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Socioeconomic Drivers of Mercury Emissions in China from 1992 to 2007

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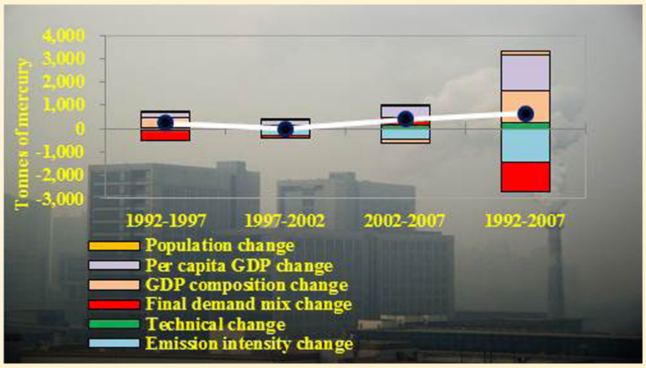
Supporting Information

ABSTRACT: Mercury emissions in China have increased by 164% during 1992–2007. While major mercury producers were among energy combustion and nonferrous metal sectors, little is known for the socioeconomic factors driving the growth of emissions. In this paper we examine the underlying drivers and their contributions to the change of mercury emissions. Results show that changes in per capita GDP and GDP composition led to increased emissions which offset the reduction of emissions made possible by technology-induced decrease of mercury emissions intensity and changes in final demand mix. In particular, changes in final demand mix caused decreasing mercury emissions from 1992 to 2002 and increasing emissions from 2002 to 2007. Formation of fixed capital was the dominant driver behind the increase of mercury emissions, followed by the increasing urban population and net exports. This systems-based examination of socioeconomic drivers for China's mercury emission increase is critical for emission control by guiding policy-making and targets of technology development.



1. INTRODUCTION

Exposure to mercury has highly toxic effects on human and wildlife health.[1,2] Given its wide distribution in the natural environment[3] and global transport potential,[4] mercury is considered as a global pollutant.[4,5] Developed countries have introduced control measures to reduce mercury emissions since the late 1980s.[6] However, the recent rapid industrialization in developing countries, especially in Asia, has substantially contributed to the increase of global mercury emissions.[3,7]

Spatially explicit global mercury emission inventories have been developed.[3,4,7−12] China is regarded as the largest contributor,[3] accounting for approximately 27% of global anthropogenic mercury emissions.[11] China's mercury emissions are roughly three times the emissions in the U.S. (second largest emitter) and India (third largest emitter) combined.[3] Given its importance in global mercury emissions, China has been the target of many studies on anthropogenic mercury emissions.[13−24]

Previous studies on China's mercury emissions mainly focus on identifying and evaluating direct mercury producers from a production perspective, such as energy combustion[17,18,25] and the burning of household wastes.[26] Such a production perspective, however, does not reveal the role that socioeconomic drivers have played behind the end-of-pipe mercury emissions. China has experienced and will continue to experience tremendous socioeconomic transition during its industrialization and urbanization processes, which will significantly impact China's anthropogenic mercury emissions. It is therefore crucial to understand how socioeconomic drivers have been shaping China's anthropogenic mercury emission trajectory, in order to better manage China's mercury emissions.

In this study, we analyze the socioeconomic drivers that contributed to the growth of China's mercury emissions from 1992 to 2007. The in-depth analysis of these drivers is critical for curbing China's soaring mercury emissions. We also discuss

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potential policy implications of the results for mitigating China's anthropogenic mercury emissions.

2. METHODOLOGY AND DATA

2.1. Structural Decomposition Analysis. Decomposition analysis (DA) methods have been widely used to uncover socioeconomic drivers of environmental pressures.[27] The DA methods are mainly grouped into two categories:[28] index decomposition analysis (IDA) and structural decomposition analysis (SDA). The IDA methods include the IPAT equation, Kaya Identity, improved LMDI, and STRIPAT.[29−32] The IDA methods have advantages on less data requirement, sound theoretical foundation, adaptability, ease of use, and ease of result interpretation.[33] However, IDA methods cannot reflect structural characteristics of the economy (such as production and final demand structures), as economic sectors are highly aggregated and final demand is not considered in IDA methods. This disadvantage limits policy decisions at sectoral or product scale as well as allocating responsibilities for environmental impacts throughout whole supply chains. The SDA based on environmental input-output (IO-SDA) model can solve this limitation of IDA methods. The IO-SDA model is widely used to analyze the contribution of socioeconomic factors to physical flows of the economy.[27,34] The environmental input-output model describes physical flows of the economy from the final demand perspective by eq 1.[35]

