).

… ,Q_{27}. The total output matrix is shown in Table 1. The correction steps are as follows: 1) To facilitate the unification of the magnitude of the data unit, all total output data are converted from 10,000 to 100 million yuan, which corresponds to a magnitude of 100 million m^3 for exhaust gas emissions, that is, the direct emission coefficient unit is m^3/yuan. 2) Assuming that the pollution emission coefficient of different regions and sectors is equal to the national average, the initial value of the coefficient is calculated based on the total output and total emissions of China. 3) The emissions are reverse derived from the initial value and the total output matrix, the ratio γ_i is calculated between the actual emissions in area i and the calculated emissions according to formula (2), and all direct emissions are corrected according to formula (3) with γ_i as the row adjustment factor coefficient.

$$\gamma_i = U_i / \sum_{j=1}^{27} x_{ij} d_{ij} \tag{2}$$

$$d_{ij}^{'} = d_{ij} \gamma_i \tag{3}$$

4) The corresponding emissions are calculated again based on the revised emission coefficient and each output data; the ratio δ_j between the actual emissions of sector j and the calculated emissions according to formula (4) is calculated, and δ_j is used as the column to adjust the coefficient to correct all direct emission factors according to formula (5).

$$\delta_j = Q_j / \sum_{i=1}^{31} x_{ij} d_{ij} \tag{4}$$

$$d_{ij}^{''} = d_{ij}^{'} \delta_j \tag{5}$$

5) Row adjustment and column adjustment are performed in turn until the difference between the calculated value and the actual value of the total emissions for each area and each sector is within 5%. The correction is stopped, and the final result is derived.

Table 1 Regional-sectoral industrial exhaust emission balance

		Sector				Calculated emissions	Actual emissions	Row adjustment factor
		Sector 1	Sector 2	…	Sector 27			
Region	Area 1	x_{11}	x_{12}	…	$x_{1,27}$	$\sum_{j=1}^{27} x_{1j}d_{1j}$	U_1	γ_1
	Area 2	x_{21}	x_{22}	…	$x_{2,27}$	$\sum_{j=1}^{27} x_{2j}d_{2j}$	U_2	γ_2
	…	…	…	…	…	…	…	…
	Area 31	$x_{31,1}$	$x_{31,2}$	…	$x_{31,27}$	$\sum_{j=1}^{27} x_{31,j}d_{31,}$	U_{31}	γ_{31}
Calculated emissions		$\sum_{i=1}^{31} x_{i1}d_{i1}$	$\sum_{i=1}^{31} x_{i2}d_{i2}$	…	$\sum_{i=1}^{31} x_{i,27}d_{i,27}$			
Actual emissions		Q_1	Q_2	…	Q_{27}			
Column adjustment factor		δ_1	δ_2	…	δ_{27}			

Source: Li et al. (2013).

2.4 Embodied pollution estimation model

This study focuses on local final use, so the final use items in the inter-regional input-output table only include consumption and capital formation, not exports. Let X_r and Y_r denote the column vector of the total output and the final use column vector of each sector in area r, respectively, and $F^r{}_h$ denote the column vector of the final use supplied by area r to h. It is known that the revised direct emission coefficient of exhaust gas, d_{ij} , and the data of each sector in area r constitute a row vector, D^r; then, m areas are connected horizontally to form a direct emission coefficient row vector, D:

$$D = \begin{bmatrix} D^1 & D^2 & \cdots & D^r & \cdots & D^m \end{bmatrix} \tag{6}$$

Then, the total exhaust gas emissions, W, can be expressed as:

$$W = DX \tag{7}$$

According to the basic theorem of the input-output table, there is a balanced relationship between the regional output and final use:

$$X = (I - A)^{-1} Y \tag{8}$$

where I is the identity matrix and $(I–A)^{-1}$ is the Leontief inverse matrix of the inter-regional input-output table. By substituting formula (8) into formula (7), we get formula (9) from the associative law of matrix multiplication:

$$W = D\left[(I - A)^{-1} Y\right] = D(I - A)^{-1} Y \tag{9}$$

Assuming that the block matrix[2] $B=(I–A)^{-1}$, the embodied pollution, W_h, that is finally used locally in area h is derived as follows:

$$\begin{aligned} W_h &= DBF_h = D(BF_h) \\ &= \begin{bmatrix} D^1 & D^2 & \cdots & D^r & \cdots & D^m \end{bmatrix} \left(\begin{bmatrix} B^{11} & B^{12} & \cdots & B^{1s} & \cdots & B^{1m} \\ B^{21} & B^{22} & \cdots & B^{2s} & \cdots & B^{2m} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ B^{r1} & B^{r2} & \cdots & B^{rs} & \cdots & B^{rm} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ B^{m1} & B^{m2} & \cdots & B^{ms} & \cdots & B^{mm} \end{bmatrix} \begin{bmatrix} F_h^1 \\ F_h^2 \\ \vdots \\ F_h^r \\ \vdots \\ F_h^m \end{bmatrix} \right) \\ &= [1 \times m]\begin{bmatrix} D^1 T_h^1 & D^2 T_h^2 & \cdots & D^r T_h^r & \cdots & D^m T_h^m \end{bmatrix}^T \end{aligned} \tag{10}$$

From the perspective of consumer responsibility, W_h represents the exhaust gas emissions caused by consumption and capital formation within area h, that is, the embodied pollution in the local final use of area h, and the difference between the actual local exhaust gas emissions, U_h , is the embodied net pollution transfer, V_h .

