Temporal variation of SO_2 emissions embodied in Chinese supply chains during 2002-2012

Abstract: Increasing attention has been focused on the embodied pollutant emissions along supply chains in China, but relatively little attention has been paid to dynamic changes in this process. The study utilized environmental extended input-output analysis(EEIOA) and structural path analysis (SPA) to investigate the dynamic variation of SO_2 emissions embodied in 28 economic sectors in Chinese supply chains during 2002-2012. The main conclusions are summarized as follows: (1) The total SO_2 emissions in China rise from 18,793 Gg in 2002 to 25,665 Gg in 2007, and then declined to 21,180 Gg in 2012. Electricity and heat production dominated SO_2 emissions from the point of production, while construction contributed most from the consumption perspective. (2) The embodied SO_2 emissions tended to change from the path (staring from consumption side to production side): "Services→Services→Power" in 2002 to the path: "Construction and Manufacturing→Metal and Nonmetal→Power" in 2012. (3) Metal-driven emissions raised dramatically from 15% in 2002 to 22% in 2012, due to the increasing demand for metal products in construction and manufacturing activities. (4) With the largest production–based emissions, power generation tended to transfer this burden to the upstream sectors in 2012. Controlling construction activities and cutting down end-of-pipe discharges in the process of power generation are the most radical cure to reduce Chinese SO_2 emissions. This study shed light on the change in SO_2 emissions in the supply chain and provided policy implications from the consumption perspective.

Keywords: Supply chain, Temporal variation, Structural path analysis, Input-output model, SO_2 emissions

1Introduction

Global pollutant emissions flatted and even decreased until 2000, with an recent surge mainly contributed by China and developing countries in general (Smith et al., 2011). With the largest population and tremendous economic capacity, China (Donkelaar et al., 2015) accounted for approximately 56% of the global total SO_2 discharges in 2010 (Li et al., 2015) and ranked , 109th of 178 countries in air quality reported in the Environmental Performance Index (Hsu A., 2016). China's anthropogenic atmospheric pollutant emissions hence has a significant contribution to global reduction.

Numerous studies have explored the key factors that drive the high releases in China from various perspectives, including energy consumption (Yang et al., 2016a), socioeconomic levels (He, 2009; He et al., 2016), coal-fired power plants (Liu and Donalds, 2013; Xu et al., 2017), and vehicles (Lang et al., 2016), etc. These studies mainly focused China's atmospheric pollutant emissions from the production side, i.e., total direct emissions from production entities. By contrast, analyzing emissions from the consumption side could provide an alternative approach to understanding the fundamental causes that trigger emission discharges. Such analyses can provide quantitative evidence for decision makers to develop and adopt appropriate policies to reduce emissions by altering consumption practices and industrial structure (Huo et al., 2014). Recently, a series of studies have investigated gaseous pollutant emissions from consumption perspective (Liang et al., 2014; Chen and Chen, 2015; Zhao et al., 2015a; Chen et al., 2016; Fan et al., 2016; Mi et al., 2016; Meng et al., 2017; Liddle, 2018), i.e., consumption-based accounting. In these studies, environmentally extended input-output model was the most common approach applied to calculate consumption attributions of emissions (Su and Thomson, 2016; Liu and Wang, 2017; Mi et al., 2017). Consumption-based emissions attributes the total emissions, including direct and the indirect emissions released along supply chains, to the final consumers(Skelton et al., 2011). The discrepancy between production-and consumption-based emissions raise questions that where the emissions related to the final products come from and how they were initiated.

To facilitate understanding of the link between production and consumption, Structural Path Analysis (SPA) has been extensively employed, which extracts individual supply chains instigated by final demand (Llop and Ponce-Alifonso, 2015; Zhang et al., 2017a; Peng et al., 2018). On the basis of emissions data, an SPA quantifies the emissions starting from the end of each supply chain (Liang et al., 2016). Decomposition in SPA is a tree-like structure, with each branch representing pollutant emissions from different sectors at different production levels. In theory, countless supply chains can be identified through the economy, but studies that take into account the computational requirements and reasonable interpretation often limit the number of supply chains (Skelton et al., 2011; Meng et al., 2015).

Although previous studies have linked the air pollutant emissions in production sector to the final users (Liang et al., 2015; Meng et al., 2015; Kikuchi et al., 2017), there is still a lag in relation to knowledge concerning temporal changes of the embodied emissions along Chinese supply chains. With the rapid economic growth and industrialization, the critical supply chain contributing to air pollutant emissions may shift greatly. It is important to identify the dynamic variation in supply chain paths that drive embodied emissions, which can provide policy implications on the identification of critical paths to efficiently reduce atmospheric pollutant emissions.

To fill the gap, this study took SO_2 emissions for example, and combined input-output model and SPA to investigate temporal variations in flows of embodied emissions through China's production system from 2002 to2012. The primary purposes of this paper are: (a) to identify the key SO_2 emission sectors in China from both the perspective of production and consumption over time, (b) to examine the dominate sectors discharging SO_2 at different production layers during 2002-2012, and (c) to reveal variations in embodied emission flows through Chinese supply chains from 2002 to 2012. The results will help to better understand the relationship between economic structure and air pollution. Consequently, sector specific policy interventions could be designed to effectively improve the air quality.