Suppose that the economy is divided into n economic sectors. The $n \times 1$ column vectors v, f, and y indicate each sector's mercury emission mass (tonnes of mercury), mercury emission intensity (tonnes of mercury/RMB), and final demand (RMB), respectively. Final demand comprises rural and urban household consumption, government consumption, fixed capital formation, inventory changes, and net exports. The $n \times n$ matrix L is referred to as the *Leontief inverse*, which represents the intersectoral flows for one unit of sectoral output.[35] Elements of the matrix L are regarded to represent technical levels of the economy. Changes in the matrix L are named as technical change in this study.

$$v = f\mathrm{L}y \tag{1}$$

The $n \times 1$ column vector y indicating each sector's final demand can be further decomposed into the form of eq 2.[36−38] The $n \times k$ matrix M indicates the final demand mix of which m_{ik} indicates the demand of products from sector i normalized by the sum of the k^{th} final demand column, where k indicates the final demand categories such as rural and urban household consumption, government consumption, fixed capital formation, inventory change, and net exports. The final demand mix M describes the shares of various products in each category of final demands. The $k \times 1$ column vector d indicates the final demand on a per capita basis for each of the final demand categories, which shows per-capita final demand share among final demand categories. The scalar p stands for population.

$$y = \mathrm{M}dp \tag{2}$$

There have been significant changes in China's GDP composition in the past several decades. Thus, we further decompose the $k \times 1$ column vector d into c and g. The $k \times 1$ column vector c represents the GDP composition, which shows the final demand share per unit GDP. The scalar g represents per capita GDP. Equation 1 is therefore converted into eq 3.

$$v = f\mathrm{LM}cgp \tag{3}$$

The structural decomposition form of eq 3 is shown in eq 4.

$$\begin{aligned} \Delta v = {} & \Delta f\mathrm{LM}cgp + f\Delta\mathrm{LM}cgp + f\mathrm{L}\Delta\mathrm{M}cgp + f\mathrm{LM}\Delta cgp \\ & + f\mathrm{LM}c\Delta gp + f\mathrm{LM}cg\Delta p \end{aligned} \tag{4}$$

The notation Δv indicates the change in mercury emissions. The right side of eq 4 indicates the mercury emission changes Δv caused by the mercury emission intensity change Δf, technical change $\Delta\mathrm{L}$, final demand mix change $\Delta\mathrm{M}$, GDP composition change Δc, per capita GDP change Δg, and population change Δp. The SDA has the nonuniqueness problem:[39] There will be $n!$ kinds of decomposition forms if the number of decomposed factors is n. We calculate the average of all possible first-order decomposition forms to address this problem.[34,36,39−42] Details on the IO-SDA model are shown in the Supporting Information. Based on five decomposed factors in previous SDA studies,[36−38] we further decompose per capita final demand volume into GDP composition and per capita GDP to reflect China's great changes of GDP composition. When using the SDA, we generally assume mutual independence among these six factors. In practice, however, there is a certain level of unavoidable dependence among them. This problem is pervasive for DA methods.[43] However, correlation issues among decomposed factors should be concerned in future studies.

2.2. Data Sources. Two categories of data are required to support the SDA: monetary input-output tables (MIOTs) and mercury emissions at the sector level. Chinese MIOTs from 1992, 1997, 2002, and 2007 are from the *National Bureau of Statistics of China*.[44−47] These MIOTs are aggregated into 45-sector form (Table S1 in the Supporting Information) to be consistent with the sector classifications from Chinese energy statistics.[48] Moreover, we convert these MIOTs into 2007 constant prices by the double deflation method.[41,42] The producer price indices used in the conversion are from the *China Statistical Yearbooks*.[49] The 'Others' column, which represents the errors of the different data sources,[41,42,50−52] is removed from the Chinese MIOTs when the total outputs are used to normalize the intermediate delivery matrix. The MIOTs display homogeneity assumption.[53] This assumption creates differences between MIOTs and practical situations. Nevertheless, MIOTs are still widely used in the SDA. The homogeneity assumption can be improved by further disaggregating economic sectors. However, disaggregating sectors is challenging for China, as there are millions of products in the economy and the highest resolution of the current Chinese MIOTs is only of 135 economic sectors.

