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LETTER

Tracing Primary PM_{2.5} emissions via Chinese supply chainsJing Meng¹, Junfeng Liu¹, Yuan Xu² and Shu Tao¹¹ Laboratory for Earth Surface Processes, College of Urban and Environmental Sciences, Peking University, Beijing, People's Republic of China² Department of Geography and Resource Management, and Institute of Environment, Energy and Sustainability, The Chinese University of Hong Kong, Hong Kong, People's Republic of ChinaE-mail: jfliu@pku.edu.cn**Keywords:** PM_{2.5}, supply chain, input–output analysis, structural path analysis, principal component analysisSupplementary material for this article is available [online](#)RECEIVED
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**Abstract**

In this study, we examine a supply-chain approach to more effectively mitigate primary PM_{2.5} emissions in China from the perspectives of production, consumption and their linkages using structural path analysis. We identify the pattern of all supply chain paths using principal component analysis. To address the severe haze problems in China, it is important to understand how final demand purchase initiates production processes and ultimately leads to primary PM_{2.5} emission. We found that consumers' demands on power and transportation mainly induce direct emissions, quite different from the demands on construction, industry and service products which largely drive emissions in upstream activities. We also found that nearly 80% of the economic sectors in China follow a similar pattern in generating primary PM_{2.5} emissions in electricity, cement and the ferrous metal industries; but only the construction sector increases the release of PM_{2.5} due to the production of non-metallic mineral products. These findings indicate that further reduction of end-of-pipe emissions in the power and transportation sectors will facilitate cleaner production in almost all the economic sectors. However, for urbanization induced emissions, China should mitigate PM_{2.5} emissions through the supply chain of construction, either severely reducing its life-cycle intensity or carefully planning to avoid extensive, unnecessary building activity.

1. Introduction

Ambient particulate matter with an aerodynamic diameter of 2.5 μm or less (PM_{2.5}) affects visibility (Menon *et al* 2002, Huang *et al* 2006), the climate (Huang *et al* 2007, Bond *et al* 2013) and human health (Delfino *et al* 2005, Timonen *et al* 2005), creating the need to better understand the sources of PM_{2.5} and to effectively mitigate them.

Ambient PM_{2.5} originates from the incomplete combustion of fossil fuel or biofuel, oxidation of precursor gases such as SO₂ and VOCs, and natural emissions from biomass burning and dust mobilization (Stevens and Boucher 2012, Wang *et al* 2012, Bond *et al* 2013). Due to rapid industrialization, anthropogenic PM_{2.5} emissions in China have increased by nearly 40% during the past decade, and are mainly generated by power and cement production from the

production perspective (Timonen *et al* 2005, Lei *et al* 2011). However, from the consumption point of view (i.e., the life cycle emissions of goods and services attributed to consumers), this rapid increase of PM_{2.5} emissions is mainly driven by the expansion of construction and metal/machinery industries (Guan *et al* 2014, Huo *et al* 2014, Lin *et al* 2014). Previous studies have quantified the discrepancy between production-based and consumption-based air pollution inventories in China (Huo *et al* 2014, Zhao *et al* 2014, Jiang *et al* 2015). Thus, revealing the PM_{2.5} emissions along the supply chain path can facilitate understanding how PM_{2.5} emissions 'flow' from producers to consumers (Skelton *et al* 2011).

One way to trace the complex supply chain of the production process initiated by a given final demand is based on structural path analysis (SPA; Defourny and Thorbecke 1984, Skelton *et al* 2011). By using SPA, it is

possible to follow the production network from final demand through the domestic production processes and, finally, extract the critical paths that drive dominant life-cycle emissions (Lenzen 2002, Peters and Hertwich 2006a, Peters and Hertwich 2006b, Lenzen *et al* 2012, Oshita 2012, Kanemoto *et al* 2014). Supply chain analysis has become an important tool in addressing these questions (Schmidt 2008a, 2008b, Skelton *et al* 2011). There is still a lag in relation to knowledge concerning the supply chain of PM_{2.5} emissions (Hoekstra and Wiedmann 2014, O'Rourke 2014), despite the merit and appeal of SPA.

In this study, we construct China's primary PM_{2.5} emission inventories in 2007 from both production and consumption perspectives and use SPA to identify the associated linkages. The SPA is applied using an input–output model for the Chinese economy. Furthermore, when performing the system input–output analysis (Chen *et al* 2007, Chen *et al* 2010, Zhang *et al* 2013), the embodied emission intensity, defined as total direct and indirect emissions released along the whole supply chain in order to generate unit monetary output, can be decomposed into a spectrum of embodied intensity contributions (EICs) from all sectors. Comparing the similarity of EIC spectrums between different sectors will help to understand the pattern of all supply chain paths that drive PM_{2.5} emissions. To address this issue, we adopt principal component analysis (PCA) to identify the major features of the composition and the underlying pattern of the embodied PM_{2.5} intensities.

2. Methods

2.1. Primary PM_{2.5} emissions

Primary PM_{2.5} emissions, also termed production-based emissions, denote the direct emissions from specific production activity. In this study, we construct China's primary PM_{2.5} emissions with sufficient sectoral detail for China in the year (2007) based on China's official energy use statistics. The sources of PM_{2.5} are classified into three categories according to the mechanisms that generate PM_{2.5}, namely, stationary combustion, industrial processes and mobile sources (open field biomass burnings, such as wild fires and agricultural waste burning, are not included). The stationary combustion sources cover all economic sectors except transportation (i.e., the mobile source) and include nine types of fuel use (coal, coke, kerosene, diesel, crude oil, gasoline, fuel oil, natural gas and other petroleum products). Due to the lack of sectoral information on biofuel consumption (i.e., mostly used for residential cooking and heating, accounting for less than 25% of China's anthropogenic PM_{2.5} emission (Lei *et al* 2011), emissions from biofuel use are not included in this study. The industrial process sources cover 15 products/processes in metallurgical industries, chemical industries and non-metallic mineral

production, among which cement production and steel production are most important contributors.

