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The socioeconomic drivers of China's primary $PM_{2.5}$ emissions

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Abstract

Primary $PM_{2.5}$ emissions contributed significantly to poor air quality in China. We present an interdisciplinary study to measure the magnitudes of socioeconomic factors in driving primary $PM_{2.5}$ emission changes in China between 1997–2010, by using a regional emission inventory as input into an environmentally extended input–output framework and applying structural decomposition analysis. Our results show that China's significant efficiency gains fully offset emissions growth triggered by economic growth and other drivers. Capital formation is the largest final demand category in contributing annual $PM_{2.5}$ emissions, but the associated emission level is steadily declining. Exports is the only final demand category that drives emission growth between 1997–2010. The production of exports led to emissions of 638 thousand tonnes of $PM_{2.5}$, half of the EU27 annual total, and six times that of Germany. Embodied emissions in Chinese exports are largely driven by consumption in OECD countries.

Keywords: $PM_{2.5}$, pollution, China, emission drivers, export, capital investment, input–output analysis, structural decomposition analysis

1. Introduction

International headlines at the beginning of 2013 continually reported the serious air pollution problems across China. Heavy smog, sustained during January and October–November, blanketed over 70 major cities in North China, which covers 1,430 thousand km^2 area in total, 15% of national territory (Xinhua News 2013). $PM_{2.5}$ (particulate matter smaller than 2.5 micrometers) is the major component of smog. In Beijing, the concentration of $PM_{2.5}$ passed 1000 $\mu g\ m^{-3}$, 40 times higher than the World Health Organization (WHO) standard level for good health (Patience 2013). $PM_{2.5}$, which includes small particles such as sulfates, black carbon, organics, and trace metals, is able to enter the bloodstream relatively easily and cause respiratory damage (Helble *et al* 2000). Outdoor air pollution contributed 1.25 million premature deaths in China in 2010, nearly 40% of the global total (Wang *et al* 2012).

Most previous research on airborne PM in China has focussed on measuring the chemical composition of PM in China (e.g. Cao *et al* 2003, Cheng *et al* 2000, Wang *et al*

2006, Xu *et al* 2004). In recent years, Chinese scholars have used $PM_{2.5}$ on-site measured samples to identify the chemical composition of $PM_{2.5}$ and the potential sources to cut emissions in Beijing and other Chinese cities (e.g. Duan *et al* 2006, He *et al* 2001, Huang *et al* 2006, Song *et al* 2006, Zhao *et al* 2013). A detailed review of formation and control of PM in China can be found in Yao *et al* (2010). Despite these advances, there is a lack of understanding on the socioeconomic drivers of PM emissions.

Identification and quantification of socioeconomic factors driving PM emission changes in China can be crucial for PM mitigation and health impact control. The available techniques in conducting such analysis include index decomposition analysis (IDA) (Ang 2004, 2005, Ang and Liu 2001) and structural decomposition analysis (SDA) (Rose and Casler 1996). Both techniques have been widely applied in assessing socioeconomic driving forces for energy and CO_2 emissions in China (e.g. Chong *et al* 2012, Dhakal 2009, Feng *et al* 2012, Liu *et al* 2012a,b), but rarely for air pollutants.

This paper first presents major sources contributing to $PM_{2.5}$ emissions in China. Second, we continue with a sectoral analysis of annual emission contributions. Third, we quantify the socioeconomic factors driving China's $PM_{2.5}$ emission changes between 1997–2010. We focus on the primary sources of $PM_{2.5}$ emission generation that account for a large fraction of ambient $PM_{2.5}$ concentration in China (Zheng *et al* 2005). The primary sources of $PM_{2.5}$ emission are from coal combustion, diesel vehicles, and industrial processes. The secondary sources are from the oxidation of other air pollutants such as sulfur dioxide (SO_2), ammonia (NH_3), nitrogen oxides (NO_x), and volatile organic compounds (VOCs) (Megaritis *et al* 2013). The secondary sources also contribute to $PM_{2.5}$ concentration, but due to their smaller contribution and uncertainties associated with atmospheric chemistry modeling, we do not consider them further in this paper.

2. Method and data

2.1. Environmentally extended input–output analysis

The calculations of emission contributions are based on environmentally extended input–output (IO) analysis. This well-established method is the basis of the System of National Accounts and is well suited to the analysis of the environmental repercussions of economic activities (Leontief 1986). A summary of the method is shown here, but more detailed descriptions are available elsewhere (e.g., Miller and Blair 2009). For clarity, in this paper, matrices are indicated by bold, upright capital letters (e.g. $\mathbf{X}$); vectors by bold, upright lower case letters (e.g. $\mathbf{x}$), and scalars by italicized lower case letters (e.g. x).