Chinese anthropogenic mercury emissions result mainly from coal and oil combustion, production activities, and the burning of biomass (grassland, forest, and agricultural residues) and household wastes. Mercury emissions from coal and oil combustion are computed by multiplying energy usage with respective emission factors. Each sector's energy usage data are from the *China Energy Statistical Yearbooks 1993−2008*.[48] The energy usage of sectors except for coal-fired power sector is their terminal energy usage, while that of coal-fired power sector comprises its terminal energy usage and energy feedstock. The mercury emission factors from coal combustion are taken from studies by Wu et al.[19] and Tian et al.,[18] while the mercury emission factors from oil combustion are from Streets et al.[16] Mercury emissions from production activities in 1997 and 2002 are from Wu et al.,[19] while those in 1992 and 2007 are calculated by multiplying product yields[49] by emission factors.[16] Mercury emissions from the burning of biomass are assumed to be unchanged over time because of data unavailability and are taken from Wu et al.[19] In particular, mercury emissions from the burning of agricultural residues in 2007 are from Hu et al.[26] Mercury emissions from the burning of household wastes in 1992, 1997, and 2002 are from Wu et al.,[19] while those in 2007 are from Hu et al.[26] Details for each sector's mercury emissions are shown in the Supporting Information. It is likely that there were uncertainties in Chinese mercury emission factors.[18] The mercury emission factors used in this study were from the recent Chinese literature on the subject, and they were considered acceptable for estimating the Chinese mercury emission inventory. Moreover, uncertainties in Chinese mercury emission factors can be reduced by additional field testing and monitoring in future studies.

In particular, energy usage data of agricultural sectors from 1992 to 2007 and that of the production of foods and equipment in 1992 are aggregated. The aggregated data are disaggregated using proportionate relationships of monetary intermediate allocation data of related rows in Chinese MIOTs, due to the unique sectoral price assumption of MIOTs.[54,55] Taking coal for example, first, we obtain monetary coal usage data of agricultural sectors from the row representing coal extraction of intermediate delivery matrix of Chinese MIOTs. Then, we calculate proportions of each agricultural sector's monetary coal usage in their total. Finally, each agricultural sector's physical coal usage is calculated by multiplying their aggregated physical coal usage by the proportions. Given that China's coal consumption from 1996 to 2003 is considered to be under-reported,[56] we adjust China's coal consumption data in 1997 and in 2002 based on empirical correlations and coal-fired electricity generation from 1953 to 2010 (details are shown in the Supporting Information).

3. OVERALL TREND AND CONTRIBUTION ANALYSIS

China's anthropogenic mercury emissions in 2007 (1,027.9 tonnes) increased by 164.0% from previous 1992 levels (389.3 tonnes) (Table 1), and the increase mainly occurred during the periods of 1992–1997 and 2002–2007. The largest direct emitters were coal and oil combustion and production activities involving nonferrous metals, cement, and mercury ores (Table 1).

Table 1. China's Anthropogenic Mercury Emissions and Corresponding Direct Emitters from 1992 to 2007

	tonne			
sources	1992	1997	2002	2007
energy consumption by production activities	161.8	282.6	240.5	376.4
cement production	12.3	21.3	29.4	54.4
iron and steel production	3.2	4.4	7.3	19.6
caustic soda production	2.4	2.5	0.2	0.0
nonferrous metals smelting	150.9	212.3	294.6	513.6
mercury mining	26.1	37.6	22.3	25.5
battery/fluorescent lamp production	18.1	49.7	6.2	14.1
coal mines spontaneous burning	3.0	3.0	3.0	3.0
biomass burning	10.9	10.9	10.9	11.4
#grassland/savanna burning	4.2	4.2	4.2	4.2
#forest burning	2.8	2.8	2.8	2.8
#agricultural residue burning	3.9	3.9	3.9	4.4
household wastes burning	0.6	0.6	7.7	9.8
total	**389.3**	**624.9**	**622.1**	**1,027.9**

