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Virtual Atmospheric Mercury Emission Network in China

Sai Liang,*[,†] Chao Zhang,[‡] Yafei Wang,[§] Ming Xu,*[,†,∥] and Weidong Liu[⊥]

[†]School of Natural Resources and Environment, University of Michigan, Ann Arbor, Michigan 48109-1041, United States

[‡]School of Economics and Management, Tongji University, Shanghai 200092, China

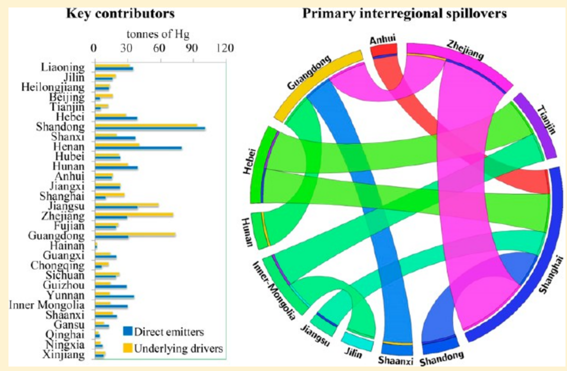
[§]Institute of National Accounts, Beijing Normal University, Beijing 100875, China

[∥]Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, Michigan 48109-2125, United States

[⊥]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

Supporting Information

ABSTRACT: Top-down analysis of virtual atmospheric mercury emission networks can direct efficient demand-side policy making on mercury reductions. Taking China—the world's top atmospheric mercury emitter—as a case, we identify key contributors to China's atmospheric mercury emissions from both the producer and the consumer perspectives. China totally discharged 794.9 tonnes of atmospheric mercury emissions in 2007. China's production-side control policies should mainly focus on key direct mercury emitters such as Liaoning, Hebei, Shandong, Shanxi, Henan, Hunan, Guizhou, Yunnan, and Inner Mongolia provinces and sectors producing metals, nonmetallic mineral products, and electricity and heat power, while demand-side policies should mainly focus on key underlying drivers of mercury emissions such as Shandong, Jiangsu, Zhejiang, and Guangdong provinces and sectors of construction activities and equipment manufacturing. China's interregional embodied atmospheric mercury flows are generally moving from the inland to the east coast. Beijing–Tianjin (with 4.8 tonnes of net mercury inflows) and South Coast (with 3.3 tonnes of net mercury inflows) are two largest net-inflow regions, while North (with 5.3 tonnes of net mercury outflows) is the largest net-outflow region. We also identify primary supply chains contributing to China's virtual atmospheric mercury emission network, which can be used to trace the transfers of production-side and demand-side policy effects.



■ INTRODUCTION

Mercury is a global pollutant,[1] exposure to which is highly toxic to human and ecosystem health.[2,3] The steady increase of global anthropogenic atmospheric mercury emissions since 1950[4] has attracted intensified attention on their toxicity effects. Over 140 nations agreed to sign the Minamata convention on controlling global anthropogenic mercury emissions in 2013.[5,6] China is regarded as the largest contributor to global anthropogenic atmospheric mercury emissions,[7] accounting for about 27% of global total.[8] Reducing China's anthropogenic atmospheric mercury emissions hence has a significant contribution to global reduction.[9]

Scholars have estimated China's atmospheric mercury emissions from coal-fired power plants,[10−12] the production of nonferrous metals,[13−15] and the burning of solid wastes and biomass.[16−18] National atmospheric mercury emission inventories for China have also been compiled.[19−23] These studies mainly analyze China's atmospheric mercury emissions based on bottom-up approaches, providing significant foundations for production-side policy design such as technology improvements and end-of-pipe control. Besides bottom-up analysis, top-down analysis is also important in supporting economy-wide strategy on atmospheric mercury reductions by directing capital investment and optimizing economic structures. Top-down analysis can identify key direct contributors from the producer perspective tying emissions to industrial sectors, as well as uncover key underlying drivers from the consumer perspective accounting for life cycle emissions generated throughout entire supply chains due to final consumption of products and services.[24] It is also a powerful tool to identify the interregional transfers of embodied atmospheric mercury emissions (named "spillover of atmospheric mercury emissions") and primary supply chains by treating the interactions between economic activities and atmospheric mercury emissions as a virtual atmospheric mercury emission network. To the best of our knowledge, such analysis has not been done at China's regional level considering both intersectoral and interregional supply chain effects. Such study, on the other hand, is much needed given its policy relevance. For example, if regions with net embodied atmospheric mercury inflows choose to import more mercury-intensive products, atmospheric mercury emissions can potentially be transferred to

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regions with net embodied atmospheric mercury outflows. Such spillovers can hence lead to unprocurable national emission reduction target. Investigating these spillovers can provide insights for efficient economy-wide and demand-side policy making.

In this study we first compile a bottom-up atmospheric mercury emission inventory for 30 provinces in China and then use an environmentally extended multiregional input-output (EE-MRIO) model to construct a virtual atmospheric mercury emission network. Next we analyze the virtual atmospheric mercury emission network for regional responsibilities from the producer and consumer perspectives and interregional spillovers. We further identify primary supply chains supporting China's virtual atmospheric mercury emission network using structural path analysis (SPA). The results provide insights for helping develop effective policies to reduce atmospheric mercury emissions and allocating regional responsibilities within China. While the results are specific for China, the analysis framework can be generally applied to other cases.