The total output of an economy, $\mathbf{x}$, can be expressed as the sum of intermediate consumption by industry, $\mathbf{Ax}$, and final consumption beyond which products are no longer processed, $\mathbf{y}$:

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y} \tag{1}$$

where each column of the matrix $\mathbf{A}$ specifies the sectoral inputs required to produce one unit of output (the economy's direct requirements matrix) and $\mathbf{y}$ is the final demand after which no further processing occurs. When solved for the output, this equation yields:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}. \tag{2}$$

We then couple the output with an environmental matrix (e.g. $PM_{2.5}$ emission), $\mathbf{F}$, which shows the emissions from each sector, normalized by the sector's total economic output. The total emissions for a given final demand can then be calculated as:

$$\mathbf{f} = \mathbf{F}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{3}$$

with $\mathbf{f}$ representing the sector-wise total supply chain emissions to meet the final demand $\mathbf{y}$.

2.2. Removing imports columns from the input–output model

The standard IO model assumes that imports are produced with domestic technology. This is clearly inadequate for China given the differences in production, energy consumption and $PM_{2.5}$ emissions across countries (Peters and Hertwich forthcoming, Weber and Matthews 2007). We remove the imports from the Chinese IO data ($\mathbf{A}$ and $\mathbf{y}$) to isolate the role of domestic factors ($\mathbf{A_d}$ and $\mathbf{y_d}$) leading to changes in China's $PM_{2.5}$ emissions. This method removes imported goods from the direct requirements table and from components of GDP other than exports (e.g. household consumption, capital investment, and government consumption). We assume that each economic sector and final demand category uses sectoral imports in the same proportions (Weber *et al* 2008). For example, it assumes that industry, government, and households each consume the same share of domestically produced and imported electronic products. A further explanation to this approach can be found in our previous work (Guan and Barker 2012, Guan *et al* 2009, Weber *et al* 2008).

There are several global multi-regional input–output (MRIO) models with environmental datasets available (e.g. EXIOPOL and WIOD), but environmental extensions including $PM_{2.5}$ emission are rare. This prevents us from estimating embodied $PM_{2.5}$ emissions in Chinese imports.

2.3. Structural decomposition analysis

$PM_{2.5}$ emission changes can be decomposed by using the input–output structural decomposition analysis (SDA), following our previous analyses on CO_2 emissions (Guan *et al* 2009, 2008, Minx *et al* 2011, Peters *et al* 2007). The $PM_{2.5}$ emissions are decomposed into five driving forces

$$PM_{2.5} = p \cdot \mathbf{F} \cdot \mathbf{L} \cdot \mathbf{y_s} \cdot \mathbf{y}_\mathrm{v}$$

where population (p) is measured by person; emission intensity ($\mathbf{F}$) is measured by tonnes of emission per unit output; production structure ($\mathbf{L}$) is measured by amount of sectoral outputs per final unit, consumption structure ($\mathbf{y_s}$) is measured by proportions of sectoral consumption in total consumption, and per capita consumption volume ($\mathbf{y}_\mathrm{v}$) is measure by monetary expenditure.

The change in $PM_{2.5}$ emissions from time t to time $t-1$ can be decomposed into changes in the component driving forces, but there is no unique solution for the decomposition; the five factors utilized in this paper have $5! = 120$ first-order decompositions. One of the 120 possible decompositions is shown in equation (4).

$$\begin{aligned}\Delta PM_{2.5} &= \Delta PM_{2.5(t)} - \Delta PM_{2.5(t-1)}\\ &= p_{(t)}\mathbf{F}_{(t)}\mathbf{L}_{(t)}\mathbf{y}_{\mathbf{s}(t)}\mathbf{y}_{\mathrm{v}(t)}\\ &\quad - p_{(t-1)}\mathbf{F}_{(t-1)}\mathbf{L}_{(t-1)}\mathbf{y}_{\mathbf{s}(t-1)}y_{\mathrm{v}(t-1)}\\ &= \Delta p\mathbf{F}_{(t)}\mathbf{L}_{(t)}\mathbf{y}_{\mathbf{s}(t)}y_{\mathrm{v}(t)} + p_{(t-1)}\,\Delta\mathbf{F}\mathbf{L}_{(t)}\mathbf{y}_{\mathbf{s}(t)}y_{\mathrm{v}(t)}\\ &\quad + p_{(t-1)}\mathbf{F}_{(t-1)}\,\Delta\mathbf{L}\mathbf{y}_{\mathbf{s}(t)}y_{\mathrm{v}(t)}\\ &\quad + p_{(t-1)}\mathbf{F}_{(t-1)}\mathbf{L}_{(t-1)}\,\Delta\mathbf{y}_{\mathbf{s}}\mathbf{y}_{\mathrm{v}(t)}\\ &\quad + p_{(t-1)}\mathbf{F}_{(t-1)}\mathbf{L}_{(t-1)}\mathbf{y}_{\mathbf{s}(t-1)}\,\Delta y_{\mathrm{v}}. \end{aligned} \tag{4}$$

Each of the four terms in equation (4) represents the contribution to change in $PM_{2.5}$ emissions triggered by one driving force while keeping the other variables constant. We allow for the non-uniqueness of individual decompositions by averaging all possible first-order decompositions (Minx *et al* 2011).