The positive or negative difference can indicate the direction of pollution transfer in the area, and the absolute value can reflect the degree of pollution transfer. The calculation expression is as follows:

$$V_h = W_h - U_h \tag{11}$$

If V_h is close to 0, area h appears as a pollution balance area. If V_h is greater than 0, it indicates a net embodied pollution input area or a net pollution pressure outflow area, that is, there is a net transfer of air pollution caused by the final demand from this area to other areas. If V_h is less than 0, it indicates a net embodied pollution output area or a net pollution

2 This is a simplified formula. Here it is assumed that the corresponding sectors are included in the block matrix of each area, and the analysis logic is consistent.

pressure inflow area, that is, the area is receiving the transfer of embodied pollution emissions.

Part of the embodied pollution from area r provided for the final use in area h by all areas is expressed as:

$$D^r T_h^r = D^r B^{r1} F_h^1 + D^r B^{r2} F_h^2 + \cdots + D^r B^{rr} F_h^r + \cdots + D^r B^{rm} F_h^m \quad (12)$$

Where $D^r B^{r1} F_h^1$ represents the embodied pollution provided by area 1 to area h for final use from area r, which is the embodied pollution produced in area r when the products in this area are used for intermediate use in area 1 to form final products for final use in area h.

The difference in the two-way embodied pollution flow between any two areas can represent the one-way net transfer flow.

3 Results and Analysis

3.1 Distribution characteristics of industrial waste gas emissions

Based on the quartile classification method (Cui et al., 2018), taking 20%, 40%, 60%, and 80% of direct industrial waste gas emissions as the boundary, all emissions are divided into five levels, and the emissions increase gradually. The regional distribution of direct industrial waste gas emissions is shown in Supplementary Table 2. As a whole, the spatial pattern presents a similar trapezoidal distribution of "heavy in the east, light in the west, and low in the middle and high ring." Among them, the direct emissions of exhaust gas in six provinces (Liaoning, Hebei, Shanxi, Shandong, Henan, Anhui, and Jiangsu), predominantly distributed in eastern and central regions, correspond to level five. In contrast, Qinghai, Hainan, Tibet, Gansu, Guizhou, and other regions with low industrialization and high air quality typically have level one or level two emissions and are predominantly distributed in the western region.

According to the top ten industries for direct industrial waste gas emissions (Figure 1), the emissions of each industry exhibit substantial differences, with an order of magnitude drop at the sectors in fourth and sixth place. The production and supply of electricity and heat (sector 25), metal smelting and rolling products (sector 14), and non-metallic mineral products (sector 13) rank in the top three, with emissions magnitudes on the order of 100,000, and total emissions accounting for 81.73% of total industry emissions. The total emissions of the top ten industries account for 96.27% of all emissions.

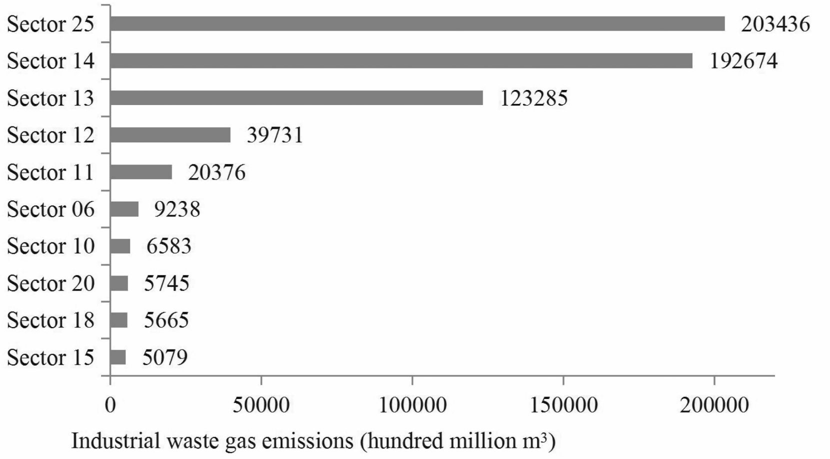


Figure 1 Distribution of top 10 industries for direct industrial waste gas emissions

The revised direct emissions of industrial waste gas in each region and sub-sector are illustrated as a heat map (Figure 2) to better reflect the distribution. A horizontal comparison shows that the results of sectoral clustering are related to the nature of the industry. Sectors with similar industry types or industries exhibit more similar emissions, with a similar distribution in various regions. The distribution of emissions within each department, coal mining products (sector 02), oil and gas extraction products (sector 03), metallic ore mining products and related product processing products (sectors 04, 14, 24), and electrical machinery and equipment (sector 19) exhibit relatively obvious bi-polarization, which indicates that the industry is somewhat unevenly distributed or agglomerated in various regions.

Conversely, a longitudinal comparison shows that the regional clustering results are approximately the same as the emission distribution shown in Supplementary Table 2. For example, Liaoning, Henan, Anhui, Hubei, Guangxi, and other regions are concentrated in the lower half of the heat map, and the overall color is darker, indicating that industrial waste gas emissions are relatively high. The distribution of emissions from various sectors within the region, the distribution of industries in regions with lower emissions exhibits some similarities. In contrast, the distribution of industries in regions with higher emissions is not the same, which may be due to different types of resource endowments. For example, Shanxi, the "Hometown of Coal Sea," ranks first in the emission of coal mining products (sector 02) and electricity and heat production and supply (sector 25); Xinjiang, where the Karamay Oilfield is located, takes the lead in oil and gas extraction products (sector 03) industry; Jiangsu has very high emissions in the three industries of electrical machinery and equipment (sector 19), instruments (sector 21), and scrap waste (sector 23); and Hebei is more prominent in metallic ore mining products and related product processing products (sectors 04, 14, 24).

