



**UNIVERSITY OF LEEDS**

This is a repository copy of *The socioeconomic drivers of China's primary PM emissions*.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/80137/>

Version: Published Version

---

**Article:**

Guan, D, Zhang, Q, Su, X et al. (4 more authors) (2014) The socioeconomic drivers of China's primary PM emissions. *Environmental Research Letters*, 9 (2). 024010. ISSN 1748-9326

<https://doi.org/10.1088/1748-9326/9/2/024010>

---

**Reuse**

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

**Takedown**

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing [eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk) including the URL of the record and the reason for the withdrawal request.



[eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk)  
<https://eprints.whiterose.ac.uk/>

The socioeconomic drivers of China's primary PM<sub>2.5</sub> emissions

This content has been downloaded from IOPscience. Please scroll down to see the full text.

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 194.80.235.251

This content was downloaded on 12/08/2014 at 13:46

Please note that [terms and conditions apply](#).

# The socioeconomic drivers of China's primary PM<sub>2.5</sub> emissions

Dabo Guan<sup>1,2</sup>, Xin Su<sup>3</sup>, Qiang Zhang<sup>1</sup>, Glen P Peters<sup>4</sup>, Zhu Liu<sup>5</sup>, Yu Lei<sup>6</sup> and Kebin He<sup>3</sup>

<sup>1</sup> Ministry of Education Key Laboratory for Earth System Modeling, Center for Earth System Science, Tsinghua University, Beijing 100084, People's Republic of China

<sup>2</sup> Centre for Climate Change Economics and Policy, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

<sup>3</sup> State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, People's Republic of China

<sup>4</sup> Center for International Climate and Environmental Research-Oslo (CICERO), N-0318, Norway

<sup>5</sup> Sustainability Science Program and Energy Technology Innovation Policy Project, Kennedy School of Government, Harvard University, Cambridge, MA 01238, USA

<sup>6</sup> Key Laboratory of Environmental Planning and Policy Simulation, Chinese Academy for Environmental Planning, Beijing 100012, People's Republic of China

E-mail: [qiangzhang@tsinghua.edu.cn](mailto:qiangzhang@tsinghua.edu.cn) and [hekb@tsinghua.edu.cn](mailto:hekb@tsinghua.edu.cn)

Received 23 July 2013, revised 19 November 2013

Accepted for publication 8 January 2014

Published 19 February 2014

## Abstract

Primary PM<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub>, 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<sub>2.5</sub>, 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<sup>2</sup> area in total, 15% of national territory (Xinhua News 2013). PM<sub>2.5</sub> (particulate matter smaller than

2.5 micrometers) is the major component of smog. In Beijing, the concentration of PM<sub>2.5</sub> passed 1000  $\mu\text{g m}^{-3}$ , 40 times higher than the World Health Organization (WHO) standard level for good health (Patience 2013). PM<sub>2.5</sub>, 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*



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](https://creativecommons.org/licenses/by/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

2006, Xu *et al* 2004). In recent years, Chinese scholars have used PM<sub>2.5</sub> on-site measured samples to identify the chemical composition of PM<sub>2.5</sub> 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<sub>2</sub> 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<sub>2.5</sub> emissions in China. Second, we continue with a sectoral analysis of annual emission contributions. Third, we quantify the socioeconomic factors driving China's PM<sub>2.5</sub> emission changes between 1997–2010. We focus on the primary sources of PM<sub>2.5</sub> emission generation that account for a large fraction of ambient PM<sub>2.5</sub> concentration in China (Zheng *et al* 2005). The primary sources of PM<sub>2.5</sub> 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<sub>2</sub>), ammonia (NH<sub>3</sub>), nitrogen oxides (NO<sub>x</sub>), and volatile organic compounds (VOCs) (Megaritis *et al* 2013). The secondary sources also contribute to PM<sub>2.5</sub> 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. **X**); vectors by bold, upright lower case letters (e.g. **x**), and scalars by italicized lower case letters (e.g. *x*).