2.4. Data source for input–output tables

We harmonize seven national input–output tables from 1997 to 2010 to 31 sectors and convert to constant prices using the 2002 producer prices with the double deflation method (United Nations 1999). The 2010 input–output table is a newly published dataset which contains China's economic flows between production sectors and other economic agents after the global economic downturns. The price deflation data with industrial sectoral details is from the Chinese Statistical Yearbook (National Bureau of Statistics 2010). The Chinese input–output tables include several vectors of final demand categories; rural households, urban households, government consumption, fixed capital formation (including physical capital investment, i.e. roads, bridges, machines and so on), capital inventory changes, exports, and imports. The imports are removed as described earlier. We aggregate the fixed capital investment and capital inventory changes into one 'capital formation' category for clear presentation.

2.5. Data source for $PM_{2.5}$ emissions and its uncertainties

The regional primary $PM_{2.5}$ emission data is from the Multi-resolution Emission Inventory for China (MEIC: www.meicmodel.org), which is developed by Tsinghua University. MEIC is a bottom-up air pollutant emission inventory with more than 700 emission sources and production categories. The MEIC model is an improvement and update of the previous work from the same group, compiled from detailed statistical data, technology information, and emission factors (Lei *et al* 2011, Zhang *et al* 2007, 2009).

In this study, the emission sources in MEIC are mapped into an environmentally extended input–output model. In particular, we aggregate the 700 emission sources and production categories into 31 production sectors by 21 fuel types. The classification complies with the format in China's official energy statistical yearbook and matches the IO table classification. Data mapping between the emission inventory and input–output dataset uses the same procedure as our previous work (e.g. Feng *et al* 2012, 2013, Lindner *et al* 2013, Liu *et al* 2012a,b) and is fully documented in Guan *et al* (2012).

Uncertainty of the regional air pollution inventory mainly comes from inconsistencies in energy consumption reported in the Chinese energy statistical yearbook. Based on the sum of the energy consumption at the provincial level and national level, the total primary $PM_{2.5}$ emissions in 2010 are 12.1 million tonnes and 11.3 million tonnes respectively. The inconsistent energy consumption not only affects the absolute value of our calculation, but has impacts on the trend of China's production-related primary $PM_{2.5}$ emissions, further influencing the results of SDA. Similar statistical inconsistencies can be found in other pollutants like CO_2 emissions (Guan *et al* 2012).

We have selected an MEIC dataset which is based on the province-sum level energy use data as a basis to estimate China's overall primary $PM_{2.5}$ emissions. The accuracy and reliability of the MEIC dataset has been validated by using satellite observations (Kondo *et al* 2011, Lin *et al* 2010). MEIC is the best available dataset for China's air pollutants to our knowledge.

3. Results

3.1. Annual primary $PM_{2.5}$ contributions by fuel types

China achieved an average double digit economic growth between 1997–2010, which was fueled by rapidly increasing energy consumption, especially regarding coal (Chen *et al* 2011). China accounts for 80% of the global increase in coal consumption between 2005 and 2010 and 47% of world annual coal consumption in 2010 (Liu *et al* 2013). China's coal and coke final consumption (used for combustion only) has increased by 62% from 726 million tonnes in 1997 to 1,175 million tonnes in 2010 (National Bureau of Statistics 2011a). Similarly, China's gasoline and diesel consumption volume has increased almost three-fold from 79 million tonnes in 1997 to 214 million tonnes in 2010, fueling the six times increase of vehicle volume from 12 million to 78 million during the same period (National Bureau of Statistics 2011b).

Since 2000, there have been two periods of change in the power and heavy manufacturing sectors in China. Between 2000–2005, the period when the power sector in China developed fastest in the past three decades, electricity consumption doubled to increase at 16% per year. As a result, SO_2 and primary $PM_{2.5}$ emissions in the power sector increased by 150% (Zhao *et al* 2008) and 30%, respectively. Between 2005–2010, annual electricity consumption increased at a slower rate of 11% per year while large-scale flue gas desulfurization (FGD) was installed in electricity plants which has led to a reduction in air pollution. Figure 1(a) illustrates the fluctuation of China's annual primary $PM_{2.5}$ emissions, which has firstly decreased from 12.3 million tonnes in 1997 to 11.5 million tonnes in 2000, then climbed back to reach a peak of 14.8 million tonnes in 2005, but gradually reduced to 12.1 million tonnes in 2010.