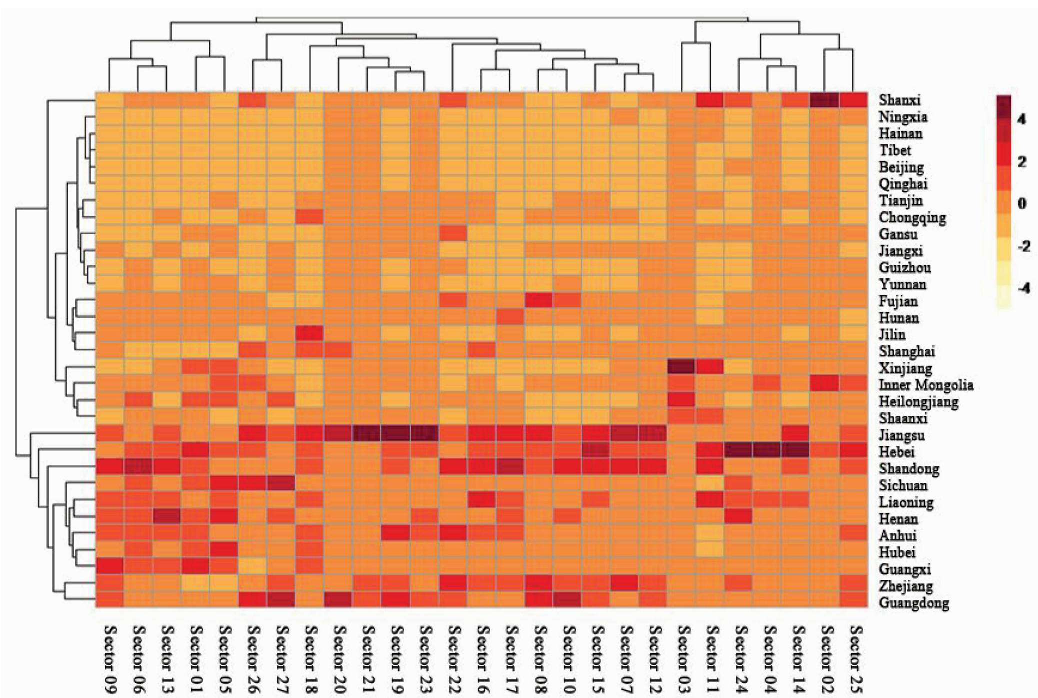
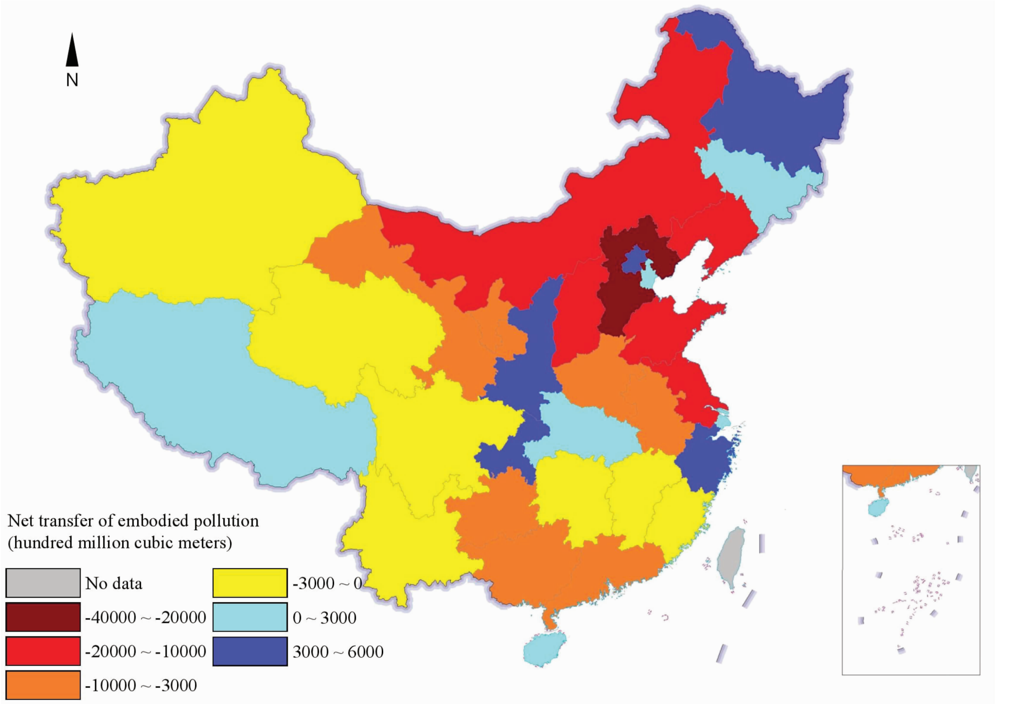


Figure 2 Revised heat map of the distribution of direct industrial waste gas emissions by sector in each region

3.2 Overview of the net transfer of interprovincial embodied air pollution

The net transfer of embodied waste gas emissions in various provinces, autonomous regions, and municipalities is shown in Figure 3. The selection of each value interval node is still based on the corresponding quartile. The national direct emissions of industrial waste gas for 2012 amounted to 635,519 billion m^3. The total amount of embodied transfer of waste gas caused by local final use in 31 provinces, autonomous regions, and municipalities was 529,930.64 billion m^3, which indicated that pollution pressure is generally flowing into the region, and emissions generated by international demand account for approximately 16.7% of China's actual emissions. Most provinces are receiving regions for the net transfer of air pollution (20 provinces, autonomous regions, and municipalities), whereas net pressure outflow regions still account for a minority (11 provinces, autonomous regions, and municipalities). There is a significant gap in the transfer volume between the two types of regions, with the highest value of embodied emissions in the pollution inflow region, approximately six times that in the outflow region. Moreover, in net inflow regions, the amount of waste gas transfer exhibits relatively obvious bi-polarization. For example, Hebei, the region with the highest net inflow, has nearly twice the transfer volume than the second-ranked Shanxi Province.