The remainder of the paper is structured as follows. In Section 2, we introduce the input-output method and the SPA method. We also provide data sources and details on the sector classification and aggregation. In Section 3, we present changes of the production- and consumption based SO_2 emissions for 28 economic sectors, in a bid to reveal shifts of the embodied emission flows among 8 aggregated sectors at various layers in China's production system. In Section 4, we conclude and present policy implications.

2 Methodology and data

2.1 Environmentally Extended Input-Output model

An environmental extended input–output analysis (EEIOA) is used to link sectoral SO_2 emissions to the final demand of goods and services through the intricate supply chain (Costello et al., 2011; Erickson et al., 2012). The standard expression of the IO model (consisting of n economic sectors) is:

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

where X is the vector (n×1) of total economic output; I is the matrix (n×n) of identity matrix. A is an n×n matrix of direct requirements or sectoral intermediate purchases matrix; an element a_{ij} of A

measures inputs from sector i necessary to satisfy unit output in sector j. L is known as the Leontief inverse or total requirements matrix (n×n), whose element (l_{ij}) measures total (including direct and indirect) requirement from sector i to generate unit output in sector j. Y is a n×1 matrix of final use, consisting of domestic final consumption and export. Note here that This study removed imports from the intermediate use and domestic final demand proportionally to isolate local emissions released in the production of finished products .

The EEIOA introduces an emission intensity vector (1×n, SO_2 emissions per unit of output). Thus,, the IO matrix can be converted into an environmental IO matrix, calculated as

$$E = \hat{f}(I - A)^{-1}\hat{Y} \qquad (2)$$

where an element e_{ij} of E measures embodied emissions in sector i to satisfy unit of output in sector j. Then the final production emissions and final consumption emissions of a sector can be derived from the environmental IO matrix (E) as

$$P_i = \sum_{j=1}^{n} e_{ij} \qquad (3)$$

$$C_i = \sum_{j=1}^{n} e_{ji} \qquad (4)$$

where P_i is the final production emissions of sector i, and C_i is the final consumption emissions of sector i. e_{ij} and e_{ji} is the elements of the environmental IO matrix (E). n is the number of sector.

2.2 Structural path analysis

SPA was applied to trace the supply chains to estimate the emissions in each production layer which is instigated by final demand. This is achieved by expanding the Leontief inverse (L) using its power series approximation as:

$$\mathrm{L} = (\mathrm{I} - \mathrm{A})^{-1} = \mathrm{I} + \mathrm{A} + \mathrm{A}^2 + \mathrm{A}^3 + \cdots + \mathrm{A}^{\mathrm{t}}, \qquad \lim_{\mathrm{t}\to\infty}(\mathrm{A}^{\mathrm{t}}) = 0 \qquad (5)$$

Each element in the right-hand side of Eq (5)is defined as a production layer (PL), that is $PL_t=A_t$. Coupling with the emission intensity, the direct emissions in each layer can be expressed as

$$D^t = \hat{f}A^tY \qquad (6)$$

where D^t is a n1 matrix of direct emissions from each sector in the PL_t.

The final consumption attribution in one layer is different from the direct emissions in the layer, and it also includes embodied emissions in the preceding layer to satisfy the output in the layer. Then final consumption attribution in one layer is the total (including direct and indirect) emissions in the layer, and it can be calculated as

$$E^t = \widehat{m}A^tY \qquad (7)$$

where E_t is a n×1 matrix of final consumption emissions from each sector in the PL_t. m is a intensity vector (1×n) of total emissions per unit of output, which can be derived from Eq. (4):

$$m = f(I - A)^{-1} \qquad (8)$$

where an element m_i in m measures emissions from all sectors that embodied in unit output from sector i, including direct emissions and indirect emissions.

Final demand for each sector purchases product of each sector in PL1, and product for each sector in PL1 purchases product of each sector in PL2, and so it goes on, yielding a tree-like structure for the production system. The quantity of branches increases exponentially with tier expansion. There are n^t branches in each tier where t and n represents the the tier and sector numbers, respectively. It is impossible and time consuming to estimate the infinite number of branches in the system, so the branches are generally pruned to a specified threshold to simplify the system. Using this tree-pruning concept, only the first three production layers (PL0, PL1, and

PL2) are included in this study.

Further, the embodied emissions flow between sectors at PL0, PL1, and PL2 were also specified. For example, $\mathrm{E}_{\mathrm{ij}}^{1\to0}$ measure the emissions embodied in the inputs from layer 1 to produce the products in layer 2.s. As the SPA equations are used to calculate direct emissions in each production layer along the supply chain, an extension of SPA proposed by Skelton et al. (2011) was applied to portray specific discharge flows along supply chains. The embodied emissions flow down to PL2 can be expressed as

$$E_{ij}^{1\to0} = \hat{f}A\hat{Y} \tag{9}$$

$$E_{ij}^{2\to1} = \hat{f}A\widehat{AY} \tag{10}$$

where $E_{ij}^{1\to0}$ indicates discharge flows from sector *i* at PL1 to sector *j* at PL0; $E_{ij}^{2\to1}$ expresses emission flows from sector *i* at PL2 to sector *j* at PL1.