Mercury emissions increased by 60.5% from 1992 to 1997 mainly because of the increasing usage of coal and oil and increasing production activities of nonferrous metals, batteries, and fluorescent lamps. Mercury emissions from 1997 to 2002 remained relatively uniform, with an increase of approximately 100.4 tonnes of mercury from 1997 to 2002 mainly due to the increasing production of cement, iron, steel, and nonferrous metals as well as the increased burning of household wastes. Simultaneously, technological improvements in energy usage and the production of caustic soda, batteries, and fluorescent lamps in addition to a decrease in mercury mining activities during this period resulted in a 103.2-tonne decrease in mercury emissions. During the period from 2002 to 2007, mercury emissions increased by 65.2%, largely because of increased energy usage, production activities, and the burning of agricultural residues and household wastes.

4. KEY DRIVERS OF MERCURY EMISSIONS—DECOMPOSITION ANALYSIS

The change in per capita GDP is the largest driver of the increase in China's mercury emissions from 1992 to 2007 (Figure 1). The per capita GDP is regarded to represent the affluence of the economy in the IPAT equation.[32,57,58] China has been struggling to encourage economic development to improve its affluence in past several decades. The per capita GDP of China in 2007 was over 3 times that of its 1992 level,[49] leading to a 1,554.9-tonne increase in mercury emissions if other factors remain constant (Figure 1).

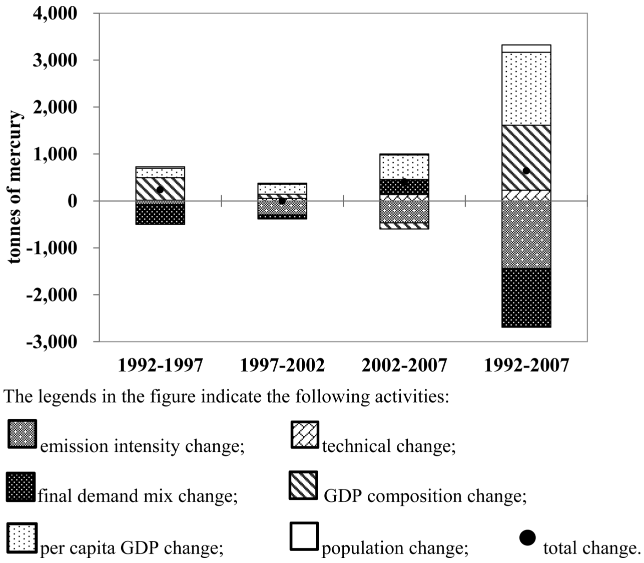


Figure 1. Contribution of changes in socioeconomic factors to changes in anthropogenic mercury emissions from 1992 to 2007.

The change in GDP composition is the second largest driver of the increase in China's mercury emissions from 1992 to 2007 (Figure 1). The GDP composition change during this period led to a 1,382.7-tonne increase in mercury emissions if other factors remain constant (Figure 1). The effect of the change in GDP composition on the increase in mercury emissions gradually weakened from 1992 to 2007 (Figure 1). China has been encouraging massive investments in infrastructures, equipment, and machinery to support rapid socioeconomic development during 1992−2007.[49] In addition, China's export increased sharply during this period,[59] due to its price superiority. Subsequently, during 1992−2007, the fraction of domestic consumption in the GDP gradually decreased, while those of fixed capital formation and international trade in the GDP increased.[49] China aims to increase the fraction of domestic consumption in its economy during the 12th five-year plan period and in future five-year plans. This plan may increase mercury emissions in China.

Technical change was the third largest driver of increased mercury emissions from 1992 to 2007 (Figure 1). China has been encouraging the development of small-scale enterprises to solve employment problems since the reform and opening-up in late 1970s. Many small-scale Chinese enterprises (including a large number of small-scale enterprises producing cement, iron, steel, and nonferrous metals) emerged from 1992 to 2007, of which many were labor and material intensive. Technical change because of the emergence of these small enterprises from 1992 to 2007 increased mercury emissions by 230.2 tonnes if other factors remain constant (Figure 1). The contribution of small-scale enterprises to China's GDP increased from 10.5% to 13.1% during 1992−2007.[49] Small-scale enterprises also created 44.1% of China's industrial job opportunities in 2007.[49] Although small-scale enterprises increased mercury emissions, they are a large contribution to economic development and employment. China is promoting cleaner production[60] and limiting small enterprises operating with inefficient technologies, and these actions may improve technical levels to offset the increase in future mercury emissions.