The embodied net transfer of air pollution trade is similar to the overall distribution of exhaust gas direct emissions, exhibiting an approximately similar trapezoidal distribution of "high in the east and low in the west, heavy in the north and light in the south." Thus, the embodied inflow of pollution is one of the important factors of local exhaust emissions. The net transfer of the embodied pollution input region is positive. It is possible because certain energy-intensive industries transfer the exhaust gas emission pressure to other regions, thereby reducing local emissions. While the embodied pollution output region becomes the recipient of high-emission industries, in addition to local demand, production links, such as intermediate input, are also employed for product demand in other regions, which indirectly increases local exhaust emissions. The distribution of the net outflow of pollution pressure has a certain degree of dispersion and uniformity. Each comprehensive economic zone contains approximately 1– 2 embodied input regions, mostly in surrounding regions with a developed economy, a high degree of urbanization, or a low proportion of heavy chemical industry regions, such as Beijing, Shanghai, Tianjin, Chongqing, Hainan, Tibet, and Heilongjiang. The net inflow of pollution pressure from the northeast to the southwest exhibits a general slope distribution from high to low, and there is a local concentration phenomenon within each comprehensive area. The region with the highest burden of embodied pollution pressure is Hebei, whose net transfer volume is nearly twice as high as that of Shanxi Province.



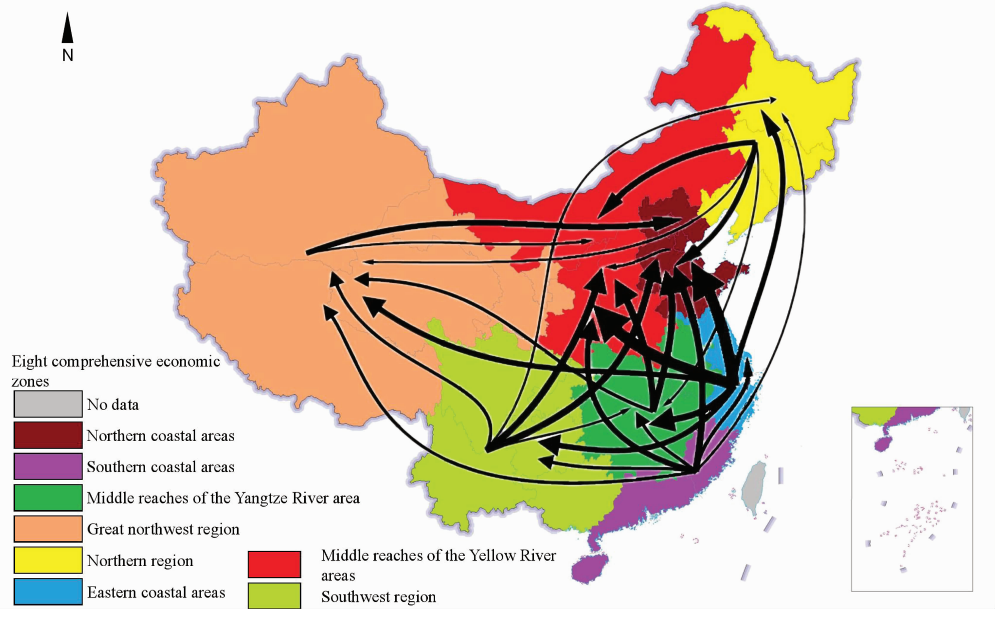
Note: This map is made based on the standard map No. GS (2020) 4630 downloaded from the Standard Map Service website of the Ministry of Natural Resources of the People's Republic of China. The details of the base map are not changed.

Figure 3 Distribution of embodied atmospheric pollution net transfer among provinces in China

3.3 Main flow directions of the embodied transfer of air pollution in the eight major regions

Local final consumption in major regions has led to double pollution pressures in this region and other regions. However, compared with the direct emissions of exhaust gas within each region, only the eastern coastal areas have higher emissions in regions other than the local region. The total amount of transfer in the northern coastal areas, the middle reaches of the Yellow River areas, and the Great Northwest areas show a state of net pollution inflow, whereas the other five regions are net pollution outflow regions. Figure 4 is a flow diagram of the embodied transfer of exhaust emissions between China's eight comprehensive economic zones, with the thickness of the arrow symbolizing the size of the transfer. The embodied air pollution pressure predominantly shifts from the east and south to the west and middle, and most of the pollution outflow areas are coastal areas with a more concentrated population and a more developed economy. The eastern coastal areas are the primary source of embodied pollution transfer; with the exception of a small amount of net inflow from the southern coastal area (52.509 billion m^3), each group of exhaust emissions is net transferred to other regions. The two places with the largest net flow in China include the area from the eastern coastal areas to the northern coastal areas (717.806 billion m^3) and the middle reaches of the Yellow River (680.648 billion m^3); the sum of the two accounts for 30.5% of China's total net transfer. The northern coastal areas and the middle reaches of the

Yellow River are the two major receiving bases with severe pollution pressure transfer, with densely distributed source regions and a typically high net transfer volume. The inflows from these two regions together account for 75.1% of China's total net transfer, and most of the provinces are rich in mineral resources, land resources, and energy resources, with a high proportion of heavy chemicals. To some extent, the advantages of location development make it difficult for the underdeveloped central and western regions to make breakthroughs in the national industrial chain, and they still export low-end primary products or provide high-polluting intermediate products to eastern coastal provinces. Therefore, the implementation of policies, such as western development, the rise of central China, and the revitalization of the old industrial base in Northeast China, may be supported by regional trade at the cost of the embodied pollution input.