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

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y} \quad (1)$$

where each column of the matrix **A** specifies the sectoral inputs required to produce one unit of output (the economy's direct

requirements matrix) and **y** is the final demand after which no further processing occurs. When solved for the output, this equation yields:

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

We then couple the output with an environmental matrix (e.g. PM<sub>2.5</sub> emission), **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:

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

with **f** representing the sector-wise total supply chain emissions to meet the final demand **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<sub>2.5</sub> emissions across countries (Peters and Hertwich forthcoming, Weber and Matthews 2007). We remove the imports from the Chinese IO data (**A** and **y**) to isolate the role of domestic factors (**A<sub>d</sub>** and **y<sub>d</sub>**) leading to changes in China's PM<sub>2.5</sub> 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<sub>2.5</sub> emission are rare. This prevents us from estimating embodied PM<sub>2.5</sub> emissions in Chinese imports.

### 2.3. Structural decomposition analysis

PM<sub>2.5</sub> emission changes can be decomposed by using the input–output structural decomposition analysis (SDA), following our previous analyses on CO<sub>2</sub> emissions (Guan *et al* 2009, 2008, Minx *et al* 2011, Peters *et al* 2007). The PM<sub>2.5</sub> emissions are decomposed into five driving forces

$$PM_{2.5} = p \cdot \mathbf{F} \cdot \mathbf{L} \cdot \mathbf{y}_s \cdot \mathbf{y}_v$$

where population (*p*) is measured by person; emission intensity (**F**) is measured by tonnes of emission per unit output; production structure (**L**) is measured by amount of sectoral outputs per final unit, consumption structure (**y<sub>s</sub>**) is measured by proportions of sectoral consumption in total consumption, and per capita consumption volume (**y<sub>v</sub>**) 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).

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

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](http://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).

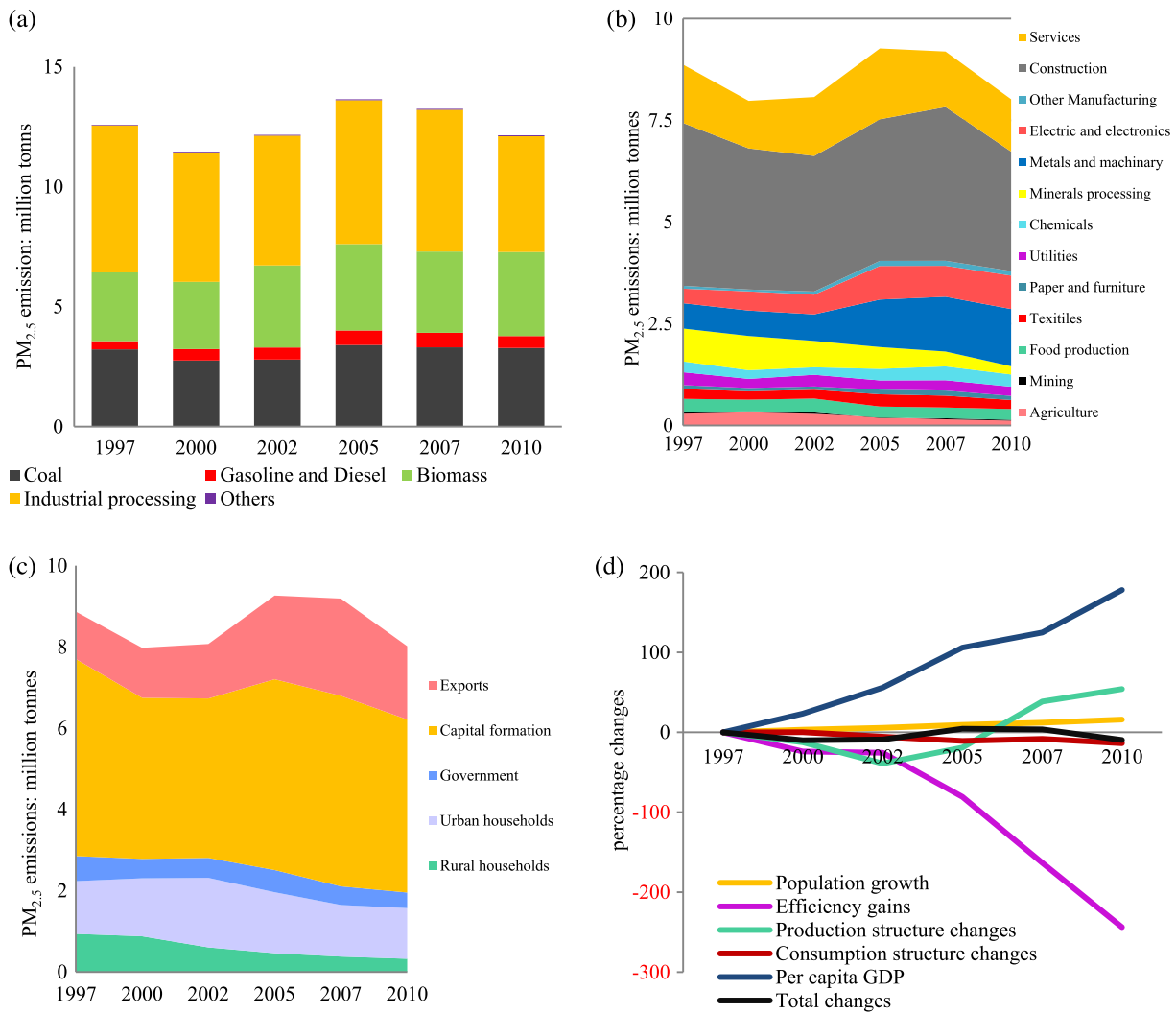
We have selected an MEIC dataset which is based on the province-sum level energy use data as a basis to estimate China’s overall primary  $PM_{2.5}$  emissions. The accuracy and reliability of the MEIC dataset has been validated by using satellite observations (Kondo *et al* 2011, Lin *et al* 2010). 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<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub> emissions to different final demand categories. Capital formation is the largest contributor to production-related primary PM<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub> emissions. Our structural decomposition analysis (see figure 1(d)) shows that efficiency gains have avoided 22 million tonnes (–244%) of PM<sub>2.5</sub> 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<sub>2.5</sub> 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