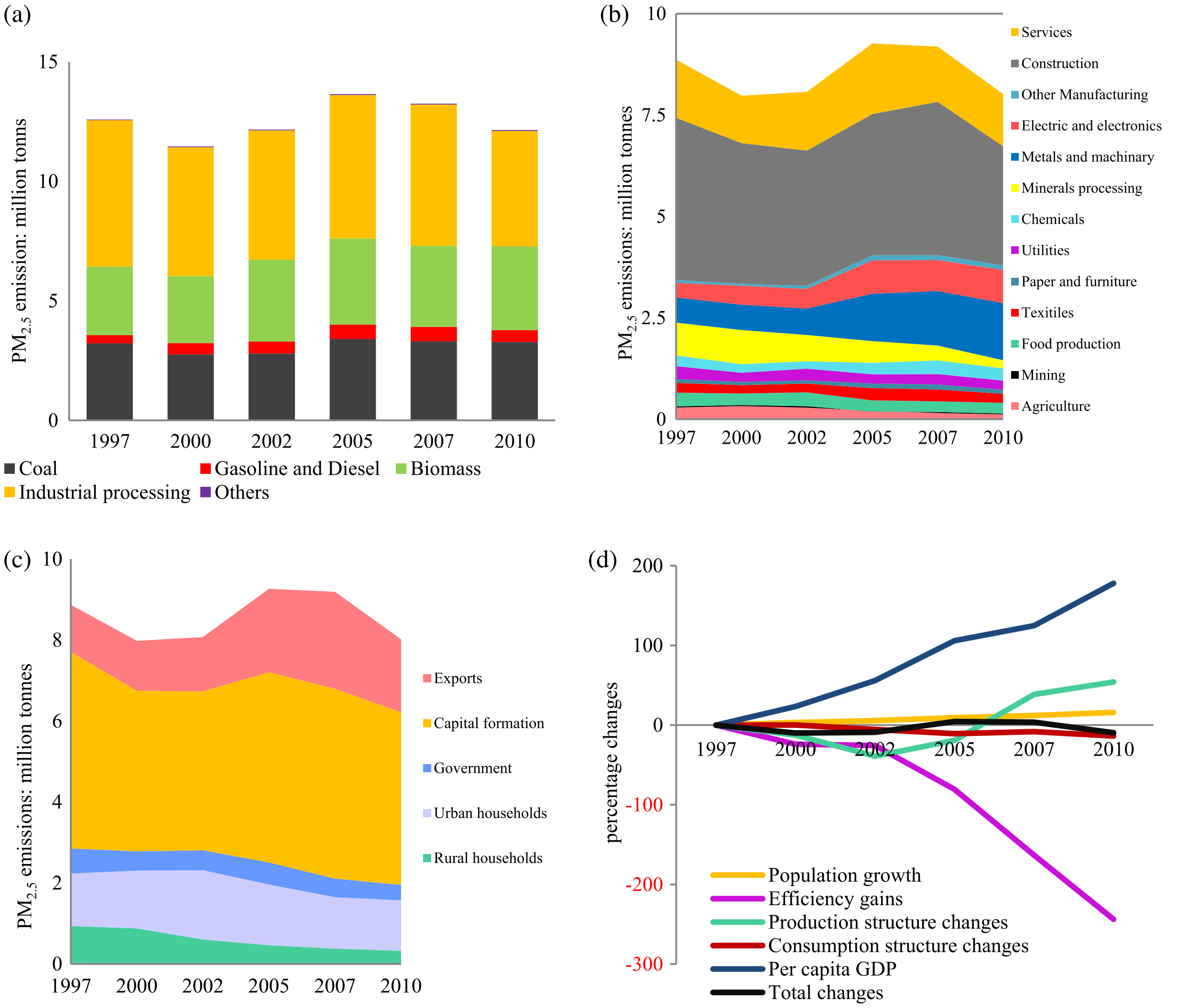

Figure 1. (a) $PM_{2.5}$ emission contributions by emission sources between 1997 and 2010. (b) Contributions of production-related $PM_{2.5}$ emissions by industrial sectors between 1997–2010. (c) Contributions of production-related $PM_{2.5}$ emissions by final demand between 1997 and 2010. (d) Contributions of drivers to production-related $PM_{2.5}$ emission changes between 1997–2010.

From a production perspective, it is often assumed that the main energy sources leading to China's $PM_{2.5}$ emission are coal combustion and transport fuels. Combustion of coal contributed to 25% of the total primary $PM_{2.5}$ emissions in China in 2010, while transport fuels contributed only 4%. More important are industrial processes and biofuel combustion (e.g. mainly for rural households' energy use) accounting for about 45% and 26% of primary $PM_{2.5}$ emissions in 2010 (shown in figure 1(a)).