For sources from stationary combustion and industrial processes, PM_{2.5} emissions are calculated based on the activity rate (energy consumption or material production), technology distribution, unabated emission factor (EF) and the penetration of emission control technologies, as well as the removal efficiency of these technologies (Klimont *et al* 2002, Zhang *et al* 2007, Lei *et al* 2011). Therefore, the PM_{2.5} emission from Sector j (E_j) is estimated as:

$$E_j = \sum_k A_{j,k} \left[\sum_m X_{j,k,m} F_{j,k,m} \right], \quad (1)$$

$$F = F_{\text{TSP}} f \sum_n C_n (1 - \eta_n), \quad (2)$$

where k is either fuel or product type; A is the activity rate; X_m is the share of fuel or production processed by a specific technology m ($\sum_m X_m = 1$) in Sector j ; F is the effective EF after adjustment by emission control devices, whereas f represents the mass fraction of PM_{2.5} relative to TSP; F_{TSP} stands for the unabated EF of TSP before emission control; C_n represents the penetration of PM control technology n (i.e., $\sum_n C_n = 1$); η_n represents the removal efficiency of control technology n .

In this study, the energy consumption and industrial product data are acquired from the China Statistic Yearbook CSY (2009). The coverage of combustion and processing technology in each sector is collected from a variety of China's statistics compiled by various industrial associations and technology reports (SEPA 1996, Lei *et al* 2011, Zhang *et al* 2000, Zhang *et al* 2006). The EFs adopted for stationary combustion and industrial processes are described in table 1.

For mobile sources (i.e., road vehicles, rail vehicles, shipping vessels, aircraft and agricultural and construction machinery), the PM_{2.5} emissions are calculated by multiplying the fuel consumption and EF. Fuel use data are acquired from CSY (2009) and the China Transportation Statistical Yearbook CTSY (2009). The EF for road vehicles, rail vehicles, shipping vessels and aircraft (see table 2) are adopted from Sugiyama *et al* (Sugiyama *et al* 2009). Generally, unregulated motor vehicles such as construction and agricultural machinery are likely to emit more particles than other ordinary vehicles, we followed earlier work and assumed freight and special-purpose vehicles have equal EFs (Sugiyama *et al* 2009).

2.2. Input–output model

An environmental input–output model is used to link the final consumption of goods and services to direct PM_{2.5} emissions through the intricate supply chain (Costello *et al* 2011, Erickson *et al* 2012). As initially described by Leontief (1970), the original input–output monetary flows among n sectors are balanced as:

Table 1. Unabated EF for PM_{2.5} from stationary combustion and industrial processes.

Category	Fuel/product	Technology	EF
Industry (g kg ⁻¹)	Coal	fluidized bed	1.89–5.40 (Zhang 2006)
	Diesel fuel		0.50 (USEPA 1995)
	Kerosene		0.90 (USEPA 1995)
	fuel oil		0.67 (USEPA 1995)
	Gas		0.17 (USEPA 1995)
Power genera- tion (g kg ⁻¹)	Coal		5.25–12.00 (Zhang 2006)
	Diesel fuel		0.50 (USEPA 1995)
	Kerosene		0.90 (USEPA 1995)
	fuel oil		0.62 (USEPA 1995)
	Gas		0.17 (USEPA 1995)
Residential (g kg ⁻¹)	Coal		1.89–6.86 (Zhang 2006)
	Kerosene		0.9 (USEPA 1995)
	Diesel fuel		0.5 (USEPA 1995)
	fuel oil		0.28 (USEPA 1995)
	Gas		0.17 (USEPA 1995)
Industrial process (g kg ⁻¹)			
Metallurgical	Sinter		2.62 (SEPA 1996)
	Pig iron		6.00 (SEPA 1996)
	Steel	Open hearth, furnace	13.80 (SEPA 1996)
		Electric arc furnace	6.02 (SEPA 1996)
		Basic oxygen furnace	10.45 (Klimont <i>et al</i> 2002)
	Casting		8.48 (SEPA 1996)
	Aluminum		5.20–18.28 (SEPA 1996)
	Alumina		297.13 (SEPA 1996)
	Other non-ferrous	meta	246.00 (SEPA 1996)
	Mineral products	Cement	
Glass			2.94–10.69 (SEPA 1996)
Bricks			0.27 (SEPA 1996)
Lime			1.40 (Klimont <i>et al</i> 2002)
Chemical	Coke		5.22 (SEPA 1996)
	Refined oil		0.10 (Klimont <i>et al</i> 2002)
	Fertilizer		0.86 (SEPA 1996)
	Carbon black		1.44 (Klimont <i>et al</i> 2002)

$$X = AX + Y + E - M, \quad (3)$$

where X represents a vector of total economic output in each sector; A is the normalized technology coefficients matrix or direct requirement coefficient matrix, whose element a_{ij} represents the required input from Sector i to produce unit output in Sector j ; Y is a vector of domestic consumption, consisting of domestically-produced portion (C^d) and imported final consumption (C^m). E and M , respectively, represent the vectors of exports and imports; AX represents the intermediate use during the production phase, including products supplied domestically ($A^d X$), and products supplied by foreign partners ($A^m X$).