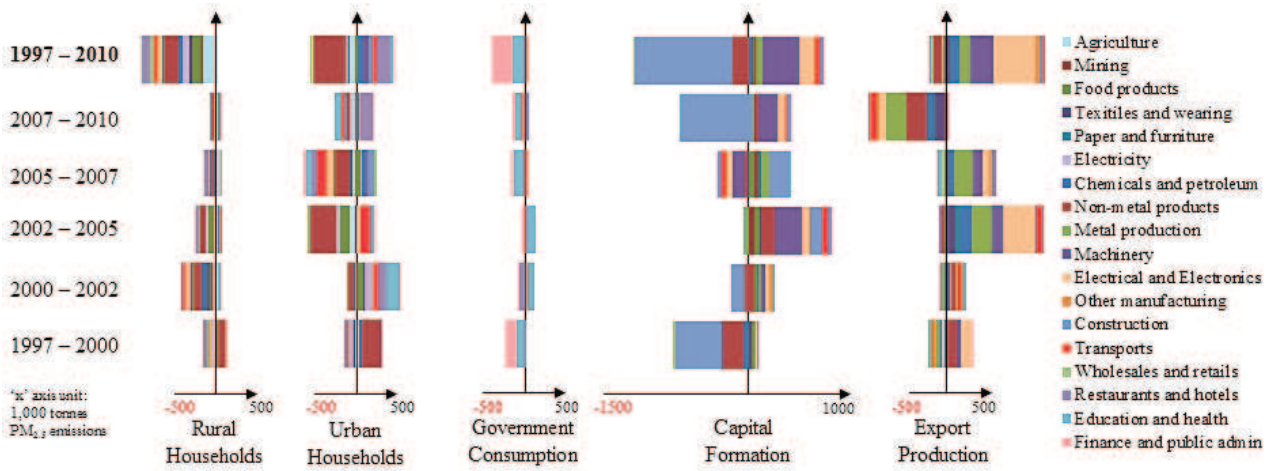


Figure 2. Emission changes in sectoral details contributed by final demand categories during 1997–2010.