Note: This map is made based on the standard map No. GS (2020) 4630 downloaded from the Standard Map Service website of the Ministry of Natural Resources of the People's Republic of China. The details of the base map are not changed.

Figure 4 Embodied air pollution pressure transfer paths among the eight regions in China

3.4 Interprovincial transfer of embodied air pollution for each industry

3.4.1 Commonality of different industry contributions to embodied air pollution transfer in different regions.

Examining the distribution of embodied air pollution transfer between different industries in each region reveals that industry rankings are approximately the same in different regions. Moreover, the closer to the two poles, the smaller the ranking difference. The transfer volume of embodied pollution was summarized for the same industry in various regions and shown in Figure 5 as a two-axis column chart of the top 10 industries. The top three industries are electricity and heat production and supply (sector 25), metal smelting and rolling products (sector 14), and non-metallic mineral products (sector 13). Their embodied pollution transfer volume accounts for more than 20%, the cumulative proportion is 83.09%, and the top five sectors cumulatively account for 92.03%. This basically conforms to the Pareto principle, that is, 80% of the pollution output comes from 20% of the industry input. Agriculture, forestry, animal husbandry, and fishery products and services (sector 01) are ranked 26th, with a relative proportion of embodied air pollution transfer of less than 0.01%.

Primary industry can involve pollution emissions in terms of land use, mechanized production, and intensive development, but its embodied transfer problem has not yet been largely reflected in regional trade. The secondary industry sector is still the main source of industrial waste gas pollution emissions, with the development of regional trade, it leads to embodied pollution transfer, whose pollution flow situation is particularly manifested in the processing and production processes of energy consumption, metal smelting, mineral chemical industries, etc.

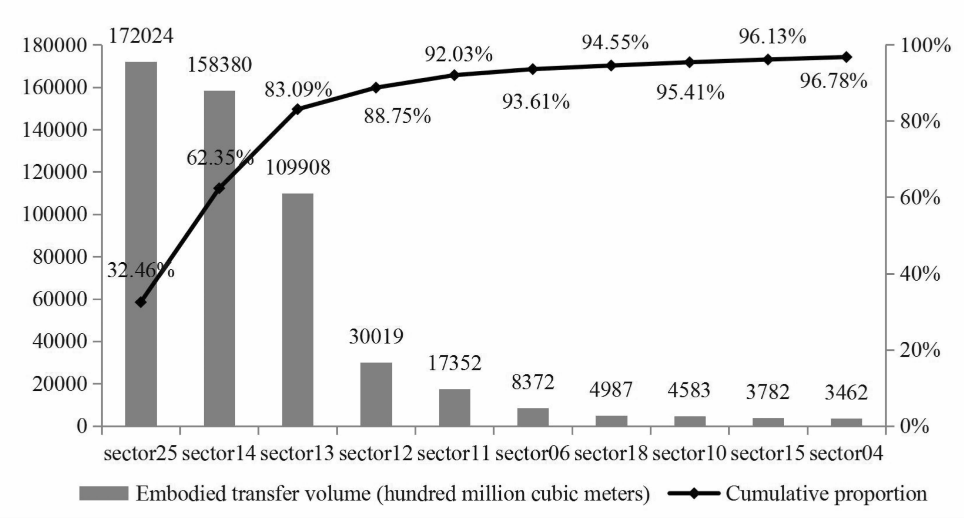


Figure 5 Distribution and cumulative proportion of the top 10 industries for the transfer of embodied atmospheric pollution

Comparing the industry contribution of direct exhaust gas emissions from Figure 1 and Figure 5 for the transfer of embodied pollution reveals a similar ranking for the top 10 industries, as well as a slight change in the rankings of some industries. Metallic ore mining products and processing and related products (sector 04, 15), transportation equipment (sector 18), and other industries with obvious characteristics of resource endowments are higher in the embodied transfer ranking and are typical industries where regional trade causes pollution transfer. Conversely, communications equipment, computers, and other electronic equipment (sector 20), papermaking, printing, and cultural, educational and sporting goods (sector 10), and other relatively basic manufacturing industries exhibit lower rankings of embodied emissions, indicating that these industries prefer a production structure of "local use and local pollution."

3.4.2 Differentiation of embodied air pollution transfer between industries in different regions

Whether observing the industry distribution from a regional perspective or examining regional differences from an industry perspective, the general distribution and agglomeration characteristics of the embodied transfer of exhaust gas (Figure 6) are similar to the direct emissions of exhaust gas (Figure 2). The transfer contribution exhibits a certain degree of agglomeration in different industries in each region, but the distribution shows substantial differences. This difference is closely related to the characteristics of different resource endowments. If there is a certain comparative advantage in regional trade, the local production structure may be adjusted to focus on consuming resources or energy with relative endowment advantages and undertake the production and export of high-emission resource-intensive products such as coal, petroleum, and metal materials. Then, through the transfer of embodied emissions from trade, a situation of "outside use, local emissions" is formed, making it a concentration area for the inflow of pollution pressure. For example, Shanxi ranks first in the embodied waste gas emissions of coal mining products (sector 02) and electricity and heat production and supply (sector 25). Among them, the embodied transfer volume of coal mining products (sector 02) in Shanxi accounts for 34.0% of total industry emissions, and the sum of the two sectors accounts for 46.3% of the total embodied transfer of all industries in the province. Moreover, the proportion of structured products is relatively high.