In this analysis, imports imbedded in the Chinese input–output table are removed to isolate the domestic supply chain. This method eliminates imports from the intermediate inputs and domestic demand (Y) and allows the estimation of local emission released due solely to domestic consumption. We follow the approach applied in previous studies (i.e., Weber

et al 2008) and assume that each economic sector and domestic demand category utilize sectoral imports in the same proportions (Weber *et al* 2008, Guan *et al* 2009, Guan and Barker 2012, Guan *et al* 2014, Huo *et al* 2014, Lin, *et al* 2014). Thus equation (3) can be expressed as:

$$X = (A^d + A^m)X + C^d + C^m + E - M, \\ = A^d X + C^d + E + A^m X + C^m - M. \quad (4)$$

Imports M are used for final consumption (C^m) and intermediate consumption ($A^m X$), namely:

$$M = A^m X + C^m. \quad (5)$$

Therefore, rearranging equation (4):

$$X = (I - A^d)^{-1} (C^d + E), \\ = (I - A^d)^{-1} C^d + (I - A^d)^{-1} E. \quad (6)$$

Table 2. PM_{2.5} emission factors for mobile sources.

Mobile sources	Fuel type	Emission factor (kg Tj ⁻¹) (Sugiyama <i>et al</i> 2009)
Passenger cars	Diesel	35.5
Buses	Diesel	58.2
Freight and special-purpose vehicles	Diesel	63.1
Trains	Diesel	73.8
	Coal	6.45
Shipping vessels	Diesel	44.2
	Heavy oils	79.3
Aircraft	Jet fuel	16.2

Local emissions in relation to domestic consumption (F_c) (Peters and Hertwich 2008, Erickson *et al* 2012, Steen-Olsen *et al* 2012) and exports (E_c) are derived as:

$$F_c = \varepsilon^d (I - A^d)^{-1} C^d,$$

$$E_c = \varepsilon^d (I - A^d)^{-1} E, \quad (7)$$

where ε^d is direct emission intensity, representing the primary PM_{2.5} emission associated with one unit industry output. I is the identity matrix. $(I - A^d)^{-1}$ here is the revised Leontief inverse matrix, whose element ∂_{ij} tracks the overall direct and indirect input along the domestic supply chain from Sector i while generating unit output in Sector j . The term $\varepsilon^d(I - A^d)^{-1}$, therefore, represents the embodied intensity (ε), a row vector with each element (ε_j) representing the embodied emission per domestic consumption from Sector j . In other words, ε_j denotes the total direct and indirect emissions generated through the whole supply chain to produce the unit product or service in Sector j . Therefore, the relationship between the embodied intensity ε and direct intensity ε^d follows:

$$\varepsilon_j = \varepsilon_1^d \partial_{1j} + \varepsilon_2^d \partial_{2j} + \dots + \varepsilon_n^d \partial_{nj}. \quad (8)$$

To match the classification of sectors from different data sources, the original input–output table for China in 2007 (CSY 2008) (with 135 sectors) is merged into 43 sectors. The abbreviations and descriptions of these aggregated sectors are presented in table 3.

2.3. Structural path analysis

SPA performed in this study is based on the matrix A^d discussed in section 2.2. The real power of SPA is to analyse the production network through inter-sector flows, and rank paths according to their generation of PM_{2.5} emissions, from which it is able to identify the key areas of the production network that require improvements (Defourny and Thorbecke 1984, Suh and Heijungs 2007, Skelton *et al* 2011). Recently, increasing studies have used SPA to identify important supply chains and their associated origins and destinations in a certain country or international trade flows (Peters and Hertwich 2006a, Peters and Hertwich

2006b, Lenzen *et al* 2007, Lenzen *et al* 2012, Kanemoto *et al* 2014).

In general SPA, the revised Leontief inverse in equation (7) is expanded using Taylor series approximation that is given by (Waugh 1950) as:

$$L = (I - A^d)^{-1}$$

$$= I + A^d + (A^d)^2 + (A^d)^3 + \dots (A^d)^t \quad (9)$$

On the right-hand side of equation (9), each element in the expansion denotes a different production tier. In this study, we calculate the PM_{2.5} embodied in domestic demand and exports which drive local emissions (i.e., $y = C^d + E$) as:

$$\varepsilon^d (I - A^d)^{-1} y = \varepsilon^d I y + \varepsilon^d A^d y + \varepsilon^d (A^d)^2 y$$

$$+ \varepsilon^d (A^d)^3 y + \dots \varepsilon^d (A^d)^t y \quad (10)$$

where $\varepsilon^d (A^d)^t y$ represents the contribution of emissions from the t th production tier. For example, assuming the case where y is a demand for a laptop: $\varepsilon^d I y$ is the PM_{2.5} emitted in the production of the laptop by the laptop manufacturer. To produce the laptop, the laptop manufacturer needs to buy inputs from other industries ($A^d y$) and these industries generate $\varepsilon^d A^d y$ of PM_{2.5}. In turn, these industries also need inputs (i.e., $A^d(A^d y)$) and meanwhile $\varepsilon^d (A^d)^2 y$ of PM_{2.5} is released. And so on and so forth, the infinite expansion of power series continues. Thus, PM_{2.5} emission in the zeroth tier is the emission during the assembly phase of the laptop. PM_{2.5} in the first tier is the PM_{2.5} emission associated with producing the parts needed by the laptop manufacturer. PM_{2.5} emission in the second or higher tier is the emission to produce the inputs for the components in the supply chain.

The quantity of nodes in the production network increases exponentially with each tier. There are n^{t+1} nodes in each tier where t is the tier and n is the number of sectors in the economy. For example, the n^3 second-tier nodes are evaluated as $\varepsilon_k^d A_{kj}^d A_{ji}^d y$; and denote the path from $i \rightarrow j \rightarrow k$. The same pattern continues for all tiers.

In practice, it is time consuming and impossible to evaluate the infinite number of nodes in the tree. The value of input nodes decreases with path length; the tree is generally ‘pruned’ when the contribution from the sub-tree below the node is below a specified threshold. Using this tree-pruning concept a dynamic tree data structure is constructed and only the relevant production paths are included. This technique has proved invaluable in sorting the production paths according to the environmental impact (Lenzen 2007).