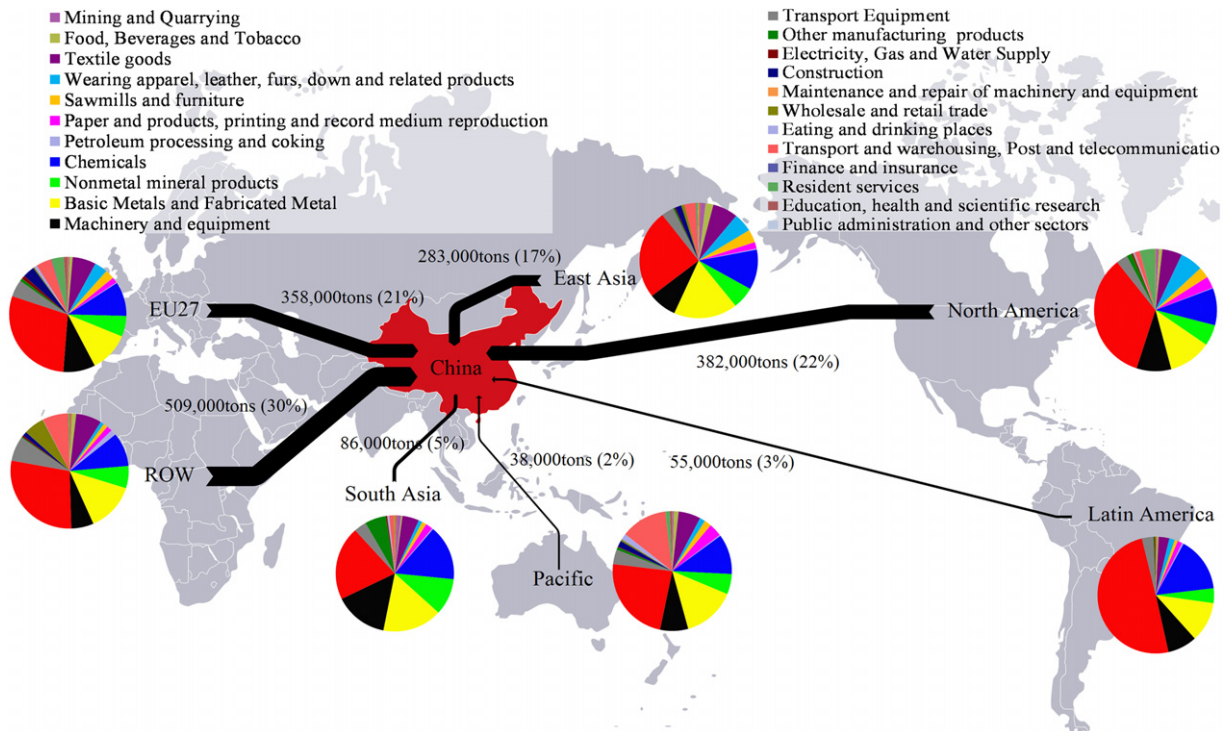


Figure 3. Outsourcing  $PM_{2.5}$  to China by trade.

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<sub>2.5</sub> 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<sub>2.5</sub> emissions in China

The Chinese government is making a great effort to curb PM<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub> emissions, or over 1 million tonnes, of primary PM<sub>2.5</sub> is for export production to satisfy consumptions in OECD countries (figure 3). In particular, 22% or 382 thousand tonnes of primary PM<sub>2.5</sub> emissions in 2010 are embodied in Chinese exports to North America (United States and Canada). One-fifth or 358 thousand tonnes of primary PM<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub> emissions from a consumption perspective. Production-related primary PM<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub> emissions. Although capital investment is always the largest final demand category in driving PM<sub>2.5</sub> 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<sub>2.5</sub> 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<sub>2.5</sub> emissions in exports are triggered by consumption in OECD countries.

China has designed and implemented timely regulations for mitigating PM<sub>2.5</sub>. 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<sub>2.5</sub> emissions in China.