2.3 Data preparation

This study required two types of data: Chinese input-output tables and SO_2 emissions inventory for 2002, 2007, and 2012. The input-output data was obtained from China input-output table in 2002, 2007, and 2012 (National Bureau of Statistics of China, 2002, 2007, 2012), the latest available dataset. We note that the dataset has been widely used to analyze input-output of air pollutants emissions, carbon emissions, and energy consumption, etc (Huo et al., 2014; Meng et al., 2015; Chen et al., 2017). It includes 42 sectors in China. The sectoral SO_2 emissions for 2002, 2007, and 2012 were obtained from China Environment Statistical Yearbook (CESY) (National Bureau of Statistics of China, 2003, 2008, 2013a) and China Energy Statistical Yearbook (CENSY)(National Bureau of Statistics of China, 2003, 2008, 2013b). The CESY divides industry into 39 sectors, but does not involve agriculture and tertiary industry. Then we estimated emissions from agriculture and service sectors based on the energy consumption of each sector listed in CENSY, getting a 44-sector SO_2 emissions inventory. However, the sector classification of the emissions inventory is different from that of IO table; the emissions inventory divides the whole economy into 39 industrial sectors and 5 agriculture and service sectors, while the IO table divides the whole economy into 26 industrial sectors and 16 agriculture and service sectors. For consistency, we incorporated both the two sources into 28 sectors which were further incorporated into 8 aggregated sectors for convenient analysis, as shown in Tables 1, S1, and S2.

Table 1 Economic sector classification in this study.

Sector code	Sector	Aggregated sector	Aggregated sector code
T1	Agriculture products and services	Other industries	C8
T2	Coal mining products		
T3	Oil and gas exploration products		
T4	Metal mining products		
T5	Non-metallic minerals		
T6	Food and tobacco		
T7	Textile		
T8	Clothing and its materials		
T9	Wood products and furniture		
T10	Paper, education and sporting goods		
T11	Oil, coking and nuclear fuel products		
T12	Chemical products	Chemical products	C1
T13	Non-metallic mineral products	Non-metallic products	C2

T14	Metal smelting and rolling	Metal production	C3
T15	Metal products		
T16	General and special equipment	Machinery manufacturing	C4
T17	Transportation equipment		
T18	Electrical machinery and equipment		
T19	electronic equipment		
T20	Instrumentation		
T21	Other manufacturing products		
T22	Electricity, heat production	Power production	C5
T23	Gas production and supply		
T24	Water production and supply		
T25	Construction industry	Construction	C6
T26	Transport, storage and postal	Service industry	C7
T27	Accommodation, catering, wholesale and retail		
T28	Other industry	Other industries	C8

3 Results and discussion

3.1 Production- and consumption-based SO_2 emissions during 2002-2012

The production- and consumption-based SO_2 emissions for Chinese 28 sectors in 2002, 2007, and 2012 are presented in Fig. 1. The resolved total SO_2 emissions raised from 18,793 Gg in 2002 to 25,665 Gg in 2007, and then declined to 21,180 Gg in 2012, corresponding closely with the previous research for 1995-2014 (Yang et al., 2016b). The dominant emission sectors were quite different between production and consumption perspectives. From the point of production, electricity and heat production (EHP) always dominated SO_2 emissions; the EHP sector alone accounted for nearly half of the total emissions in 2002 and 2007 (41% and 48%, respectively), but declined to 38% in 2012 (Fig. 1). The tremendous demand of electricity spreading across nearly all economic sectors may be the main determinant. Also, coal-driven electricity and heat generation is the dominant manner for Chinese enterprises (Liu et al., 2015), and the high sulfur content in coal inevitably brought much SO_2 releases into atmosphere (Yang et al., 2016b; Yang et al., 2017a). The slight drop of EHP-driven emissions during 2007-2012 reveals that after 2007 the emission intensity of EHP has been much controlled. Installing end-of-pipe removal facilities in pollutant-intensive industries and closing down heavily polluting power plants may exert tremendous effects on reduction emissions for power generation (Yang et al., 2018).

Transport, nonmetal and metal were responsible for another quarter of SO_2 discharges; they accounted for 10%, 9%, and 8% of the total emissions in 2002. Among the three key sectors, the significance of metal production raised to 17% in 2012, while the transport declined to 7% in 2012. China is currently facing the overcapacity of iron and steel mainly due to the growing metal production (Dai, 2015; Zhou and Yang, 2016; Liu et al., 2017; Wang et al., 2017), also leading to the increase of SO_2 releases from this sector. The SO_2 from vehicles dropping by 21% during 2002-2012 primarily thanks to vehicle restrictions for the air quality, fuel economy standards raise and automobiles with lower emissions development (Meng et al., 2015). Together, the four sectors mentioned above contribute about three-fourths of China's man-made sulfur dioxide emissions. Production emissions from each of the remaining 24 industries are relatively small.