In response to air pollution problems, China has implemented a strict policy limiting the growth of air pollution from coal-power plants. Since 1998, approximately 11% of national territory has been designated as acid rain and SO_2 pollution control zones (Hao *et al* 2000). In 2000, the electricity production capacity in those control zones was 138 GW, and could have increased to 313 GW by 2010 (Zhao *et al* 2008). The installation of FGD systems in the Chinese electricity plants has increased from 2.0% in 2000 to 11.8% in 2005 and further still to 85.8% in 2010. In contrast, pollution control measures in industrial processes and household sectors are limited.

3.2. Primary $PM_{2.5}$ emissions contributions from a consumption perspective

Figure 1(b) shows the production-related emissions allocation to industrial sectors. Production-related emissions include all emissions from economic activities, but exclude direct emissions from the households sector (which accounts for 30%–34% of annual primary $PM_{2.5}$ emissions between 1997–2010). The industrial sectors consist of agriculture, manufacturing, processing sectors, and services. The production-related emissions in 1997 were 8.9 million tonnes, which increased slightly by 4% to 9.2 million tonnes in 2007 but quickly dropped 10% (relative to 1997 levels) to 8.0 million tonnes by 2010.

Construction and metal and machinery production are the largest emissions sectors from a consumption perspective in China, representing 37% and 18% of production-related emissions in 2010. Both sectors are the major components of capital formation (discussed below), which are characterized with energy- and emission-intensive supply chains. Consumption-based $PM_{2.5}$ emissions for the services sectors are also fairly emission intensive. For example, transport and servicing sectors are together responsible for 1.1 million tonnes or 16% of $PM_{2.5}$ emissions in 2010. In particular, residential services, education and health services, and transportation account for 301 thousand tonnes, 292 thousand tonnes, and 271 thousand tonnes of emissions, respectively.

China is gradually developing towards a high value-added manufacturing and service-based economy. Such a shift will only have moderate environmental gains, and the supply chain can still be emission-intensive (Suh 2006). Unless emissions along the whole supply chain of service sectors can be reduced, China cannot transform to a low emission or emission free economy. The utility sector (i.e. electricity and gas supply) is responsible for 256 thousand tonnes or 3% of annual $PM_{2.5}$ emissions from a consumption perspective Yet, cleaner production in the utility sector plays a critical role in the development of low emission supply chains (Skelton *et al* 2011).

Figure 1(c), from another point of view, demonstrates the allocation of production-related primary $PM_{2.5}$ emissions to different final demand categories. Capital formation is the largest contributor to production-related primary $PM_{2.5}$ emissions, accounting for 32–39% emissions per year between 1997–2010. Of the 4.3 million tonnes emitted from capital formation in 2010, construction activities contributed 67% or 2.9 million tonnes of emissions. Exports ranked as the second largest contributor in terms of production-related emissions, accounting for 9–18% of total annual emissions between 1997–2010. In 2010, exports were responsible for 1.8 million tonnes of $PM_{2.5}$ emissions, mainly from producing electronic and electric products, metals, mineral material and chemical products.

Production-related emissions from consumption in rural households have gradually declined, decreasing by 70% from around 0.9 million tonnes of $PM_{2.5}$ emissions or 11% of the annual total in 1997 to 0.3 million tonnes or 4% of the annual total in 2010. The decrease can be partly explained by population migration from rural to urban areas during China's rapid urbanization process. The rural population has decreased from 832 million to 671 million between 1997–2010. Per capita rural households' consumption-based emissions have reduced from 1.1 kg per person to 0.4 kg per person during the same period. This reflects the efficiency improvements in producing goods and services for consumption. In addition, rural households' direct energy usages for cooking and heating have produced 3.4 million tonnes of primary $PM_{2.5}$ emissions in 1997, and the figure has increased to 3.9 million tonnes by 2010. Per capita direct emission by rural residents has increased from 4.0 kg in 1997 to 5.8 kg. Such increases have reflected more direct energy consumed in rural households and there is no significant emission control at household level in rural China.

Production-related emissions from consumption in urban households have only slightly reduced from 1.3 million tonnes in 1997 to 1.2 million tonnes in 2010. Consumption of goods and services in urban households contributed to 11–16% of $PM_{2.5}$ emissions between 1997–2010. Per capita urban households' emissions have decreased by 43% from 3.3 kg to 1.9 kg during the same period. In addition, urban household direct energy consumption produced 0.4 million tonnes of primary $PM_{2.5}$ emissions in 1997, and the figure has reduced to 0.2 million tonnes in 2010. This is a result of the efficiency improvement in district central heating systems in cities. The per capita direct emission of city dwellers has declined from 0.9 to 0.4 kg between 1997–2010.