## Acknowledgments

The authors are thankful for support provided by the National Science Foundation of China (41328008, 41222036

and 71341025), Tsinghua University Initiative Research Program (2011Z01026). Dabo Guan acknowledges the UK ESRC funding for the Centre for Climate Change Economics and Policy (CCCEP). Glen Peters acknowledges funding from the Norwegian Research Council project 'Centre for Strategic Challenges in International Climate and Energy Policy (CI-CEP)'. Zhu Liu acknowledges the Giorgio Ruffolo fellowship and the support from Italy's Ministry for Environment, Land and Sea.

## References

- Ang B W 2004 Decomposition analysis for policymaking in energy: which is the preferred method? *Energy Policy* **32** 1131–9
- Ang B W 2005 The LMDI approach to decomposition analysis: a practical guide *Energy Policy* **33** 867–71
- Ang B W and Liu F L 2001 A new energy decomposition method: perfect in decomposition and consistent in aggregation *Energy* **26** 537–48
- Cao J J, Lee S C, Ho K F, Zhang X Y, Zou S C, Fung K, Chow J C and Watson J G 2003 Characteristics of carbonaceous aerosol in the Pearl River Delta Region, China during the 2001 Winter period *Atmos. Environ.* **37** 1451–60
- Chen Q, Kang C, Xia Q and Guan D 2011 Primary exploration of the low-carbon technology roadmap of China's power sector *Energy* **36** 1500–12
- Cheng Z L, Lam K S, Chan L Y, Wang T and Cheng K K 2000 Chemical characteristics of aerosols at coastal station in Hong Kong. I. Seasonal variation of major ions, halogens and mineral dusts between 1995 and 1996 *Atmos. Environ.* **34** 2771–83
- Chong W H B, Guan D and Guthrie P 2012 Comparative analysis of carbonization drivers in China's mega-cities *J. Ind. Ecol.* **16** 564–75
- Dhakal S 2009 Urban energy use and carbon emissions from cities in China and policy implications *Energy Policy* **37** 4208–19
- Duan F K, He K B, Ma Y L, Yang F M, Yu X C, Cadle S H, Chan T and Mulawa P A 2006 Concentration and chemical characteristics of PM<sub>2.5</sub> in Beijing, China: 2001–2002 *Sci. Total Environ.* **355** 264–75
- EEA 2012 European Union emission inventory report 1990–2010 under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP) *Rep.*, European Environment Agency
- Feng K, Davis S J, Li X, Sun L, Guan D, Liu W, Zhu L and Hubacek K 2013 Outsourcing CO<sub>2</sub> within China *Proc. Natl Acad. Sci. USA* **110** 11654–9
- Feng K, Hubacek K, Siu Y and Guan D 2012 Analyzing drivers of regional carbon dioxide emissions for China *J. Ind. Ecol.* **16** 600–11
- Guan D and Barker T S 2012 Low carbon development in the least developed region: a case study of Guangyuan, Sichuan province, Southwest China *Natural Hazards* **62** 243–54
- Guan D, Hubacek K, Weber C L, Peters G P and Reiner D M 2008 The drivers of Chinese CO<sub>2</sub> emissions from 1980 to 2030 *Glob. Environ. Change* **18** 626–34
- Guan D, Liu Z, Geng Y, Lindner S and Hubacek K 2012 The gigatonne gap in China's carbon dioxide inventories *Nature Clim. Change* **2** 672–5
- Guan D, Peters G P, Weber C L and Hubacek K 2009 Journey to world top emitter—an analysis of the driving forces of China's recent emissions surge *Geophys. Res. Lett.* **36** L04709
- Guan D and Reiner D 2009 Emissions affected by trade among developing countries *Nature* **462** 159
- Hao J, Wang S, Liu B and He K 2000 Designation of acid rain and SO<sub>2</sub> control zones and control policies in China *J. Environ. Sci. Health A* **35** 1901–14