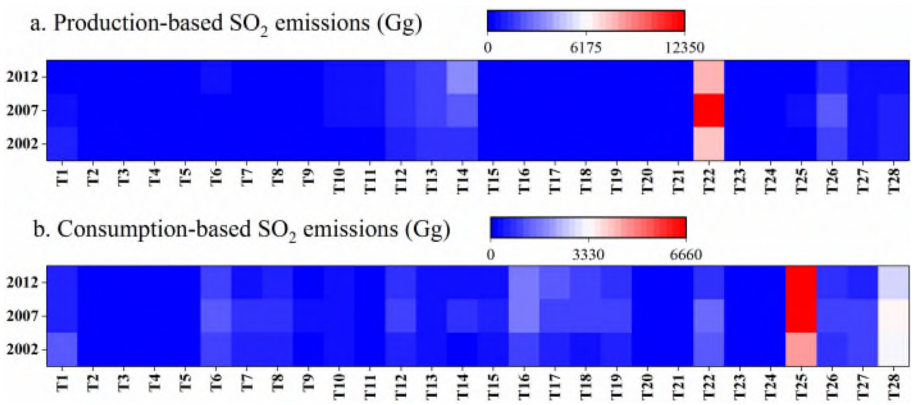


Fig. 1 Sectoral production- and consumption-based SO2 emissions in China during 2002-2012. The horizontal axis shows sector codes which are specified in Table 1, and the vertical axis indicates the time.

From the consumption perspective, construction contributed most for China's SO_2 discharges; it accounted for 25% of the overall emissions in 2002, afterwards enhanced to 30% in 2012. With the rapid urbanization in recent years, a large number of people poured into cities (Yang et al., 2017b; Guan et al., 2018; Wang and Zhao, 2018), leading to an increase in demand for housing in urban China (Jiao et al., 2017; Zhang et al., 2017b). The great migration definitely aggravated pollutant emissions from construction activity in China.

Further, the machinery manufacturing, services and other industry also played key roles in emitting SO_2, especially for other industry (covers information technology services, financial, real estate, rental and business services, scientific research and technical services, public facilities management, resident services, repairs and other services, education, health and social work, culture, sports and entertainment, and public administration) and general & special equipment manufacturing. Other industry accounted for 17% of the total emissions in 2002, and this figure continually declined into 13% in 2012, while general & special equipment emitted 5% of the total emissions in 2002, and this percentage consistently increased to 8% in 2012. The portion resulting is reasonable, as consumers in China become more prosperous than before, and they have larger purchasing power for durable goods, like computers, electrical equipment and transportation equipment, etc (Zhang et al., 2017c; Zhu et al., 2017). Meanwhile, following the improvement of Chinese residents' energy conservation awareness, more energy-saving products, like electricity saving lamps, energy-saving building materials, etc, were utilized (Lo, 2013; Lin and Wang, 2015; Sun et al., 2017), resulting in the less significance for pollutant emissions from other industry.

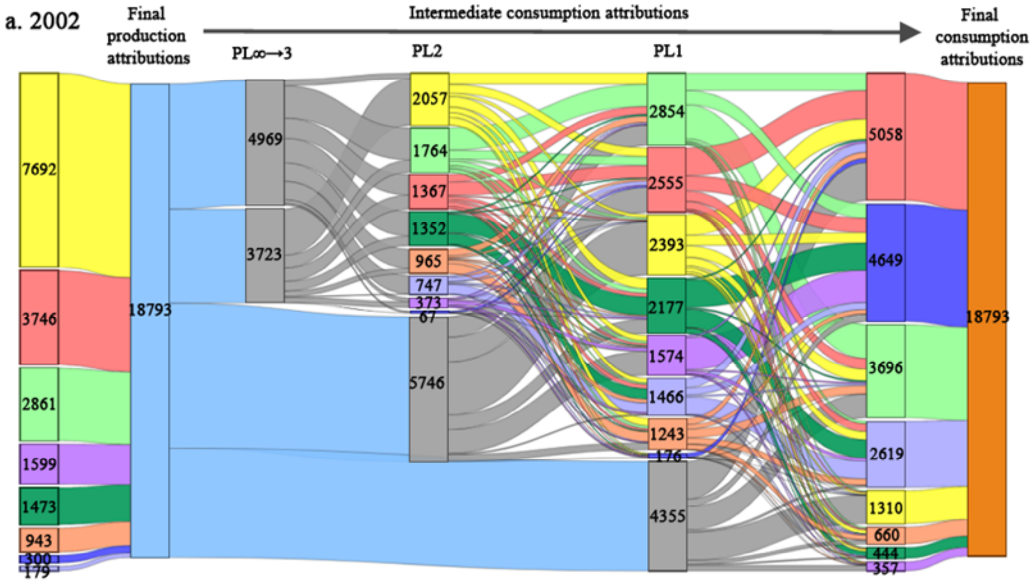
3.2 Embodied SO_2 emissions in different production layers during 2002-2012

To understand the discrepancies between production and consumption emissions and the relevant link between emissions in the production and the final products, we conducted an SPA. The SPA actually provides a network with an infinite number of pathways between sectors. To give a comprehensive picture of the teleconnection among sectors, we aggregated the original 28 sectors into 8 broad categories: Chemical, Nonmetal, Metal, Manufacturing, Power, Construction, Services, and Others (see Table 1), and then merged the impacts of the corresponding sectors in each production layer.