Population growth also contributed to China's mercury emission increase (Figure 1). China's population in 2007 increased by 12.8% from 1992,[49] although the population growth rate slowed from 1992 to 2007.[49] As a result, population growth led to a 158.0-tonne increase in mercury emissions during this period if other factors remain constant (Figure 1). Concurrently, the effects of population growth on increasing mercury emissions gradually weakened during this period.

Improvements to the intensity of mercury emissions were the main force for mercury emission mitigation from 1992 to 2007 (Figure 1). Energy combustion and production activities were the main sources of mercury emissions (Table 1). Technological improvements in energy usage and improvements in mercury removal technologies during production activities from 1992 to 2007 greatly reduced the intensity of mercury emissions, resulting in an offset in mercury emissions from 1992 to 2007 of 1,438.3 tonnes if other factors remain constant (Figure 1).

The change in final demand mix was another force that offset increases in mercury emissions by approximately 1,248.9 tonnes from 1992 to 2007 if other factors remain constant (Figure 1). China's final demands were dominated by labor-intensive manufactured goods from 1992 to 2002.[44−46] From 2002 to 2007, heavy manufacturing goods dominated final demands,[46,47] as China's heavy manufacturing sectors developed quickly.[49] Heavy manufacturing goods usually have a larger life cycle material intensity than do labor-intensive manufactured goods.[61] Therefore, the change in the final demand mix caused a decrease in mercury emissions from 1992 to 2002, followed by an increase from 2002 to 2007 (Figure 1).

5. DRIVERS FROM FINAL DEMAND PERSPECTIVE

The final demand perspective accounts for both direct and indirect material impacts caused by final demand activities.[50] It is therefore appropriate to allocate responsibilities. The results from the final demand perspective show that changes in urban residential consumption, fixed capital formation, and net exports mainly contributed to China's mercury emission increases from 1992 to 2007 (Figure 2). We then attributed the overall mercury emission changes in Figure 3 to various economic sectors (Figure 3).

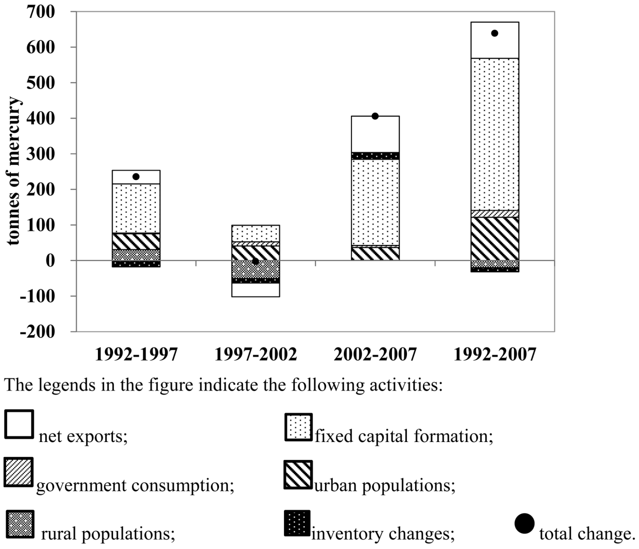
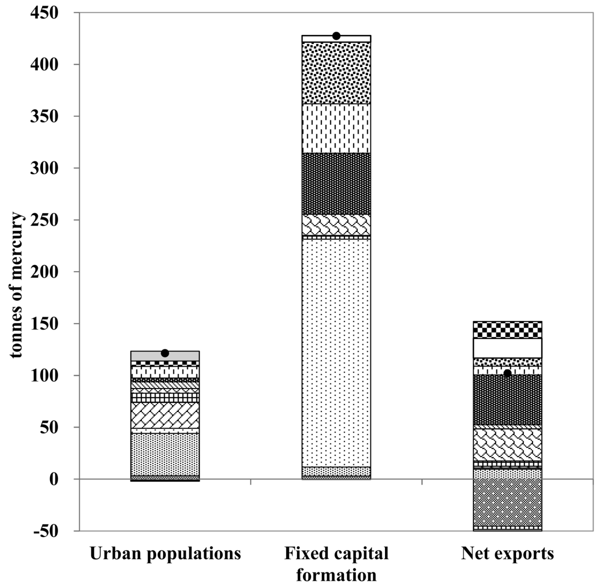


Figure 2. Contribution of changes in different final demand categories to changes in anthropogenic mercury emissions from 1992 to 2007.