Emissions from governmental consumptions (e.g. health and education, and public administration) have reduced by nearly half from 0.6 million tonnes in 1997 to less than 0.4 million tonnes by 2010.

3.3. Socioeconomic driving forces of $PM_{2.5}$ emissions

We decompose the production-related emission changes between 1997–2010 into five socioeconomic driving forces: population growth, emission efficiency gains, production structure changes, consumption structure changes and per capita gross domestic production (GDP). Efficiency has been a vital factor in reducing production-related $PM_{2.5}$ emissions. Our structural decomposition analysis (see figure 1(d)) shows that efficiency gains have avoided 22 million tonnes (−244%) of $PM_{2.5}$ emissions between 1997–2010 if China's population, economic structure and per capita GDP had remained constant. This effort has been tempered by per capita GDP growth and production structural changes, which have increased emissions by 16 million tonnes (178%) and 5 million tonnes (54%), respectively. The two other remaining drivers have had smaller effects on emission trends. Population growth has contributed to 1.4 million tonnes (16%) of emission growth, while consumption structural changes have offset 1.2 million tonnes (14%) of emissions between 1997–2010.

Figure 2 shows the full decomposition results for the five final demand categories with industrial sectoral breakdowns for all time periods. Between 1997–2010, the total production-related emissions have reduced emissions by 852 thousand tonnes (shown in figures 1(b) and (c)). But without the contribution from export production, China could reduce primary $PM_{2.5}$ emissions by a further 638 thousand tonnes (shown in figure 2, export production).

Rural households offset 613 thousand tonnes of emissions due to production efficiency, with leading emission declines in non-metal minerals, agriculture products and processed food. Urban households reduced emissions by 51 thousand tonnes, largely due to production efficiency with largest declines in non-metal minerals (i.e. 248 thousand tonnes of emission reduction). This decline is tempered by increasing consumption of residential services (72 thousand tonnes of emission increase), eating out (34 thousand tonnes of emission increase), transport equipment production (32 thousand tonnes of emission increase) and petroleum processing (29 thousand tonnes of emission increase). Per capita urban dwellers' spending on residential services has increased by 4.6 times from 362 Yuan to 1655 Yuan at 2002 prices between 1997–2010. Meanwhile, the spending on restaurants has grown three-fold from 141 Yuan to 446 Yuan at the 2002 price.

Emissions driven by capital formations led to a reduction of 593 thousand tonnes between 1997–2010. This is mainly

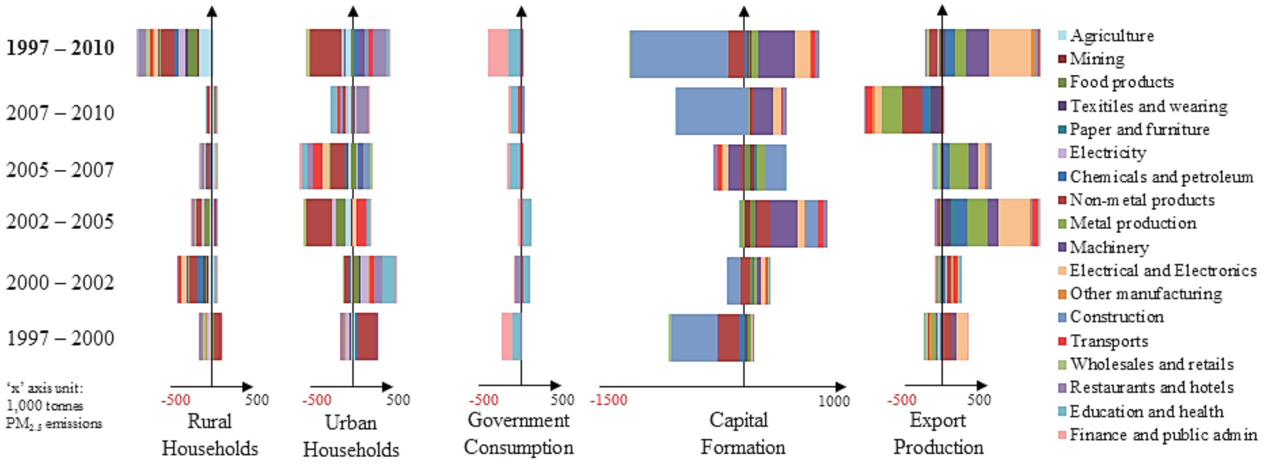

Figure 2. Emission changes in sectoral details contributed by final demand categories during 1997–2010.