2.4. Principal component analysis

Equation (8) indicates that a sector’s embodied emission intensity is composed of direct intensities from all sectors in an economic system. In principle, the

Table 3. Sector code, abbreviation and description of the aggregated 43 sectors. The 43 sectors are subdivided into six categories: agriculture (Sector 1), industry (Sectors 2–36), power (Sectors 37–39), construction (Sector 40), transportation (Sector 41) and service (Sectors 42–43).

Code	Abbreviation	Sector	Description
1	AGR	Agriculture	Agriculture, forestry, fishery and water conservancy
2	MWC	Coal	Mining and washing of coal
3	EPG	Petroleum and gas	Extraction of petroleum and natural gas
4	MPF	Ferrous metal	Mining and processing of ferrous metal ores
5	MPN	Non-ferrous metal	Mining and processing of non-ferrous metal ores
6	MPO	Non-metal ores	Mining and processing of non-metal ores and other ores
7	PFA	Agricultural products	Processing of food from Agricultural Products
8	MFI	Foods	Manufacture of foods
9	MFB	Beverages	Manufacture of beverages
10	MFT	Tobacco	Manufacture of tobacco
11	MFE	Textiles	Manufacture of textiles
12	MFW	Clothing products	Manufacture of clothing, footwear and caps
13	MFL	Leather products	Manufacture of leather, fur, feather and related products
14	PTM	Wood products	Processing of timber, manufacture of wood, bamboo, rattan, palm, and straw products
15	MFF	Furniture	Manufacture of furniture
16	MPP	Paper products	Manufacture of paper and paper products
17	PRM	Recording media	Printing, reproduction of recording media
18	MFA	Cultural articles	Manufacture of articles for culture, education and sport activities
19	PPC	Petroleum products	Processing of petroleum, coking, processing of nuclear fuel
20	MRC	Chemical products	Manufacture of raw chemical materials and products
21	MFM	Medicines	Manufacture of medicines
22	MCF	Chemical fibres	Manufacture of chemical fibres
23	MFR	Rubber	Manufacture of rubber
24	MFP	Plastics	Manufacture of plastics
25	MNM	Non-metallic mineral products	Manufacture of non-metallic mineral products
26	SPF	Ferrous metals products	Smelting and pressing of ferrous metals
27	SPN	Non-ferrous metals products	Smelting and pressing of non-ferrous metals
28	MMP	Metal products	Manufacture of metal products
29	MGP	General purpose machinery	Manufacture of general purpose machinery
30	MSP	Special purpose machinery	Manufacture of special purpose machinery
31	MTE	Transport equipment	Manufacture of transport equipment
32	MEM	Electrical machinery	Manufacture of electrical machinery and equipment
33	MCE	Electronic equipment	Manufacture of computers and other elect. equipment
34	MMI	Cultural machinery	Manufacture of measuring instruments and machinery for cultural activity and office work
35	MAM	Artwork	Manufacture of artwork and other manufacturing
36	RDW	Waste	Recycling and disposal of waste
37	PSE	Power generation	Production and supply of electric power and heat power
38	PSG	Gas	Production and supply of gas
39	PSW	Water	Production and supply of water
40	CSI	Construction	Construction industry
41	TSP	Transportation	Transport, storage and post
42	WRT	Trades and hotels service	Wholesale and retail trades, hotels and catering services
43	OSI	Other service industry	Other service industry

embodied intensity is the sum of contributions from all sectors, but scaled by the Leontief inverse matrix (i.e., the transformed intermediate flows of input). Therefore, each term on the right hand side of equation (8) measures the magnitude of the EIC from itself and other sectors (Lin and Sun 2010). To compare the pattern of interdependence of EICs between sectors, we conduct a PCA on these decomposed sectoral $PM_{2.5}$ emission intensities (i.e., EICs) and derive the empirical orthogonal functions (EOFs).

The EOFs (also termed ‘principal component (PC) loadings’) represent the eigenvectors of the correlation matrix (Wilks and Haman 1996) of the

normalized EICs and denote the independent modes of sectors. The eigenvalues of each eigenvector is the amount of variance explained by the eigenvector. Generally, first few EOFs can represent much of the variance, making PCA a powerful tool to screen out the most representative variation patterns among variables for a data set. Projection of the sectoral intensity onto the EOFs defines the PCs (also referred to as PC scores; Wilks and Haman 1996). These PC scores show the sectors’ most representative distribution of EICs associated with the EOF, and thereby depict the general feature of an economic system that generates $PM_{2.5}$ emissions.