The change in urban residential consumption contributed to 19.0% (121.4 tonnes) of increased mercury emissions from 1992 to 2007 (Figure 2), when China was experiencing a stage of rapid urbanization.[49] Approximately 46% of the Chinese population lived in urban areas in 2007, while only 27.5% in 1992.[59] Increasing demands for food, textiles and clothing, vehicles, instruments and office machinery, electric and heat power, buildings and roads, transportation, and commercial services by urban residents from 1992 to 2007 led to the increase in mercury emissions caused by the change in urban residential consumption (Figure 3). China's rapid urbanization will continue to improve the quality of life for the population,[38] and thus the contribution of urban residents to China's mercury emissions will continue to increase in the future.

The change in fixed capital formation created a 66.9% (427.4 tonnes) increase in mercury emissions from 1992 to 2007 (Figure 2), mainly because of the fixed capital formation of machinery and equipment, buildings, and roads (Figure 3). China's rapid urbanization and cleaner production in future years will increase the demands for machinery and equipment, buildings, and roads. This increase will drive the fixed capital formation of these products and further increase the contribution of fixed capital formation to mercury emission increases.

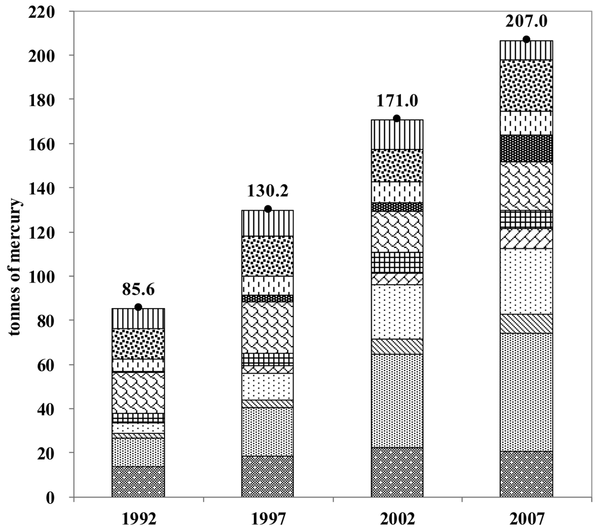
The change in net exports caused a 16.0% (101.9 tonnes) increase in mercury emissions from 1992 to 2007 (Figure 2). Increasing exports of textiles and clothing, metal products, machinery, and equipment accounted for most of the increased mercury emissions from net exports (Figure 3). China is



The legends in the figure indicate the following activities:

□ foods; ▩ textiles and clothing; ▥ metals; □ metal Products; ▨ general and special machinery; ▨ vehicles; ■electric equipment and machinery; ▨electronic and telecommunication equipment; ▦instruments and office machinery; ▨electric and heat power; ▨buildings and roads; ▧transportation; ▨commercial services; ▨other products; ● total change.

Figure 3. Contribution of changes in the final demand of different products to changes in anthropogenic mercury emissions caused by urban populations, fixed capital formation, and net exports from 1992 to 2007.



The legends in the figure indicate the following activities:

▥crops, forestry products and animals; ▨foods; ▨textiles and clothing; ■vehicles; ▨electric equipment and machinery; ▦electronic and telecommunications equipment; ▨instruments and office machinery; ▨electric and heat power; ▧transportation; ▨commercial services; ▨other products; ● total emissions.

Figure 4. Contribution of various products to anthropogenic mercury emissions caused by urban populations from 1992 to 2007.

limiting the export of energy- and pollution-intensive products (such as energy products, cement, and metals) and encouraging the export of high-end products such as equipment and machinery. Encouraged products have a lower life cycle energy intensity[61] and can contribute to the mitigation of China's mercury emissions.