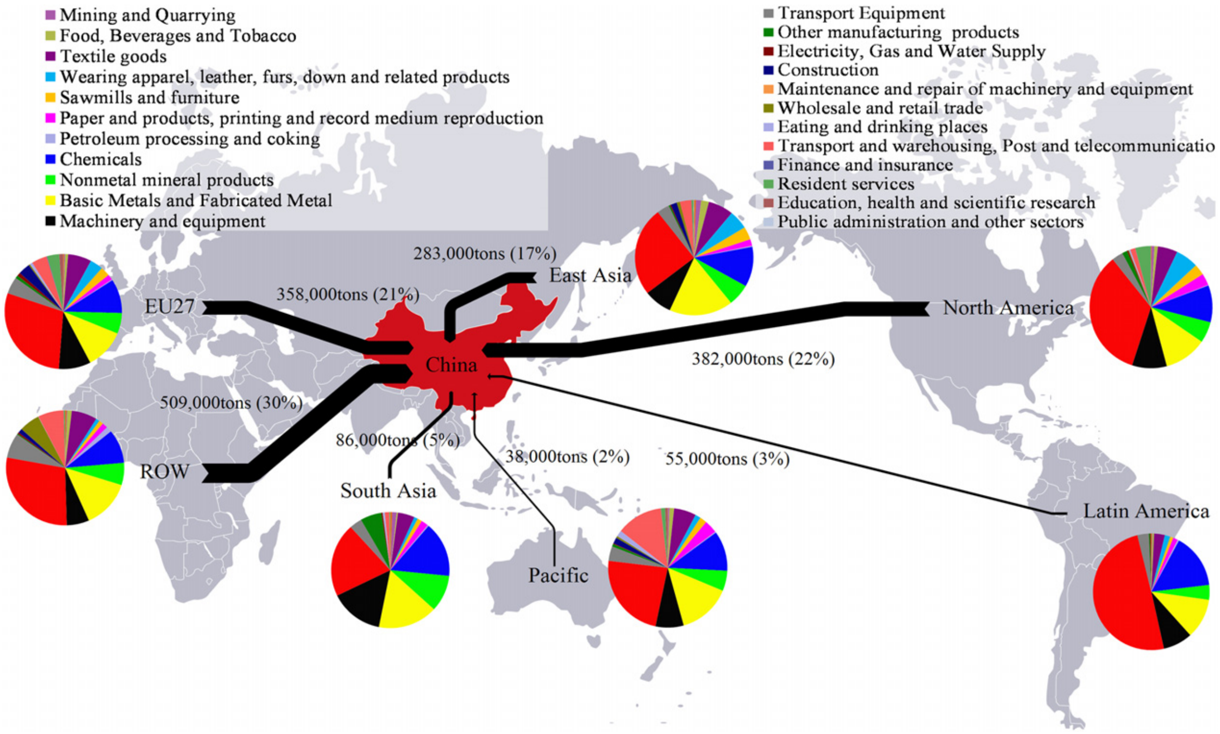

Figure 3. Outsourcing $PM_{2.5}$ to China by trade.

achieved through efficiency gains in the construction sector and its supply chain (1,126 thousand tonnes of emission) cumulated between 1997–2000 and 2007–2010. In contrast, the growth in demand for transport equipment, general machinery and electrical and electronic products has triggered 211 thousand tonnes, 210 thousand tonnes and 156 thousand tonnes of emission increases between 1997–2010. For example, total vehicle production has increased over ten-fold from 1.6 million in 1997 to 18 million in 2010; production machinery such as metal cutting machine tools has increased over three-fold from 186 thousand to 697 thousand over the past 13 years (National Bureau of Statistics 1996–2012).

Exports is the only final demand category that drives an emission increase between 1997–2010. The increase is 638 thousand tonnes, which was largely achieved between 2002–2005 (719 thousand tonnes) and 2005–2007 (332 thousand tonnes), but offset between 2007–2010 (589 thousand tonnes decrease). This trend is consistent with the literature of exports as a driver of China's CO_2 emission growth. For example the production of exports led to half of the CO_2 emission increase between 2002–2005 (Guan *et al* 2009) and one-quarter of the emission increase between 2005–2007 (Minx *et al* 2011, Peters *et al* 2010). From the perspective of industrial sectors, the emission increase between 1997–2007 was driven by electronic products (250 thousand tonnes), metal smelting and processing (212 thousand tonnes), electrical equipment (133 thousand tonnes), general equipment (123 thousand tonnes), and chemicals (111 thousand tonnes). The global economic recession starting in 2007 resulted in a decline in China's exports. The $PM_{2.5}$ emissions associated with export production has decreased by 589 thousand tonnes between 2007–2010. Given that the global economic condition is gradually improving, the magnitude of embodied emissions in Chinese exports may be quickly restored to the levels achieved prior to 2007 and even increase in the near future.