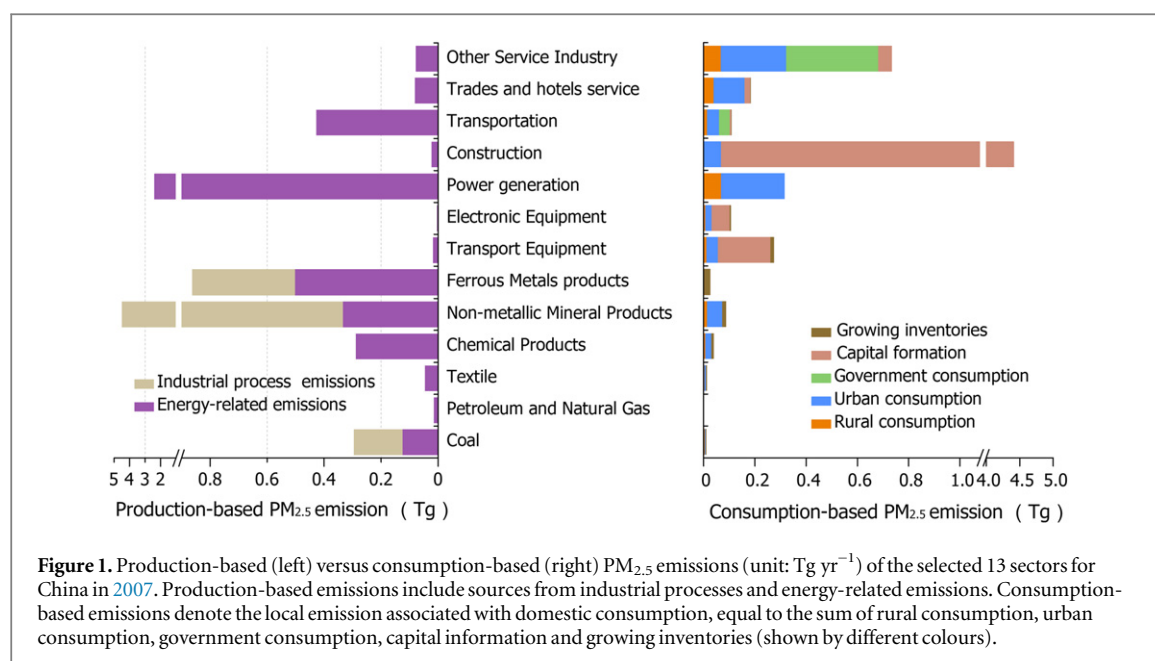


Figure 1. Production-based (left) versus consumption-based (right) PM_{2.5} emissions (unit: Tg yr⁻¹) of the selected 13 sectors for China in 2007. Production-based emissions include sources from industrial processes and energy-related emissions. Consumption-based emissions denote the local emission associated with domestic consumption, equal to the sum of rural consumption, urban consumption, government consumption, capital information and growing inventories (shown by different colours).

3. Production-based versus consumption-based PM_{2.5} emissions

The production-based emissions from industrial processes and energy related sectors, as well as the consumption-based emissions from capital formation, inventory growth, government consumption, urban consumption and rural consumption for China in 2007 (ignoring the emissions embodied in imports) are presented in figure 1 (illustrated by 13 representative sectors) and table S1 in the Supporting Information (SI). The resolved total PM_{2.5} emission from the industrial sectors (excluding biofuel source) in China in 2007 (9.68 Tg) corresponds closely with the previous estimation for 2005 (8.56 Tg) (Lei *et al* 2011). If taking into account the direct emissions from household commercial fuel use, total PM_{2.5} emission in China is 10.3 Tg in 2007.

Fossil fuel combustion is the dominant source of PM_{2.5} (4.89 Tg) across nearly all economic sectors. Industrial processes generate equal amounts of PM_{2.5} emissions, but are spread across only a narrow range of sectors, such as the manufacture of non-metallic mineral products (MNM, 4.15 Tg). The MNM sector alone accounts for 43.3% of total PM_{2.5} emissions (4.48 Tg, figure 1), mainly because China is the world's largest producer of cement. Power generation with the responsibility to provide heat and electricity accounts for another quarter of the PM_{2.5} source. The manufacture of ferrous metals products ranks third and emits approximately 10% of anthropogenic PM_{2.5} in China. The abovementioned three sectors together contribute three quarters of the anthropogenic PM_{2.5} emissions in China. Direct emissions from the other 40 aggregated sectors are relatively small.

The consumption-based inventory here represents the domestic emissions instigated by final

demand purchases of final products, traced through the domestic supply chain. The portion resulting from domestic demand of China in 2007 was 7.13 Tg from the consumption perspective, lower than the actual amount released (9.68 Tg) by 26%, mainly due to the export of goods and services (2.55 Tg). Different fundamentally from the production-based inventory, the dominant contributors of China's PM_{2.5} emissions, from the consumers' perspective, are the construction industry, other service industry, transport equipment and power generation sectors (figure 1).

To understand the discrepancies between the two inventories and the relevant interlinking paths that trace PM_{2.5} emissions embodied in final products, we conduct a SPA. The SPA actually derives an infinite number of pathways between sectors. To give a complete picture of the interdependence among sectors, we aggregate the original 43 sectors into six broad categories: power, transport, agriculture, industry, service and construction, and then merge the impact of each production layer (or tier). Figure 2 (and table 4) shows the components of embodied and direct emissions driven by the final consumption at Tier 0, Tier 1, and higher Tiers (Tier 2 and Tier 3 → ∞), which denote the emissions from the manufacture of the final products, emissions from producing the required inputs, and all other associated emissions from making the components for the required inputs, respectively. From the consumption point of view, PM_{2.5} emissions are relatively small from power, transportation and agriculture productions (altogether accounting for ~6% of the total), and approximately 30–50% of the emissions occur directly (i.e., in the zeroth Tier, see table 4). Emissions attributed to Tier 1 and higher tiers account for another half for power and transportation. For power generation, substantial amounts of fossil fuels (e.g., coal, natural gas) are combusted, which