As we can see from results of Figure 2, urban living is a key driver of anthropogenic mercury emission from the final demand perspective. It is expected that China will continue the rapid urbanization in future decades. Urban populations will play a more important role in China's anthropogenic mercury mitigation. Figure 4 illustrated impacts of consumption behavior changes of urban populations on anthropogenic mercury emissions caused by urban populations from 1992 to 2007. Basic living demand (such as crops, foods, electric equipment and machinery, electric and heat power, and basic commercial services) mainly contributed to mercury emissions caused by urban populations before 2002 (Figure 4). Along with the growth of urban residents' income,[59] the contribution of higher living demand (such as clothing, vehicles, electronic and telecommunications equipment, transportation, and high-end commercial services) to mercury emissions caused by urban populations became stronger after 2002 (Figure 4). This change of urban populations' consumption behavior was responsible for the increase in mercury emissions caused by the change in urban residential consumption (Figure 3).

6. POLICY ANALYSIS

It is expected that China will continue its family planning policy to control the population, implying continuously low population growth rate. The contribution of population change to mercury emissions will be gradually weakened. However, GDP is expected to continue increasing on a per capital basis, which will signify the contribution of per capita GDP growth to mercury emission increments. Moreover, domestic consumption is also expected to increase as an additional driver for economic growth. According to results in Figure 1, increasing the fraction of domestic consumption in GDP while reducing those of fixed capital formation and net exports will contribute to increasing mercury emissions. Thus, among those six socioeconomic factors, mercury mitigation should mainly rely on the improvement of technology to reduce emission intensity and the optimization of final demand mix.

China has been promoting cleaner production in a variety of industries since 2003. Moreover, small enterprises with inefficient technologies are being closed down or reorganized. These actions, mainly relying on government mandates, could significantly improve China's overall technology level and reduce mercury emission intensities. If financial incentives (such as tax rebates and financial subsidies) are integrated into these policies, effects of technology improvement in reducing mercury emissions are expected to be more critical.

To further reduce the intensity of mercury emissions, China is introducing two types of actions: integrated waste removal facilities and cleaner energy sources. China introduced mandatory requirements on reductions of SO_2 and NO_x emissions in the 12th Five-Year Plan, the main social and economic development initiative implemented by the central government covering 2011−2015. Integrated removal of SO_2 and NO_x emissions can also reduce mercury emissions in a variety of industries including cement, iron and steel, nonferrous metals, batteries, and fluorescent lamps.[62] China is also encouraging cleaner energy sources (such as hydropower, wind power, and solar power) to substitute for fossil fuels. In addition to reducing CO_2, SO_2, and NO_x emissions, cleaner energy sources also reduce mercury emissions.

According to the results of Figure 1, optimizing the final demand mix can provide more potential for mercury emission mitigation. To support China's rapid urbanization and cleaner production, more fixed capital formation of machinery and equipment, buildings, and roads is expected. Thus, the optimization of the final demand mix will rely on household consumption and exports. Encouraging green lifestyles (such as using energy-saving appliances and mercury-free products) and giving preferences to mass transit over private transportation can effectively reduce mercury emissions as well as other air pollutants (such as CO_2, SO_2, and NO_x). Policies will be more effective if priorities are given to optimize green consumption behaviors of urban residents. Mercury mitigation will also benefit from limiting the export of products that have large life cycle mercury emission intensities as well as encouraging the export of high-end products with a lower life cycle mercury emission intensities.

Other developing countries can benefit from China's experiences. China's developmental trajectory from 1992 to 2007 and in future years is representative of many developing countries. Significant socioeconomic changes are occurring in many of the developing countries that are mainly responsible for the increase of global mercury emissions.[3,7] The analysis of the underlying drivers of China's anthropogenic mercury emissions can provide guidance for policy-making in other developing countries.

In future work, the accuracy of China's mercury emission factors should be improved, which will provide more accurate information for the SDA that is more reliable. In addition, Chinese MIOTs at higher resolution should be developed to reduce uncertainties resulting from the homogeneity assumption of the input-output model.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Additional information on (1) the structural decomposition analysis model; (2) the classification of economic sectors in Chinese monetary input-output tables; (3) the regression analysis between coal consumption and coal-fired electricity generation; and (4) input data and the results. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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