Fig. 2 shows the components of embodied and direct emissions at different layers (Tier 0, Tier 1, Tier 2, and Tier 3→∞) driven by the final consumption. The left-hand side of the map shows the sectoral composition of SO_2 emissions, and the right-hand side shows the final consumption attribution of SO_2 emissions, which correspond to the production- and consumption-based emissions described in Section 3.1. In addition to the previous findings, we note here that the second largest sector for production emissions changed from services in 2002 (20%) and 2007 (15%) to metal production (17%) in 2012. Coincidently, the three largest sectors for consumption-based emissions changed from services (27%)/construction (25%)/others (20%) in 2002 into construction (26%)/services (21%)/manufacturing (20%) in 2007, and further into construction (30%)/manufacturing (22%)/services (20%) in 2012. Considering the large expenditure for metal products in construction and manufacturing and the enhanced significance of construction and manufacturing in final demand, the production-based emissions from metal production inevitably increased.

The central part of Fig. 2 reveals the emissions in the production of intermediate inputs for each sector at PL1 and PL2. It can be obtained that the largest inputs to sectors at PL0 from PL1 were others (20%), services (18%), and power (17%) in 2002, and changed into metal (18%), power (17%), and others (16%) in 2007, and further changed into metal (22%), nonmetal (15%), and others (15%) in 2012. This indicates that in the first production layer, the dominate sector shifted gradually from services to metal sector, which was the result of the increasing demand for metal products in construction and manufacturing activities during the study period. At the second layer, the leading sectors in 2002 were power (24%), others (20%), and services (16%), and they changed into power (29%), others (20%), and metal (17%) in 2007, and further changed into power (23%), metal (21%), and others (18%) in 2012. Comparing the priority of metal in PL1, the significance of metal in PL2 weakened, but it also gradually reinforced during the study period, and replaced the services, becoming the second dominate sector at PL2 in 2012. The power sector always displayed the absolute leadership at PL2 during the study years. Considering the greatest amount of production-based emissions from power generation, it is obvious that power generation played its predominance starting from PL2 and continuing at the preceding production layers.

It can be roughly concluded from the above analysis that the embodied SO_2 emissions tended to change from the path (staring from consumption side to production side, and the same below): Services→Services→Power in 2002 to the path: Construction and Manufacturing→Metal and Nonmetal→Power in 2012, primarily due to the rise of construction industry resulting from the growing urbanization rate in China during the study period.