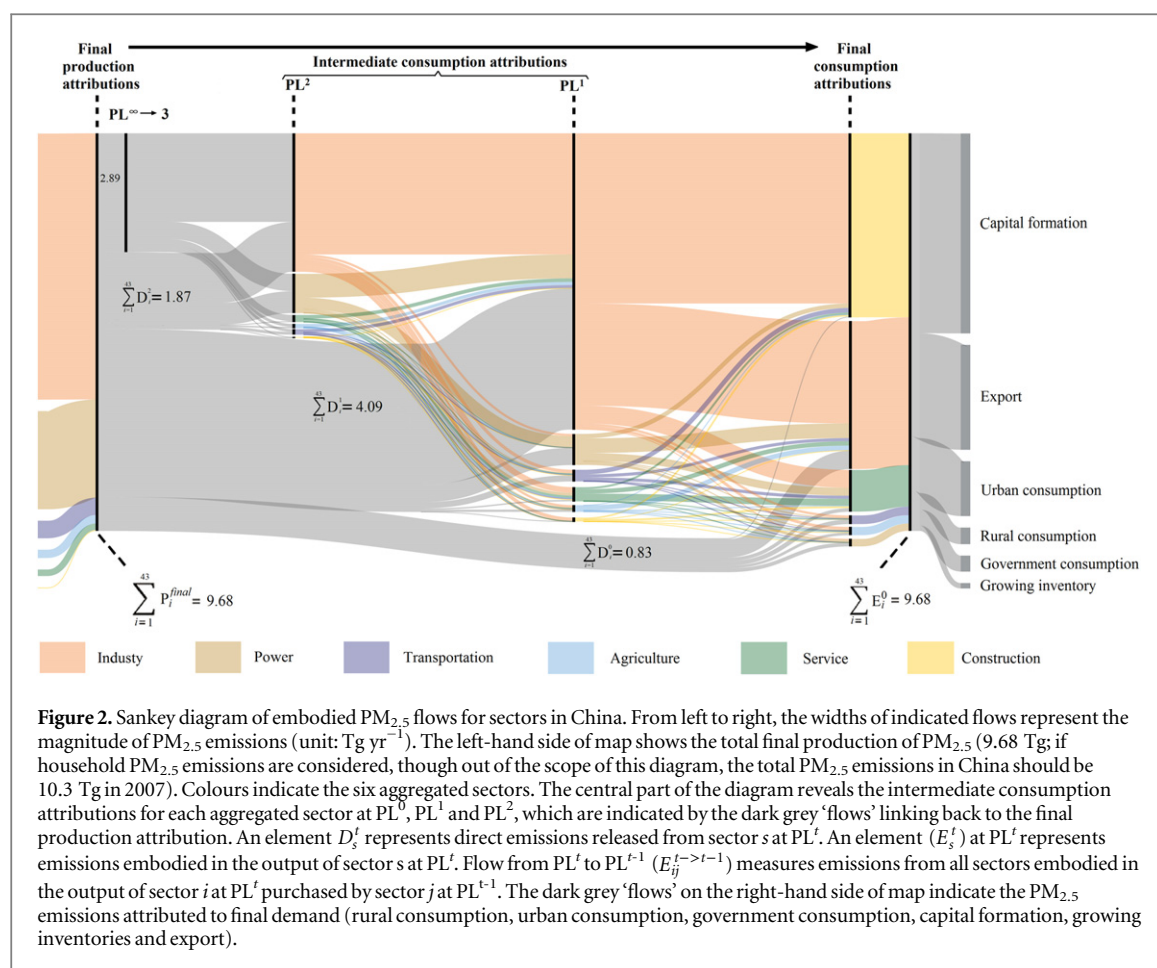


Table 4. Distribution of induced direct $PM_{2.5}$ emissions in the production tier along the supply chain from consuming power, transportation, agriculture, industry, service and construction products.

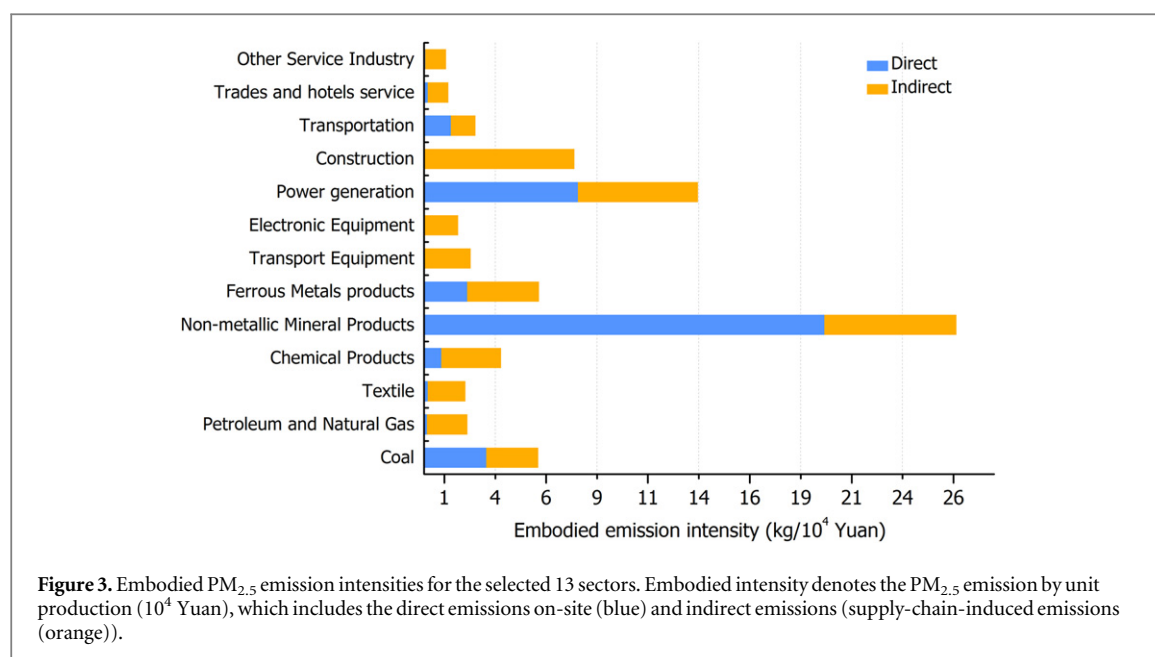
	Consumption-based emission (Tg)	GDP (Billion Yuan)	Attribution of direct emissions		
			Tier 0	Tier 1	Tier 2 $\rightarrow \infty$
Power	0.18	184	51.95%	24.16%	23.89%
Transportation	0.21	731	52.34%	11.73%	35.93%
Agriculture	0.20	1455	33.32%	19.45%	47.23%
Industry	3.60	9176	12.50%	25.68%	61.81%
Service	1.01	8986	8.52%	23.78%	67.70%
Construction	4.48	6072	0.49%	63.02%	36.49%