3.4.3 Key regions and industries with interprovincial embodied air pollution net transfer

Here, the top 25 flow combinations with the largest absolute value of net transfer flow of one-way embodied waste gas pollution between provinces, regions, and cities were selected. The top three industries in each group's transfer contribution represent more than 80% of the embodied emissions, which conforms to the Pareto principle of the industry contributions mentioned above. The results are shown in Table 2. In combination with a large embodied net transfer volume, the inflow of pollution pressure is predominantly energy- and resource-based regions or underdeveloped areas, including Hebei (15 times), Shanxi (seven times), Inner Mongolia (twice), and Henan (once), concentrated in northern coastal areas and the middle reaches of the Yellow River, which is consistent with the regional flow conclusions. The main pollution pressure outflow areas are distributed outside of the northwestern region, and the areas with a higher frequency of occurrence or larger input emissions typically have a developed economy and dense population, such as Zhejiang (four times), Jiangsu (three times), Shanghai (twice), and Beijing (once). The key transfer industries are concentrated in high-energy, high-emission resource- and energy-intensive industries. There are six sectors in total, including metal smelting and rolling products (25 times), electricity and heat production and supply (25 times), non-metallic mineral products (13 times), petroleum coking products, and nuclear fuel processing products (eight times), coal mining products (three times), and metallic ore mining products (once). Among them, metal smelting and rolling products, electricity and heat production, and supply are in the 25 key regions, which also corresponds to the industrial development status of the four typical pollution pressure inflows.

Table 2 Key regions and major industries embodying the net transfer of waste gas pollution

Pollution pressure outflow areas	Pollution pressure inflow areas	Key industries
Zhejiang, Jiangsu, Chongqing, Heilongjiang, Guangdong, Shaanxi, Henan, Shanghai	Hebei	①Metal smelting and rolling products ②Electricity and heat production and supply ③Non–metallic mineral products

Pollution pressure outflow areas	Pollution pressure inflow areas	Key industries
Shandong, Anhui, Sichuan, Fujian	Hebei	①Metal smelting and rolling products ②Electricity and heat production and supply ③ Petroleum, coking products, and nuclear fuel processing products
Beijing, Tianjin	Hebei	①Metal smelting and rolling products ②Non–metallic mineral products ③Electricity and heat production and supply
Hubei	Hebei	①Metal smelting and rolling products ②Electricity and heat production and supply ③Metallic ore mining products
Zhejiang	Shanxi	①Metal smelting and rolling products ②Electricity and heat production and supply ③ Petroleum, coking products, and nuclear fuel processing products
Jiangsu	Shanxi	①Metal smelting and rolling products ②Electricity and heat production and supply ③Coal mining products
Hubei, Jiangxi	Shanxi	①Electricity and heat production and supply ②Metal smelting and rolling products ③Coal mining products
Chongqing, Shaanxi, Shanghai	Shanxi	①Electricity and heat production and supply ②Metal smelting and rolling products ③ Petroleum, coking products, and nuclear fuel processing products
Zhejiang, Jiangsu	Inner Mongolia	①Metal smelting and rolling products ②Electricity and heat production and supply ③Non–metallic mineral products
Zhejiang	Henan	①Non–metallic mineral products ②Metal smelting and rolling products ③Electricity and heat production and supply

4 Conclusions

1) Overall, China exhibits a net influx of atmospheric pollution pressure into regions, and a significant gap in the embodied transfer of exhaust gas between provinces, regions, and cities.

2) The direct emission of air pollution and the net transfer of embodied pollution are similar, exhibiting a pattern of "high in the east and low in the west, heavy in the north and light in the south." Net outflow areas are more evenly distributed and scattered, whereas net inflow areas show local agglomeration characteristics.

3) Embodied air pollution pressure transfer exhibits a dynamic path from east to west and south to north. In addition to the principle of proximity, the eastern coastal areas (Jiangsu, Zhejiang, and Shanghai) are the primary sources of embodied pollution transfer, and the northern coastal areas (Hebei and other places) and middle reaches of the Yellow River (Shanxi and other places) are the primary concentrations of pollution inflows.

4) The rankings of direct emissions and embodied pollution transfer of various industries are approximately similar to the regional distribution; however, different industries are

unevenly distributed in various regions, and different resource endowments may trigger the transfer of embodied pollution from regional trade and lead to industry differences.

5) The major industries causing the embodied transfer of air pollution trade in various regions exhibit similar common contributions and regional differences. The contribution of industries basically agrees with the Pareto principle. The key transfer sectors are concentrated in resource-intensive industries with high-energy consumption and high emissions, such as energy consumption, metal smelting, and mineral chemicals.

5 Future Research Prospect

There are some innovations in the indicators, methods, and perspectives of this study, which can provide a reference to the subsequent research on the embodied transfer of exhaust gases. Specifically, in terms of the selection of indicators, the total amount of industrial waste gas emissions is used in the measurement of the embodied transfer of exhaust gases, covering all kinds of pollutants, and the calculation results are comprehensive. Regarding the application of the method, the direct emissions of subdivided industries in each region are calculated using the revised emission coefficient of pollutants, the general distribution of inter-provincial embodied pollution transfer is compared with that, and the specific analysis is carried out based on the dual perspectives of region and industry, static and dynamic dimensions. In addition, aiming at the problem of regional division, this study selects the classification criteria of eight comprehensive economic zones during the "11th Five-Year Plan" period, and considers the geographical location and economic development level, to analyze the spatial distribution and dynamic path of the implied transfer of inter-regional trade.

Although this study has carried out a relatively objective measurement of the implied transfer of air pollution at the provincial level in China, there are still some limitations, which is also a possible future research direction. For example, this study uses the multi-regional input-output model in 2012 to measure the embodied transfer of exhaust gas between provinces, regions, and cities. Although the data are from the latest available years, there is still a certain degree of lag. In future studies, previous and updated annual data can be added to cover the impact of international trade, and the hidden emissions of each year can be vertically compared in the form of time series to further investigate the spatio-temporal evolution trend.