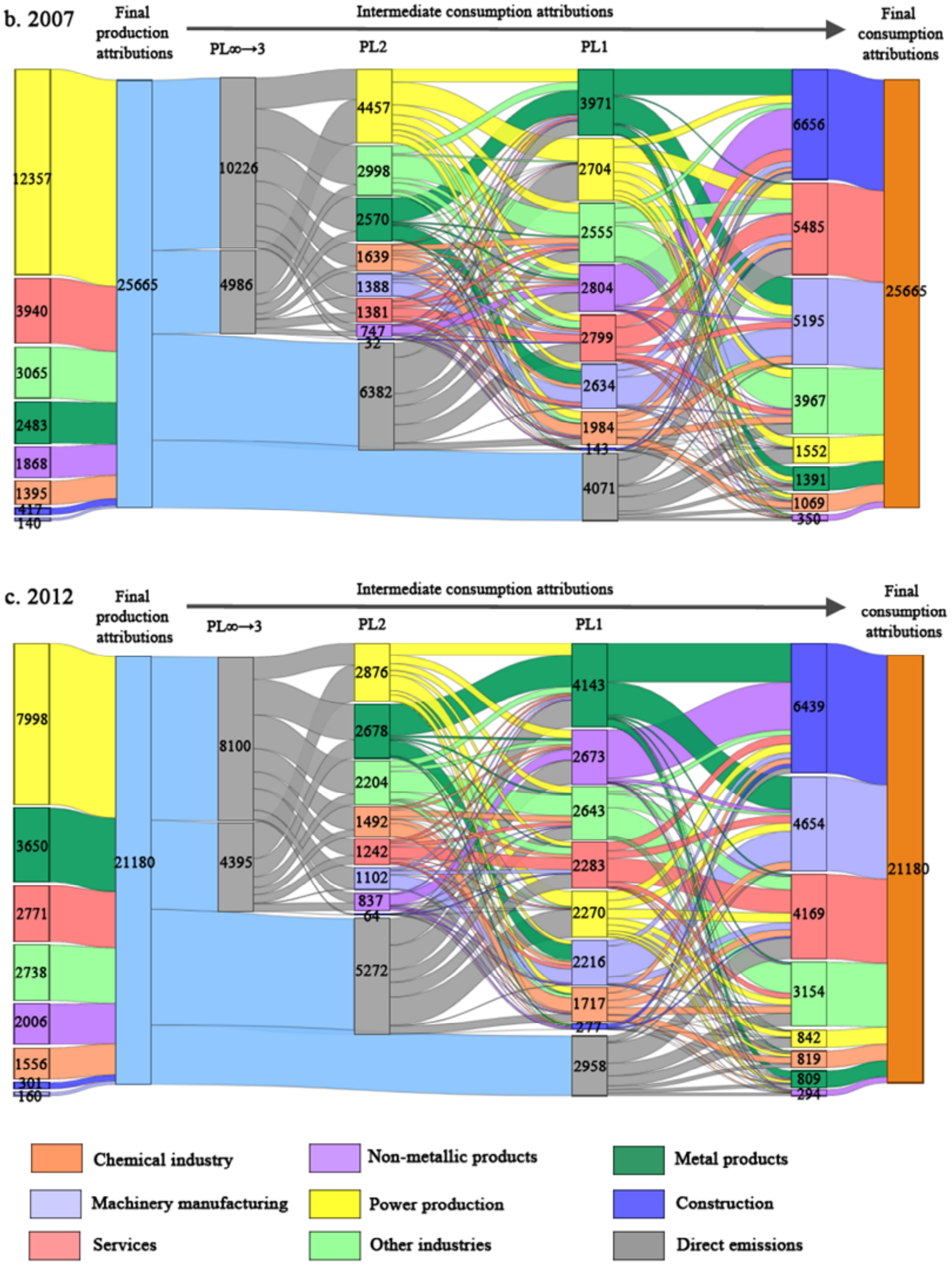


Fig. 2 Map of embodied SO_2 emission flows for China's sectors in 2002, 2007, and 2012. Diagram flows from left to right are of Sankey-types, where the widths of indicated flows represent their magnitude in Gg SO_2. Direct emissions released by each sector at PL0, PL1, and PL2 are indicated in the bottom of each production layer by dark gray flows linking back to the final production attribution. Contributions from PL3 and all earlier layers have been combined to provide a comprehensive view of the system.

Fig. 3 displayed the direct SO_2 emissions instigated by final consumption of each sector at each layer. It can be seen that the direct emissions of each sector along the supply chains changed little during the study period. Only power and nonmetal had a significant shift. In 2002, direct emissions from power primarily happened at Tier 0 (80%), while in 2007 and 2012, it dropped into only 33%, and exerted more emissions on other tiers (67% totally). Direct emissions from nonmetal also decreased from 51% at Tier 0 in 2002 to 36% at Tier 0 in 2012, and transferred more releases on earlier layers. We also note from Fig. 4 that up to 98% of emissions from manufacturing did not emit directly, but embodied in higher tiers. Similarly, only 5% emissions of contribution occurred directly, and production of building materials (e.g., cement, steel and glass) in the first tier as well as preparation of additional higher tiers' input account for 95% emissions. This indicates that embodied emissions were nearly 18 times more than direct emissions when one unit of construction output value was produced. This is due, primarily, to intensive investment in construction, which accounted for more than 50% of China's total investment in 2012 (National Bureau of Statistics of China, 2013). Infrastructure investment is an important driving force for China's economic growth (Feng et al., 2013; Yang et al., 2018).

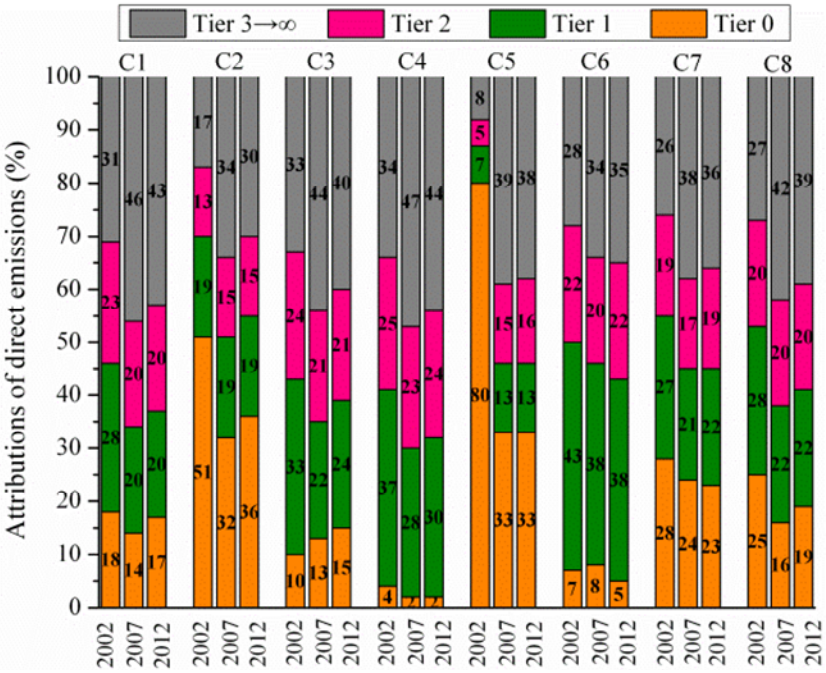


Fig. 3 Distributions of direct SO_2 emissions in production tiers along supply chains from eight aggregated sectors in 2002, 2007, and 2012. (C1: Chemical, C2: Nonmetal, C3: Metal, C4: Manufacturing, C5: Power, C6: Construction, C7: Services, C8: Others.)

3.3 Embodied SO_2 emission flows between different production layers during 2002-2012

In this section, we specifically examined the virtual SO_2 emission flows between sectors at different layers. The embodied emissions for each sector in PL1 and PL2 were calculated by using the same direct requirement coefficient according to Eqs (7), (9) and (10), so $E_{ij}^{1\to0}/E_j^0$ is equal to $E_{ij}^{2\to1}/E_j^1$ in the same year. This means that the proportion of sector j at PL0 from sector i at PL1 is equal to the proportion of sector j at PL1 from sector i at PL2 in the same year. With this knowledge, we calculated the proportions of all sectors' intermediate inputs to each sector at final demand. For construction, merely 6% of direct emissions occurred at PL0 in 2002 and 2007, and further declined to 4% in 2012, while the inputs purchased from nonmetal sector at PL1 had very high embodied emissions, accounting for 27% (1,276Gg), and metal production 23% (1,090 Gg) in 2002, and further increased to 37% and 30% respectively in 2012. This indicates that nonmetal (e.g. cement, and glass) and metal products were the primary inputs for construction, which supports the estimation in Section 3.2. In view of the increasingly strong dependence of construction on metal and nonmetal, the demand for metal and nonmetal products will rise if construction industry continues to maintain high growth in the following years.