release tremendous amounts of gaseous and particulate pollutants. Furthermore, the mining of fossil fuel as well as the building and maintenance of power plants demand additional power and equipment inputs. This drives additional $PM_{2.5}$ release. For example, if one household consumes one kilowatt of electricity, there must be approximately two kilowatts of electricity generated to feed this consumption and to secure the associated production activities along the supply chain. Similarly, burning gasoline or diesel fuels for transportation activities directly releases substantial carbonaceous particles, while the preparation of vehicles and fuels drives even more $PM_{2.5}$ release from power and industrial production.

Consumption of industry and service products drives about 40% of China's total primary $PM_{2.5}$

emissions, but nearly 70% of which occur at the second and higher tiers (table 4) with an almost identical structure in sector contribution (figure 2 and table 4). This feature indicates that restructuring China's economy from industry to services is only a temporary solution in terms of air pollution control. It cannot fundamentally solve the problem, but only moderately slow down the pace of $PM_{2.5}$ release (from figure 3, the embodied emission intensity of service products is only half of that of industrial products). In the long run, as demand for service products increases, $PM_{2.5}$ emissions will rebound if the end-of-pipe emissions from power and industries are not sufficiently controlled.

As presented in figure 2 (and table 4), the structural path of attributed emissions for construction is



distinct. Almost no emissions occur directly to meet final demand (Tier 0, table 4). However, 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 2.8 Tg and 1.6 Tg PM_{2.5} emissions, respectively. This indicates that to produce one unit of building material, nearly 60% more PM_{2.5} emissions must be released. Note that in figure 1, capital formation (especially in the construction sector) holds the highest share, up to 51% (4.9 Tg). This is due, primarily, to intensive investment in construction, which accounted for more than 50% of China's total investment in 2007 (CSY 2008). In many developing countries such as China, investments in infrastructure are an important driver for maintaining economic growth (Zhang *et al* 2013). For example, the length of highways has been extended by more than 90% from 187 million kilometres in 2002–358 million kilometres in 2007 (CSY 2008). This greatly increases the production of electricity, cement, non-ferrous metals, and products from steel industries. In contrast, in developed countries, such as Japan, the share of capital formation in driving PM_{2.5} emissions is much less. In 2000, only 20% of PM_{2.5} emissions in Japan were embodied in capital formation (Sugiyama *et al* 2009). Since the embodied emission intensity for construction is twice that of industry and quadruple that of service production (inferred from table 4), an expansion of construction activity in China will inevitably accelerate the degradation of air quality.

In addition, the ten top-ranking paths through which demand drives the production processes are presented in table 5. The supply chain involving the largest PM_{2.5} emissions (in China in 2007) was 'capital formation→construction→non-metallic mineral products' which accounted for 25.2% of the overall PM_{2.5} emissions. six of the top ten ranking paths are

associated with construction related activities, and the non-metallic mineral products sector appears in four top ranking paths which involve approximately one third of the PM_{2.5} emissions. In addition, power generation is responsible for three of the high-ranking paths.

4. Embodied PM_{2.5} emission intensity

The pattern of the structure path in figure 2 indicates that most final consumption will ultimately produce PM_{2.5} emissions from power and industrial production in the higher tiers of the production chain. However, the efficiencies, in terms of emission per monetary output, are quite different between sectors. In this section, we focus on understanding the key sectors which solely contribute most to PM_{2.5} emissions, and investigate the importance of those sectors facilitating the rest of the economy. Figure 3 shows the embodied PM_{2.5} emission intensities of selected important sectors (selected from the 43 sectors in table 1) for China in 2007 (values are given in table S2), in conjunction with details of the source contribution. In 2007, the gross domestic production (GDP) in China was 26.6 trillion Yuan (CSY 2008). Therefore, the average PM_{2.5} intensity of GDP across all sectors was 3.6 Kg PM_{2.5} 10⁻⁴ Yuan. However, sectors such as non-metallic mineral products (MNM, mainly contributed by cement production; 26.1 Kg 10⁻⁴ Yuan), power generation (13.4 Kg 10⁻⁴ Yuan), and construction (7.4 Kg 10⁻⁴ Yuan) have PM_{2.5} intensities significantly above the average level. The high emission intensities of MNM and power generation are mainly caused by the direct release of limestone or that generated during the combustion of fossil fuel. In contrast, the embodied PM_{2.5} emissions in the construction sector reflect the complex supply chain or

to reduce the PM_{2.5} intensity of the MNM sector, which in turn will significantly cut down the embodied intensity of construction.

The EOF3 mainly represents the embodied emission intensities from the manufacture of equipment and machinery, which requires the supply of ferrous metals products. Therefore, the ferrous metals products sector is considered as the main contributor to the embodied intensities of metal products, general purpose machinery, special purpose machinery and transport equipment.

The above EOF analysis further indicates that these 43 sectors can be arranged into three independent groups, which separately drive PM_{2.5} emissions mainly from power, MNM, and the ferrous metal products sectors. Consequently, controlling PM_{2.5} emissions from power generation will significantly reduce the embodied intensity for almost all consumptions. In contrast, emissions reduction in the cement or ferrous metal industry will only lower the PM_{2.5} intensity for a few consumer industries (i.e., construction and the equipment and machinery industry, respectively). These origin patterns of PM_{2.5} emissions suggest that as well as further controlling end-of-pipe emissions from power plants, curbing the rapid expansion of construction or relying more on green building materials could be an alternative way to effectively control PM_{2.5} emissions in China, which will have little impact on other sectors of the economy.