Acknowledgments

The corresponding author was supported by the Major Projects of the National Social Science Fund of China (grant no. 18ZDA126).

References

Ackerman, F., Ishikawa, M., & Suga, M. (2007). The carbon content of Japan–US trade. *Energy Policy, 35* (9), 4455– 4462. https://doi.org/10.1016/j.enpol.2007.03.010

Brizga, J., Feng, K., & Hubacek, K. (2017). Household carbon footprints in the Baltic States: A global multi–regional input– output analysis from 1995 to 2011. *Applied Energy, 189*, 780– 788. https://doi.org/10.1016/j.apenergy.2016.01.102

Chen, N., Liu, X., & Yuichi, H. (2016). Industry transfer and driving facts of trade embodied carbon in China–

Japan——based on vertical specialization. *Science and Technology Management Research, 36* (15), 236–241 + 246. (in Chinese).

Cui, P., Zhang, Y., Zhang, L., Sun, Y., Zhang, Z., Wang, W., & Xu, X. (2018). Analysis on the spatial and temporal evolution of indirect carbon emissions and its driving mechanism in China. *Journal of Natural Resources, 33* (05), 879– 892. (in Chinese).

Du, H., Guo, J., Mao, G., Smith, A. M., Wang, X., & Wang, Y. (2011). CO_2 emissions embodied in China–US trade: Input– output analysis based on the emergy/dollar ratio. *Energy Policy, 39* (10), 5980– 5987. https://doi.org/10.1016/j.enpol.2011.06.060

Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D., & Pozzer, A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature, 525* (7569), 367– 371. https://doi.org/10.1038/nature15371

Lenzen, M. (1998). Primary energy and greenhouse gases embodied in Australian final consumption: An input – output analysis. *Energy Policy, 26* (6), 495– 506. https://doi.org/10.1016/S0301–4215(98)00012–3

Li, F., Liu, W., & Tang, Z. (2013). Study on interregional transfer of embodied pollution in China. *Acta Geographica Sinica, 68* (06), 791– 801. (in Chinese).

Li, Y., Zhang, W., Jiang, H., Wang, F., Hou, L., & Wang, J. (2019). Transfers of air pollutant emissions embodied in China´s foreign trade based on MRIO model. *China Environmental Science, 39* (02), 443– 450. (in Chinese).

Liu, Q., & Wang, Q. (2015). Reexamine SO_2 emissions embodied in China´s exports using multi–regional input – output analysis. *Ecological Economics, 113* (May), 39– 50.

Liu, Q., & Wang, Q. (2016). Comparative study on the accounting methods of embodied emission in China´s interprovincial trade. *Statistical Research, 33* (10), 12– 20. (in Chinese).

Liu, W., Tang, Z., & Han, M. (2018). *The 2012 China multi–regional input– output table of provincial units.* China Statistics Press. (in Chinese).

Meng, B., Xue, J., Feng, K., Guan, D., & Fu, X. (2013). China´s inter–regional spillover of carbon emissions and domestic supply chains. *Energy Policy, 61*, 1305– 1321. https://doi.org/10.1016/j.enpol.2013.05.108

Muradian, R., O´Connor, M., & Martinez –Alier, J. (2002). Embodied pollution in trade: Estimating the " environmental load displacement" of industrialised countries. *Ecological Economics, 41* (1), 51– 67. https://doi.org/10.1016/S0921–8009(01)00281–6

Ni, H., Li, S., & He, J. (2012). Measurement of embodied SO_2 and structural decomposition analysis of the factors. *Statistical Research, 29* (7), 54– 60 (in Chinese).

Pan, Y., Pan, W., & Wu, T. (2013). Measurement of embodied CO_2 in China´s regional trade. *Statistical Research, 30* (9), 21– 28 (in Chinese).

Pang, J., Shi, Y., Li, Z., & Zhang, J. (2017). Interprovincial transfer of embodied pollution in Beijing–Tianjin–Hebei region based on the MRIO model. *China Environmental Science, 37* (08), 3190– 3200 (in Chinese).

Petrovits, C., Shakespeare, C., & Shih, A. (2011). The causes and consequences of internal control problems in nonprofit organizations. *Accounting Review, 86* (1), 325– 357. https://doi.org/10.2308/accr.00000012

Sheng, L. (2007). The changes of China´s foreign trade structure is harmful to energy –saving and consumption–reducing. *Management World, 2007* (10), 43– 50+171– 172. (in Chinese).

Shi, M., Wang, Y., Zhang, Z., & Zhou, X. (2012). Regional carbon footprint and interregional transfer of carbon emissions in China. *Acta Geographica Sinica, 67* (10), 1327– 1338. (in Chinese).

Veiga, J. P. S., Malik, A., Lenzen, M., Ferreira Filho, J. BdS., & Romanelli, T. L. (2018). Triple–bottom–line assessment of Sao Paulo state´s sugarcane production based on a Brazilian multi–regional input– output matrix. *Renewable and Sustainable Energy Reviews, 82* (1), 666 – 680. https://doi.org/10.1016/j.rser.2017.09.075

Walter, I. (1973). The pollution content of American trade. *Economic Inquiry, 11* (1), 61– 70. https://doi.org/10.1111/j.1465–7295.1973.tb00961.x

Wang, G., Liu, J., Chen, H., Xiao, P., Jiang, Y., & Du, B. (2016). Analysis of dynamic relationship between PM2.5 and other air pollutants based on VAR model. *Journal of Atmospheric and Environmental Optics, 11*