- He K, Yang F, Ma Y, Zhang Q, Yao X, Chan C K, Cadle S, Chan T and Mulawa P 2001 The characteristics of PM<sub>2.5</sub> in Beijing, China *Atmos. Environ.* **35** 4959–70
- Helble J J, DeVito M S, Wu C-Y, Smith F L and Marrack D 2000 Combustion aerosols: factors governing their size and composition and implications to human health *J. Air Waste Manage. Assoc.* **50** 1619–22
- Huang X-F, He L-Y, Hu M and Zhang Y-H 2006 Annual variation of particulate organic compounds in PM<sub>2.5</sub> in the urban atmosphere of Beijing *Atmos. Environ.* **40** 2449–58
- Kondo Y, Oshima N, Kajino M, Mikami R, Moteki N, Takegawa N, Verma R L, Kajii Y, Kato S and Takami A 2011 Emissions of black carbon in East Asia estimated from observations at a remote site in the East China Sea *J. Geophys. Res. Atmos.* **116** D16201
- Lei Y, Zhang Q, He K B and Streets D G 2011 Primary anthropogenic aerosol emission trends for China, 1990–2005 *Atmos. Chem. Phys.* **11** 931–54
- Leontief W 1986 *Input–Output Economics* 2nd edn (New York: Oxford University Press)
- Lin J, McElroy M B and Boersma K F 2010 Constraint of anthropogenic NO<sub>x</sub> emissions in China from different sectors: a new methodology using multiple satellite retrievals *Atmos. Chem. Phys.* **10** 63–78
- Lindner S, Liu Z, Guan D, Yong G and Li X 2013 CO<sub>2</sub> emissions from China's power sector at the province level: consumption versus production perspectives *Renew. Sustainable Energy Rev.* **19** 164–72
- Liu Z, Geng Y, Lindner S and Guan D 2012a Uncovering China's greenhouse gas emission from regional and sectoral perspectives *Energy* **49** 1059–68
- Liu Z, Geng Y, Lindner S, Zhao H, Fujita T and Guan D 2012b Embodied energy use in China's industrial sectors *Energy Policy* **49** 751–8
- Liu Z, Guan D, Crawford-Brown D, Zhang Q, He K and Liu J 2013 Energy policy: a low-carbon roadmap for China *Nature* **500** 143–5
- Megaritis A G, Fountoukis C, Charalampidis P E, Pilinis C and Panis S N 2013 Response of fine particulate matter concentrations to changes of emissions and temperature in Europe *Atmos. Chem. Phys.* **13** 3423–43
- Miller R E and Blair P D 2009 *Input–Output Analysis: Foundations and Extensions* (Cambridge: Cambridge University Press)
- Minx J C, Baiocchi G, Peters G P, Weber C L, Guan D and Hubacek K 2011 A carbonizing dragon: China's fast growing CO<sub>2</sub> emissions revisited *Environ. Sci. Technol.* **45** 9144–53
- National Bureau of Statistics 1996–2012 *China Statistical Yearbook* (Beijing: China Statistics Press)
- National Bureau of Statistics 2010 *China Statistical Yearbook 2009* (Beijing: China Statistics Press)
- National Bureau of Statistics 2011a *China Energy Statistical Yearbook 2010* (Beijing: China Statistics Press)
- National Bureau of Statistics 2011b *China Statistical Yearbook 2010* (Beijing: China Statistics Press)
- National Bureau of Statistics 2012 *China Statistical Yearbook 2012* (Beijing: China Statistics Press)
- National Development and Reform Commission (NDRC) 2011 *The 12th Five-Year Plan Outline of National Economy and Social Development of People's Republic of China*, Beijing
- Patience M 2013 Beijing smog: when growth trumps life in China, *BBC* edited, Beijing [www.bbc.co.uk/news/magazine-21198265](http://www.bbc.co.uk/news/magazine-21198265)
- Peters G P, Webber C, Guan D and Hubacek K 2007 China's growing CO<sub>2</sub> emissions—a race between lifestyle changes and efficiency gains *Environ. Sci. Technol.* **41** 5939–44