5. Discussion and policy implications

The production perspective is better suited to identifying the PM_{2.5} emission of different production processes, while the consumption perspective identifies the consumer purchases that lead to PM_{2.5} emission. A comparison between the consumption and production perspectives highlights the difference in making policies for air pollution mitigation. For instance, the construction sector contributes just 0.2% of total direct PM_{2.5} emission, but it drives nearly 50% of industrial PM_{2.5} emissions from upstream sectors such as non-metallic mineral products and the steel industry. The SPA identifies that the industrial inputs are the main cause of PM_{2.5} emissions instigated by the construction sector (i.e., tier 1 in figure 2), while according to PCA, the high embodied emission intensity of the construction sector is solely contributed by non-metallic mineral products. Therefore, policymaking aimed at reducing primary PM_{2.5} could abate emissions from cement production (MNM sector) or choose materials with lower embodied PM_{2.5} intensities during the pre-construction phase. For example, our calculation indicates that substituting 50% of cement use by Celitement (Miles 2012), a cleaner alternative than the widely used ordinary portland cement, may avoid 1.12 Tg anthropogenic PM_{2.5} emissions in China.

For the other sectors (except construction), as indicated by the PCA results, most of the embodied PM_{2.5} emissions stem from power generation and the manufacture of products. The SPA also reveals that the impact of agriculture, industry and service occurs in the higher tiers and is due to the power and industrial supply. Therefore, ways to lower emissions should focus on the production process in the supply chain, including improving energy use efficiency and relying more on environmentally friendly energy sources (Li and Fan 2008, Tapiador 2009, Poizot and Dolhem 2011, Ward and Inderwildi 2013). Measures such as phasing out inefficient industrial boilers and optimizing the energy mix could cut down end-of-pipe emissions to some extent. Using these approaches, the low emission intensity goal of most economic sectors can be achieved.

Being a developing country, China is undergoing rapid urbanization. Efforts made to control existing pollution units could be quickly overtaken by a rapid increase in demand for new production activities. For instance, the urban population has risen by 148 million during 2000s, and the urbanization rate of the country has increased from 35.8% in 2000 to 44.9% in 2010 (CSY 2010). A large area of farmland on the urban fringe has been converted to provide housing, infrastructure and services for new migrants. However, the urban sprawl is low-density, compared to existing inner city development (Chen *et al* 2008). Good design of new cities could avoid huge amounts of air pollution released in both the building and subsequent operational phases. In general, there is a positive relationship between urban compactness and agglomerated environmental performance to a certain extent (Chen *et al* 2008). An appropriate compact level could be adopted in China's urban planning to maximize the environmental advantages.

As well as pursuing compact urban development, the Government could gradually impose a property tax for families with multiple houses, which could prevent the building of more vacant houses. According to a nationwide survey covering 262 counties in 29 provinces by researchers from China's Southwestern University of Finance and Economics (SRC 2014), the vacancy rate of sold urban residential homes reached approximately 20% in 2013. This is comparable to an area amounting to all the completed buildings from 2007 to 2008. Therefore, proper policies should be formulated to stimulate usage of unoccupied houses and avoid building more vacant units. Assuming that 20% of the investment in construction goes on vacant homes (i.e., equal to the vacancy rate) and another 20% can be avoided by reducing existing vacant units, our calculation based on the embodied emission intensity indicates that PM_{2.5} emissions in China could be reduced by 1.94 Tg (approximately one quarter of total emissions in 2007), primarily in MNM (1.7 Tg), ferrous metals products (0.11 Tg), and the transportation (0.04 Tg) sectors. There are even more

health and climate co-benefits if the reduction of CO₂ and other PM_{2.5} precursors (i.e., SO₂ and NO_x) are considered. This will fundamentally mitigate China's air pollution by relying less on emission-intensive industries.

6. Conclusion

Like other societies, China's economy is a complicated system involving many sectors, and each of them is interdependent and linked to PM_{2.5} emissions through the supply chain. We use SPA to identify the linkages between production and consumption and use PCA to examine the pattern of all supply chain paths, which enable policymaking more orientated towards efficient emission mitigation through the systematic supply-chain approach.

The results reveal that the direct PM_{2.5} emissions instigated from final demand are responsible for only 8%, and most emissions (92%) are triggered in the supply chains. Sectors drive PM_{2.5} emissions in different ways. In the power and transportation sectors, direct emissions (Tier 0) instigated from consumer products are relatively large, contributing nearly half of the consumption-based emissions. In contrast, PM_{2.5} emissions driven by construction, industry, and service products are mainly embedded in the higher tiers of the production activities. Based on PCA, we found that nearly 80% of the economic sectors in China follow a similar pattern in driving PM_{2.5} emissions in electricity, coal, petroleum, cement, chemical products and ferrous metal industries. An exception is the construction sector, which relies heavily on inputs from non-metallic mineral products.

The above inter-linkage pattern of the production chains indicates that as well as further reducing end-of-pipe emissions, there are several approaches available to China to reduce PM_{2.5} emissions. Substituting emission-intensive products (e.g., cement) in the supply chain with cleaner alternatives (e.g., Celitement) could effectively reduce PM_{2.5} emissions driven by construction. Phasing out inefficient industrial boilers and optimizing the energy mix could cut down the embodied emission intensities for almost all the supply chain. Importantly, in the demand-driven economy, measures taken to constrain construction (particularly the investment) may also be effective in reducing PM_{2.5} emissions. This study offers a more comprehensive and accurate picture of how consumers' demand for each industry contributes to emissions, as well as opportunities to reduce them by restructuring China's economy and blocking the paths that induce indirect emissions.

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