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$PM_{2.5}$ footprint of household energy consumption

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HIGHLIGHTS

- An energy-related $PM_{2.5}$ footprint inventory framework for households is constructed.
- $PM_{2.5}$ footprint is decreasing from urban households (high income) to rural households (low income).
- Sectors related to food, residence and health care are the main contributors of $PM_{2.5}$ footprint.

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ABSTRACT

Particulate matter 2.5 ($PM_{2.5}$) as a major hazardous constituent is strongly associated with household energy consumption. In this paper, we investigate the $PM_{2.5}$ footprint of household energy consumption in Beijing based on input–output analysis. An inventory of primary and secondary household energy consumption is developed to quantify the direct $PM_{2.5}$ emissions. The household $PM_{2.5}$ footprint is then traced through goods or services that ultimately consumed by households to unveil the indirect $PM_{2.5}$ emissions triggered by economic activities. $PM_{2.5}$ fingerprint is also proposed to describe the characteristic of household $PM_{2.5}$ footprint. Results show that $PM_{2.5}$ footprint of Beijing households in 2010 is 7831.36 kt, of which 92.61% is contributed by urban households. The source of direct $PM_{2.5}$ emissions in urban area is diversified, which is composed of coal (42.07%), heat and electricity (32.83%), gasoline (21.29%), natural gas (3.04%) and liquefied petroleum gas (0.77%), while in rural area, coal (98.09%) plays a dominant role. The indirect $PM_{2.5}$ accounts for 99.96% of the total footprint in urban area, about one third of which is contributed by sectors of “Food Processing and Production”, “Healthcare and Social Security”, and “Farming, Forestry, Animal Husbandry and Fishery”. The disparity between urban and rural households $PM_{2.5}$ footprints is further evaluated with income levels. The $PM_{2.5}$ footprint from living expenditures of urban households is found to be nearly twice as much as that of rural households. Such inventory of $PM_{2.5}$ footprint and examination of drivers for $PM_{2.5}$ emissions may be essential for urban pollution mitigation policy.

1. Introduction

Due to rapid industrialization and urbanization, occurrence of haze characterized by the high fine particulate matter ($PM_{2.5}$) levels has been widely reported over the past two decades, especially in the most developed and high-populated cities [1,2]. Urban $PM_{2.5}$ originates mainly from anthropogenic activities remains much challenging to trace the sources of PM and quantify their real contributions, which will smooth the implementation of control strategies to mitigate air pollution in cities [3,4].

Previous studies showed that the major contributors of direct $PM_{2.5}$ emissions were the fossil fuel combustion and heavy industrial production [5,6]. Some researchers suggested reducing the emissions by identifying the most energy-efficient path through an extended greedy algorithm and integrating the optimal route to cut down on energy consumption [7,8]. However, from the consumption-based perspective, considering the emissions embodied in goods or services that are traded through economic activities and then ultimately attributed to consumers, this accelerating growth of $PM_{2.5}$ emissions in recent decades is mainly triggered by the development of equipment, machinery and

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Table 1
The $PM_{2.5}$ emission factors of household energy consumption.

	Coal	Gasoline	Diesel Oil	LPG	Natural Gas	Heat	Electricity
	(g·kg^{-1})				(g·m^{-3})	(g/kJ)	(g/kWh)
Urban	1.89 [38]	0.31 [36]	0.5 [36]	0.17 [36]	0.10 [39]	0.0005	1.41
Rural	6.86 [37]	0.31 [36]	0.5 [36]	0.17 [36]	0.10 [39]	/	1.41

devices manufacturing, and the expansion of construction [9–11]. Various studies have indicated that the indirect emissions from final consumers are far more serious than those direct ones [12–15]. Mitigation efforts of air pollution should therefore be devoted to emissions embodied in urban sectors, particularly the households with $PM_{2.5}$ emissions contributing notably to ambient air pollution. For example, Liu et al. [16] evaluated the contribution of residential air pollutant emissions to regional air pollution in key regions of China during the heating season, and found that the reduction in residential emissions markedly improved the air quality.

Ecological footprint, proposed by Rees and Wackernagel, stands for the total area of land required to sustain an urban region [17,18]. It traces throughput of energy and resource in a specific region by transforming them into biologically productive areas required to produce the products [19]. Through trade and natural flows of goods and services, wealthy nations appropriate the carrying capacity of remote areas, which is more than their fair share [20]. So far, footprint family has been expanded to carbon footprint [21,22], water footprint [23,24] and energy footprint, etc. [25,26]. Generally, methods of quantifying footprint can be classified into two different directions, i.e., bottom-up mode based on process analysis and top-down model based on input-output analysis [27,28]. Both methodologies have been developed to examine the full life cycle environmental impacts, of which the top-down approach can distribute the responsibility to the intermediate and final consumers as well as identify driving forces, which has been widely applied to investigate the environmental emissions [29,30].