It is a quite different story for the power generation sector: direct emissions at PL0 accounted for 86% (1,128 Gg), with a further 6% (82 Gg) from upstream inputs, and the remaining 8% (100Gg) from inputs from other sectors at PL1 in 2002, and the ratios changed into 58%, 35% and 7% respectively in 2012. The changes provide evidence that power generation induced less emissions in other sectors, but emitted gaseous pollutants directly; however, the direct emissions from power generation decreased significantly, and it transferred this burden to its intra-industry inputs. This means that the mining of fossil fuel and the building and maintenance of power plants demand a larger percentage of additional power and equipment inputs than before. For example, the demand for one kilowatt of electricity would generate a greater ratio of electricity than before to fulfil this consumption and to ensure the associated production activities along the supply chain (Meng et al., 2015).

From Fig. 4, the top two embodied emission sectors for each sector changed little during 2002-2012, but the contributions of the sectors varied significantly. For instance, the final demand for chemical triggered a larger proportion of embodied emissions in itself (from 41% in 2002 to 51% in 2012), the final demand for nonmetal products brought a greater percentage of embodied emissions in itself (from 20% in 2002 to 35% in 2012), and power generation rely more on power inputs from 45% in 2002 to 83% in 2012. Furthermore, six sectors (chemical, nonmetal, metal, power, services, and others) held significant embodied missions from power, while only manufacturing and construction depended more on metal, nonmetal and manufacturing, which was the reason why power generation always showed overwhelming superiority in production emissions during the study period.

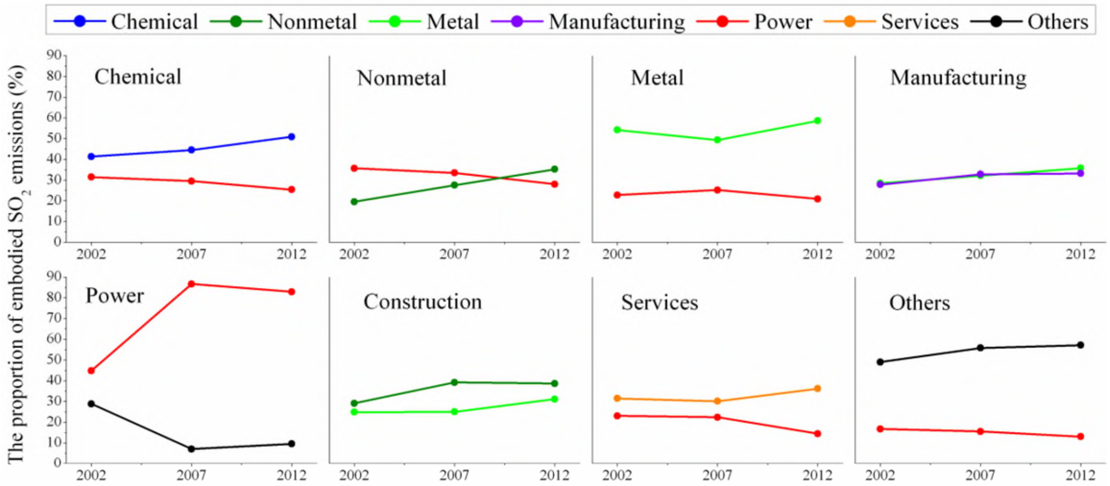


Fig. 4 Changes in embodied SO_2 emissions from top two sectors purchased by each of the eight aggregated sectors during 2002-2012.

Table 2 sets out the top ten highest paths to demand-driven manufacturing processes. The supply chain which covers China's biggest SO_2 emissions in 2002 occurred at PL0, with "Services" accounting for 8% of the total emissions. Six of the top 10 paths were related to electricity-related activities, while service industry emerged in five top ranking paths in 2002. By contrast, in 2012, the largest emissions along the supply chain changed into “Construction→ Nonmetal” which took 5% of the total emissions. There were also 6 routes involving power generation among the top 10 ranking paths, but the construction sector (appeared in four top ranking paths in 2012) replaced the services sector, becoming the second significant sector in 2012. Table 2 shows that sulfur dioxide emissions from higher-level electricity production in the supply chain was the earliest implicit emissions of most final consumption.

This suggests that controlling construction activities and cutting down end-of-pipe discharges in the process of power generation are the most radical cure to reduce SO_2 emissions in China.

Table 2 The top ten paths for SO_2 emissions in 2002, 2007, and 2012, starting from final demand for one sector and ending with final production for one sector.