(02), 91– 102 (in Chinese).
Wang, Y. (2016). Virtual water transfer calculation among China´s regional trade based on whole industry caliber. *China Population, Resources and Environment, 26* (04), 107– 115. (in Chinese).
Wiedmann, T., Wood, R., Minx, J. C., Lenzen, M., Guan, D., & Harris, R. (2010). A carbon footprint time series of the UK–results from a multi–region input– output model. *Economic Systems Research, 22* (1), 19 – 42. https://doi.org/10.1080/09535311003612591
Wu, L., Zhong, Z., Liu, C., & Wang, Z. (2017). Measurement and spatial transfer of China´s provincial PM2.5 emissions embodied in trade. *Acta Geographica Sinica, 72* (02), 292– 302. (in Chinese).
Wyckoff, A. W., & Roop, J. M. (1994). The embodiment of carbon in imports of manufactured products. *Energy Policy, 22* (3), 187– 194. https://doi.org/10.1016/0301–4215(94)90158–9
Xue, W., Fu, F., Wang, J., Tang, G., Lei, Y., Yang, J., & Wang, Y. (2014). Numerical study on the characteristics of regional transport of PM2.5 in China. *China Environmental Science, 34* (06), 1361– 1368. (in Chinese).
Xin, J., Ma, S., & Zhang, H. (2022). Spatial agglomeration and influencing factors of pulmonary tuberculosis in the Chinese mainland from 2015 to 2019. *Data Science and Informetrics, 2* (4), 26–37.
Zhang, C., & Anadon, L. D. (2014). A multi–regional input– output analysis of domestic virtual water trade and provincial water footprint in China. *Ecological Economics, 100*, 159– 172. https://doi.org/10.1016/j.ecolecon.2014.02.006
Zhang, Y. (2010). Carbon contents of the Chinese trade and their determinants: An analysis based on noncompetitive (import) input– output tables. *China Economic Quarterly, 9* (04), 1287– 1310. (in Chinese).
Zhu, W., Li, S., & Zhu, L. (2019). Ecosystem service footprint flow and the influencing factors within provinces, China. *Geographical Research, 38* (02), 147– 157. (in Chinese).

Appendix

Supplementary Table 1 Trade classification comparison table

ID	Interregional input–output table departments	Industry from China Environmental statistical yearbook
01	Agricultural, forestry, animal husbandry and fishery products and services	Agriculture, forestry, animal husbandry, fishing services
02	Coal mining products	Coal mining and washing industries
03	Products of oil and gas extraction	Oil and gas extraction industry
04	Metal mining products	Black metal mining and processing industry
		Non–ferrous metal ore mining and processing industry
05	Products from non –metallic and other minerals	Non–metallic mining industry
		Mining auxiliary activity
		Other mining industry
06	Food and tobacco	Agricultural and sideline food processing industry
		Food manufacturing industry
		Wine, beverage and refined tea manufacturing
		Tobacco products industry
07	Textile products	Textile industry
08	Textile clothing shoes and hats leather down and its products	Textile and garment industry
		Leather, fur, feathers and their products and footwear industry

ID	Interregional input–output table departments	Industry from China Environmental statistical yearbook
09	Woodworking products and furniture	Wood processing and wood, bamboo, rattan, brown, grass products industry
		Furniture manufacturing industry
10	Paper printing and cultural and educational sporting goods	Paper and paper products industry
		Printing and recording media reproduction industry
		Manufacturing of cultural, educational, industrial, sports and entertainment products
11	Petroleum, coking products and nuclear fuel processing products	Petroleum processing, coking and nuclear fuel processing industries
12	Chemical product	Manufacturing of chemical raw materials and chemical products
		Pharmaceutical manufacturing industry
		Chemical fiber manufacturing industry
		Rubber and plastic products industry
13	Non–metallic mineral products	Non–metallic mineral products industry
14	Metal smelting and calendering products	Ferrous metal smelting and rolling industry
		Nonferrous metal smelting and rolling industry
15	Metal products	Metal products industry
16	General purpose equipment	General equipment manufacturing industry
17	Special equipment	Special equipment manufacturing industry
18	Transportation equipment	Automobile manufacturing industry
		Manufacturing of railway, shipping, aerospace and other transportation equipment
19	Electrical machinery and equipment	Electrical machinery and equipment manufacturing
20	Communication equipment, computers and other electronic equipment	Manufacturing of computers, communications and other electronic equipment
21	Instrument and meter	Instrumentation manufacturing industry
22	Other manufactured products	Other manufacturing industries
23	Waste product waste	Comprehensive utilization of waste resources
24	For services to metal products, machinery	Metalwork, machinery and equipment repair industry
25	The production and supply of electricity and heat	Electricity and heat production and supply industry
26	Gas production and supply	Gas production and supply industry
27	Water production and supply	Water production and supply industry

Supplementary Table 2 Regional distribution of direct industrial waste gas emissions (Unit: millimetric cubic meter)

Region	Total industrial exhaust emissions	Level	Region	Total industrial exhaust emissions	Level
Beijing	3263.7	1	Hubei	19512.5	4
Tianjin	9032.2	1	Hunan	15887.5	3
Hebei	67647.4	5	Guangdong	27078.2	4
Shanxi	38124.3	5	Guangxi	27610.7	4
Inner	28132.7	5	Hainan	1960.3	1
Liaoning	31917	5	Chongqing	8359.9	1
Ji Lin	10316.3	2	Sichuan	21909.6	4
Heilongjiang	10444.6	2	Guizhou	14311.6	2
Shanghai	13361.3	2	Yunnan	14955.2	3
Jiangsu	48623.3	5	Tibet	114	1
Zhejiang	23967.3	5	Shaanxi	14767.4	3
Anhui	29645	5	Gansu	13899.7	2
Fujian	14739.3	3	Qinghai	5507.6	1
Jiangxi	14814.1	3	Ningxia	9324.5	2
Shandong	45420.2	5	Xinjiang	15869.9	3
Henan	35001.9	5	—	—	—