3.4. International trade as a driver of primary $PM_{2.5}$ emissions in China

The Chinese government is making a great effort to curb $PM_{2.5}$ emissions from manufacturing and household consumption, for example, by the phasing out of inefficient factories and the efficiency improvements in heating systems in rural areas National Development and Reform Commission (NDRC) (2011). Little attention has been placed on the emissions embodied in exports. China's exports have grown 7.6 times between 1997–2010, although there was a significant drop between 2008–2009 due to the economic downturn in the US and EU (National Bureau of Statistics 2012). The associated primary $PM_{2.5}$ emissions by 2010 reached 1.8 million tonnes, which is 38% higher than the annual emissions in the EU27 (EEA 2012). Over 60% of the $PM_{2.5}$ emissions, or over 1 million tonnes, of primary $PM_{2.5}$ is for export production to satisfy consumptions in OECD countries (figure 3). In particular, 22% or 382 thousand tonnes of primary $PM_{2.5}$ emissions in 2010 are embodied in Chinese exports to North America (United States and Canada). One-fifth or 358 thousand tonnes of primary $PM_{2.5}$ emissions are for EU27 consumption. The embodied emissions to East Asia (e.g. Japan, Korea, and Taiwan) and Russia account for 17% of the total or 283 thousand between 1997–2010. The average annual growth rate of 17% is 1.2 times the export growth from China to OECD countries. Comparatively speaking, the one-way trade (from China to developing countries) amounted to 730 billion $US in 2010, which is still 85% of the China to OECD countries' trade figure. Nevertheless, embodied emissions of Chinese trade to developing countries accounts for 41% of total embodied primary $PM_{2.5}$ emissions, or 700 thousand tonnes in 2010.

China has become the 'world manufacturing hub' connecting primary material manufacturing to final consumers (Guan and Reiner 2009). Of the total emissions in 2010, electrical and electronic productions accounted for 29% or 503 thousand tonnes. OECD countries' consumption has triggered 310 thousand tonnes of embodied emissions in those products, where 131 thousand tonnes (26%), 104 thousand tonnes (21%), and 80 thousand tonnes (16%) of emissions are from North America, EU27 and Asia-Pacific countries respectively. Metal products and chemical production are the major contributors to embodied emissions in Chinese exports, which accounted for 13% and 10% of the total amount in 2010. The destination for those products is mainly OECD countries.

4. Conclusion

This paper is a first attempt to adopt environmentally extended input–output analysis to the study of the driving forces of $PM_{2.5}$ emissions from a consumption perspective. Production-related primary $PM_{2.5}$ emissions account for about two-thirds of overall emissions in China, which is a major contributor to China's urban air pollution. Rural residents are mainly responsible for the remaining one-third of direct household emission. China has invested a great effort in achieving efficiency gains in major industrial sectors to control primary $PM_{2.5}$ emissions. Our structural decomposition analysis has shown that such an effort is able to sufficiently offset the emission growth triggered by economic growth and the other drivers. Yet, by solely relying on technology improvements, China is not able to reduce the $PM_{2.5}$ emission level down to an accepted level recommended by the World Health Organization.

Construction and metal and machinery production sectors are the largest industrial sectors driving the changes in $PM_{2.5}$ emissions. Although capital investment is always the largest final demand category in driving $PM_{2.5}$ emissions between 1997–2010, export production is the only category that has led to emission growth. For example, the share of exported emissions has increased by 9% in 1997 to 18% in 2010. Recent research has shown that air pollutants transported from Asia (in particular China) across the Pacific to North America has resulted in air quality concerns in the Pacific and North America (Yienger *et al* 2000, Zhang *et al* 2008). The emissions embodied in Chinese exports used to fulfill final consumption in the west are significant. In 2010, 1.8 million tonnes of $PM_{2.5}$ produced in China, 38% higher than the annual emissions in the EU27 in 2010, were for Chinese export production. Over 60% of China's embodied $PM_{2.5}$ emissions in exports are triggered by consumption in OECD countries.

China has designed and implemented timely regulations for mitigating $PM_{2.5}$. For example, the State Council has announced 'ten measures of air pollution reduction' in Spring 2013 that emphasizes the phasing out of inefficient industrial boilers, improving fuel quality, promoting cleaner production, optimizing the energy mix, enhancing regulations, and a marketing stimulus for green energy development. All these measures aim at cutting direct emissions from production activities rather than rectifying the underlining drivers which lead to the emission increases through the national and international supply chain. While strong policies continue in strengthening investments in low emission production technologies, more effort is needed to improve the economic structure and adjust export patterns. Pollution intensive exports need be considered: limiting highly emission intensive but low value-added exports can be an important step to effectively reduce $PM_{2.5}$ emissions in China.

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