Year	Rank	Tier	Contribution (%)	Path
2002	1	0	8.03	Services
	2	0	6.00	Power
	3	0	5.04	Other industries
	4	3	4.79	Services-Power-Power-Power
	5	1	4.80	Construction-Nonmetal
	6	1	3.85	Services-Power
	7	2	3.33	Services-Power-Power
	8	3	2.70	Other industries-Power-Power-Power
	9	3	2.34	Construction-Power-Power-Power
	10	1	2.29	Services-Services
2007	1	3	6.23	Services- Power-Power-Power
	2	0	5.90	Services
	3	3	4.24	Manufacturing- Power-Power-Power
	4	3	4.04	Power-Power-Power-Power
	5	1	3.92	Construction-Nonmetal
	6	3	3.63	Others-Power-Power-Power
	7	0	3.46	Power
	8	3	3.42	Construction-Power-Power-Power
	9	0	2.50	Others
	10	2	2.47	Services-Power-Power
2012	1	1	5.02	Construction-Nonmetal
	2	0	4.78	Services
	3	3	4.11	Services- Power-Power-Power
	4	3	3.98	Construction-Power-Power-Power
	5	3	3.61	Manufacturing-Power-Power-Power
	6	0	3.05	Others
	7	0	2.95	Others-Power-Power-Power
	8	1	2.92	Construction-Metal
	9	3	2.75	Construction-Metal-Power-Power
	10	3	2.64	Power-Power-Power-Power

4 Conclusion and policy implications

China is one of the world's largest emitters of atmospheric pollutants, and each economic sector in China is interdependent and linked to air pollutant emissions through supply chains. Previous research has explored the embodied pollutant emissions along supply chains in China, but few related to dynamic changes of this process. The study utilized EEIOA and SPA to examine the dynamic variation of SO_2 emissions embodied in 28 economic sectors in Chinese supply chains during 2002-2012. The main conclusions are summarized as follows:

(1) The total SO_2 emissions in China raised from 18,793 Gg in 2002 to 25,665 Gg in 2007, and then declined to 21,180 Gg in 2012. From the point of production, electricity and heat production (EHP) dominated SO_2 emissions; but the significance of EHP decreased from 41% in 2002 to 35% in 2012. From the consumption perspective, construction contributed most for China’s SO_2 discharges; its proportion increased from 25% in 2002 to 30% in 2012.

(2) Aggregating the original 28 sectors into 8 broad categories, the SPA results show that the embodied SO_2 emissions tended to change from the path (staring from consumption side to production side): “Services→Services→Power” in 2002 to the path: “Construction and Mmanufacturing→Metal and Nonmetal→Power” in 2012. Nonmetal and metal products were the primary inputs for construction. Only 5% emissions from construction belonged to direct releases, indicating that embodied emissions were nearly 18 times more than direct emissions when one unit of construction output value was produced. Manufacturing had a similar structure with construction; only 2% emissions of it happened directly, and other 98% emissions occurred at higher tiers.

(3) Metal-driven emissions raised dramatically in the supply chains during 2002-2012; at the first production layer, it increased from 15% in 2002 to 22% in 2012, and production emissions from it also increased from 9% in 2002 to 17% in 2012, which were all primarily due to the large expenditure for metal products in construction and manufacturing activities. Similarly, emissions from nonmetal products also enhanced from 11% in 2002 to 15% in 2012 at the first layer, which was the result of increasing demand for nonmetal products in construction sector during these years. “Construction→Nonmetal” replaced “Services” becoming the largest emission path in 2012.

(4) As the largest production–based emission sector, power generation had little embodied emissions from other sectors, but primarily emitted gaseous pollutants directly. However, It tended to transfer this burden to its intraindustry inputs in 2012. Final consumption for most sectors also ultimately produced SO_2 emissions from power generation in the higher tiers, making the largest production emissions come from power sector.

To abate air pollutant emissions in China, previous studies had proposed numerous strategies, e.g., cleaner fuels application, industry structure transformation, and end-of-pipe treatment, etc. On account of the results of this study, we proposed the following suggestions from supply chain perspective. First, power generation, especially electricity and heat production should be controlled or coal should be replaced by cleaner energy to be the dominant fuel in generating electricity. As described above, power sector took nearly half of the production SO_2 emissions during the study years. Therefore, cutting down emissions intensity of power generation could greatly deplete SO_2 emissions nationally. Second, construction activities should be planned reasonably, and haphazard investment and redundant construction should be prevented. From this study, construction was the biggest source for consumption SO_2 emissions; nearly one third of the emissions were instigated by construction and this figure continued to increase in recent years. This is different from the beginning of the 21 century when the service sector dominated the consumption emissions. The rapid urbanization in China was responsible for the marked change. But if the government strictly control the housing market, pollutant emissions from construction might be greatly mitigated. Third, steel production should be reduced, not only because the large demand for power in metal production, but also because the over capacity of the iron products in China. In reality, metal production is currently hardly profitable in inland China, hence changing steel industry to other industries and extending the steel production chain to increase its added value are robust approaches for both emission reduction and economic development.

The analysis framework developed in this study could be applied in other regions to distinguish the different pollutant emission sources along supply chains. It also offers a complete understanding of embodied emissions from both the terminal and intermediate perspectives. Corresponding strategies could then be developed by considering the local context. Future research opportunities exist to further explore the driving forces of variations in the pollutant emission flows via supply chains. Additionally, emission intensity embodied in the interconnected production layers could also be further studied in the perspective of environmental economics.

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