Integrating the $PM_{2.5}$ emissions with footprint idea, we define $PM_{2.5}$ footprint as the amount of $PM_{2.5}$ emissions directly and indirectly produced throughout the entire life cycle of a product /service or within a certain set of boundary. The $PM_{2.5}$ emissions from households can thus be estimated from two aspects: direct $PM_{2.5}$ emissions resulting from fuel combustion for heating, cooking and driving, and indirect $PM_{2.5}$ emissions caused by producing the products or consuming energy in economic sectors to satisfy the needs and desires of households. To avoid double counting, we strictly separate fuel and products consumed by households according to the form of fuel or goods and the way they are produced and consumed. Direct emissions are calculated based on inventory analysis, while indirect emissions are estimated with input-output analysis. In this paper, we investigate the household $PM_{2.5}$ footprint in a city, aiming to provide insights from consumer and life cycle perspective when formulating urban air pollution mitigation policy.

This paper is organized as follows. In Section 2, the methodology of $PM_{2.5}$ footprint calculation is briefly described. Section 3 presents the distribution of $PM_{2.5}$ footprints resulted from households. Section 4 presents the discussions and conclusions. Finally, policy implications are provided in Section 5.

2. Materials and methods

2.1. Study site

Beijing is the financial, technological and political center of China. With nearly 20 million permanent residents, household expenditure in Beijing has dramatically increased by 134.71% since 2000. Although coal combustion has been banned in most urban areas, rural households' cooking and space heating in Beijing are still heavily relied on coal combustion, especially scattered coal [31]. In 2010, the annual average concentration of daily $PM_{2.5}$ was 101.2 μg/m^3 [32], which largely exceeded the standard concentration of $PM_{2.5}$ (35 μg/m^3). According to the previous study [33], particulate matter emission abatement technologies utilized in coal-fired power plant in Beijing are mainly wet electrostatic precipitator (WET-ELE) and electrostatic dust collector (ELE). Besides, households take up 17.2% of heating consumption and 17.8% of electricity consumption [31].

2.2. Data source

The activity data for $PM_{2.5}$ emissions are derived from a wide range of studies and reports. $PM_{2.5}$ emission factors for fuel combustion from households, power plant and heating system are mostly taken from USEPA [34], Zhang et al. [35,36], and Jiang and Tang [37], which are presented in Table 1. Energy consumption by urban and rural households complied in Table 2 can be accessed from the Beijing Statistical Yearbook 2011 [31]. The original input-output table of 42 economic sectors corresponding to Beijing's economy in 2010 is obtained from Beijing Municipal Bureau of Statistics. Population of permanent residents from rural and urban areas and annual expenditure of households are derived from the Beijing Statistic Yearbook [31]. Removal efficiencies of $PM_{2.5}$ emissions from power plant based on different technologies, mainly the wet scrubbers (WET) and ELE, can be accessed from previous research [38–40]. The distributions of emission abatement technologies applied to power plant in Beijing are collected from He et al. [33].

2.3. Direct household $PM_{2.5}$ emission

The energy utilized in urban and rural households can be classified into primary and secondary energy. Primary energy contains scattered coal that is directly consumed by residents and catering services for heating and cooking [41], vehicle fuel, natural gas, and liquefied petroleum gas (LPG). Secondary energy mainly includes the electricity and heat. $PM_{2.5}$ emissions from production and supply of electricity and heat are embodied in products based on consumption-based perspective. However, while calculating $PM_{2.5}$ emission related energy consumption from households, consumptions of electricity and heat are regarded as direct source of $PM_{2.5}$ footprint. It is assumed that household $PM_{2.5}$ emissions directly from primary energy are immediately released to the atmosphere without being controlled. Considering coal properties (such as sulfur and fly ash content) and coal forms (like honeycomb briquette and pulverized coal), two $PM_{2.5}$ emission intensities are respectively set for the urban and rural areas of Beijing.

The direct $PM_{2.5}$ emissions of primary energy consumed by

Table 2
The amount of household energy consumption of Beijing.

	Coal	Gasoline	Diesel Oil	LPG	Natural Gas	Heat	Electricity
	(10^6 t)				(10^8 m^3)	(10^{10} kJ)	(10^8 kWh)
Urban	0.72	2.24	0.00	0.15	9.89	2851.00	95.38
Rural	2.06	0.06	0.01	0.07	0.26	0.00	43.95