- Peters G P and Hertwich E G 2008 CO<sub>2</sub> embodied in International trade with implications for global climate policy *Environ. Sci. Technol.* **42** 1401–7
- Peters G P, Guan D, Hubacek K, Minx J and Weber C 2010 Effects of China's economic growth *Science* **328** 825–6
- Rose A and Casler S 1996 Input–output structural decomposition analysis: a critical appraisal *Econ. Sys. Res.* **8** 33–62
- Skelton A, Guan D, Peters G P and Crawford-Brown D 2011 Mapping flows of embodied emissions in the global production system *Environ. Sci. Technol.* **45** 10516–23
- Song Y, Zhang Y, Xie S, Zeng L, Zheng M, Salmon L G, Shao M and Slanina S 2006 Source apportionment of PM<sub>2.5</sub> in Beijing by positive matrix factorization *Atmos. Environ.* **40** 1526–37
- Suh S 2006 Are services better for climate change? *Environ. Sci. Technol.* **40** 6555–60
- United Nations 1999 Handbook of input–output table compilation and analysis *Studies in Methods Series F, No 74. Handbook of National Accounting United Nations* (New York: United Nations)
- Wang H, Dwyer-Lindgren L, Lofgren K T, Rajaratnam J K, Marcus J R, Levin-Rector A, Levitz C E, Lopez A D and Murray C J L 2012 Age-specific and sex-specific mortality in 187 countries, 1970–2010: a systematic analysis for the global burden of disease study 2010 *Lancet* **380** 2071–94
- Wang X, Bi X, Sheng G and Fu J 2006 Chemical composition and sources of PM<sub>10</sub> and PM<sub>2.5</sub> aerosols in Guangzhou, China *Environ. Monit. Assess.* **119** 425–39
- Weber C L and Matthews H S 2007 Embodied environmental emissions in US international trade, 1997–2004 *Environ. Sci. Technol.* **41** 4875–81
- Weber C L, Peters G P, Guan D and Hubacek K 2008 The contribution of Chinese exports to climate change *Energy Policy* **36** 3572–7
- Xinhua News 2013 70 Chinese cities suffer serious air pollution in Q3 *Xinhua Net* edited, Beijing <http://news/xinhuanet.com>
- Xu M, Yan R, Zheng C, Qiao Y, Han J and Sheng C 2004 Status of trace element emission in a coal combustion process: a review *Fuel Process. Technol.* **85** 215–37
- Yao Q, Li S Q, Xu H W, Zhuo J K and Song Q 2010 Reprint of: studies on formation and control of combustion particulate matter in China: a review *Energy* **35** 4480–93
- Yienger J J, Galanter M, Holloway T A, Phadnis M J, Guttikunda S K, Carmichael G R, Moxim W J and Levy H 2000 The episodic nature of air pollution transport from Asia to North America *J. Geophys. Res. Atmos.* **105** 26931–45
- Zhang L et al 2008 Transpacific transport of ozone pollution and the effect of recent Asian emission increases on air quality in North America: an integrated analysis using satellite, aircraft, ozonesonde, and surface observations *Atmos. Chem. Phys.* **8** 6117–36
- Zhang Q, Streets D G, He K and Klimont Z 2007 Major components of China's anthropogenic primary particulate emissions *Environ. Res. Lett.* **2** 045027
- Zhang Q et al 2009 Asian emissions in 2006 for the NASA INTEX-B mission *Atmos. Chem. Phys.* **9** 5131–53
- Zhao P S, Dong F, He D, Zhao X J, Zhang X L, Zhang W Z, Yao Q and Liu H Y 2013 Characteristics of concentrations and chemical compositions for PM<sub>2.5</sub> in the region of Beijing, Tianjin, and Hebei, China *Atmos. Chem. Phys.* **13** 4631–44
- Zhao Y, Wang S, Duan L, Lei Y, Cao P and Hao J 2008 Primary air pollutant emissions of coal-fired power plants in China: current status and future prediction *Atmos. Environ.* **42** 8442–52
- Zheng M, Salmon L G, Schauer J J, Zeng L, Kiang C S, Zhang Y and Cass G R 2005 Seasonal trends in PM<sub>2.5</sub> source contributions in Beijing, China *Atmos. Environ.* **39** 3967–76