METHODS AND DATA

Bottom-Up Inventory Compilation. We first compile a bottom-up atmospheric mercury emission inventory from sources where atmospheric mercury emissions first enter the environment. Atmospheric mercury emission sources in China mainly comprise fuel combustion, production processes, biomass burning, household waste burning, and coal mine spontaneous burning. The detailed bottom-up atmospheric mercury emission inventory is shown in the Supporting Information (SI).

Atmospheric mercury emissions from fuel combustion are calculated by multiplying energy consumption with emission factors. Each sector's energy consumption data are compiled following Feng et al.[25] Atmospheric mercury emission factors of coal and oil are from Tian et al. [26] and Streets et al.,[20] respectively.

Production processes include production of cement, pig iron, zinc, copper, lead, gold, mercury, aluminum, batteries, and fluorescent lamps. The production of caustic soda is not considered, as mercury-related technologies in caustic soda production have been eliminated since 2003 in China.[21,27] Emissions from various production processes are calculated by multiplying the amount of product yields with corresponding emission factors. The production data of cement, pig iron, and primary aluminum by regions are from China Industry Economy Statistical Yearbook 2008,[28] and that of primary zinc, copper, lead, and mercury by regions are from China Nonferrous Metals Industry Yearbook 2008.[29] The production data of gold by regions are from China Mining Yearbook 2008,[30] and those of batteries and fluorescent lamps are from China Light Industry Yearbooks.[31,32] Atmospheric mercury emission factors for zinc, copper, and lead are from Wu et al.,[13] and those for cement, pig iron, gold, mercury, and aluminum are from AMAP/UNEP.[33] Atmospheric mercury emission factors for batteries and fluorescent lamps are from Streets et al.[20]

Atmospheric mercury emissions from biomass burning by regions are from Huang et al.,[18] comprising emissions from forest fires, grassland fires, in-field crop residues burning, in-home crop residues burning, and fuel wood burning. Atmospheric mercury emissions from household waste burning by regions are from Hu et al.,[17] including emissions from the burning of municipal solid wastes and rural household wastes. China's coal mines spontaneous burning mainly happen in Xinjiang, Gansu, Qinghai, Ningxia, Shaanxi, Inner Mongolia, and Shanxi.[34] We disaggregate national atmospheric mercury emissions from coal mines spontaneous burning[19,22,23] by proportional relationships of coal mines spontaneous burning areas of these regions.[34]

Top-Down Analysis Using the EE-MRIO Model. To link the bottom-up atmospheric mercury emission inventory to the MRIO table, we add up emissions from different sources belonging to the same sector in the MRIO table. Treating each sector's atmospheric mercury emissions as the satellite account of the MRIO table, we can construct the EE-MRIO model. Each sector's atmospheric mercury emissions from the producer and consumer perspectives can then be calculated by:

$$\text{mercury emissions from the producer perspective} = \mathbf{F}\,\mathrm{diag}(x) \quad (1)$$

$$\text{mercury emissions from the consumer perspective} = \mathbf{F}(\mathbf{I}-\mathbf{A})^{-1}\mathrm{diag}(y) \quad (2)$$

where intensity matrix **F** indicates atmospheric mercury emissions per unit of each sector's total output x; matrix **A** is the direct requirement coefficient matrix characterizing intraregional and interregional economic interactions between sectors;[35,36] matrix **I** is the identity matrix; column vector y represents each sector's final demand; and diag(y) represents a diagonal matrix from the vector y.

To examine domestic interregional atmospheric mercury emission spillovers, we calculate each region's production-based and consumption-based atmospheric mercury emissions within China's domestic economy (different from the producer and consumer perspective accounting). System boundaries of each region's production-based and consumption-based atmospheric mercury emissions are China's domestic supply chains. Production-based atmospheric mercury emissions measure emissions embodied in final products that are produced in a particular region, while consumption-based emissions describe emissions embodied in a region's consumption:

$$\text{production-based mercury emissions of region } s = \mathbf{F}(\mathbf{I}-\mathbf{A})^{-1}\,\mathrm{diag}(p^s) \quad (3)$$

$$\text{consumption-based mercury emissions of region } s = \mathbf{F}(\mathbf{I}-\mathbf{A})^{-1}\,\mathrm{diag}(c^s) \quad (4)$$

where column vector p^s represents product flows from region s to final demands of all regions; and column vector c^s stands for product flows from all regions to the final demand of region s. The framework and detailed descriptions of the EE-MRIO model can be found in existing studies.[36]

We use an augmented gravity model to compile China's 2007 MRIO table,[37] which covers 30 regions (26 provinces and 4 municipalities, Table S1) excluding Tibet, Hong Kong, Macau, and Taiwan due to data unavailability. Each region is further disaggregated into 30 economic sectors (Table S1). Moreover, we remove the column named "others" in China's 2007 MRIO table, which is regarded as the error of different statistics.[19,23,38]

Structural Path Analysis (SPA). The complex interactions among sectors within an economy can be regarded as an assembly of supply chains, represented by the MRIO model. SPA traces and extracts important supply chains in the virtual

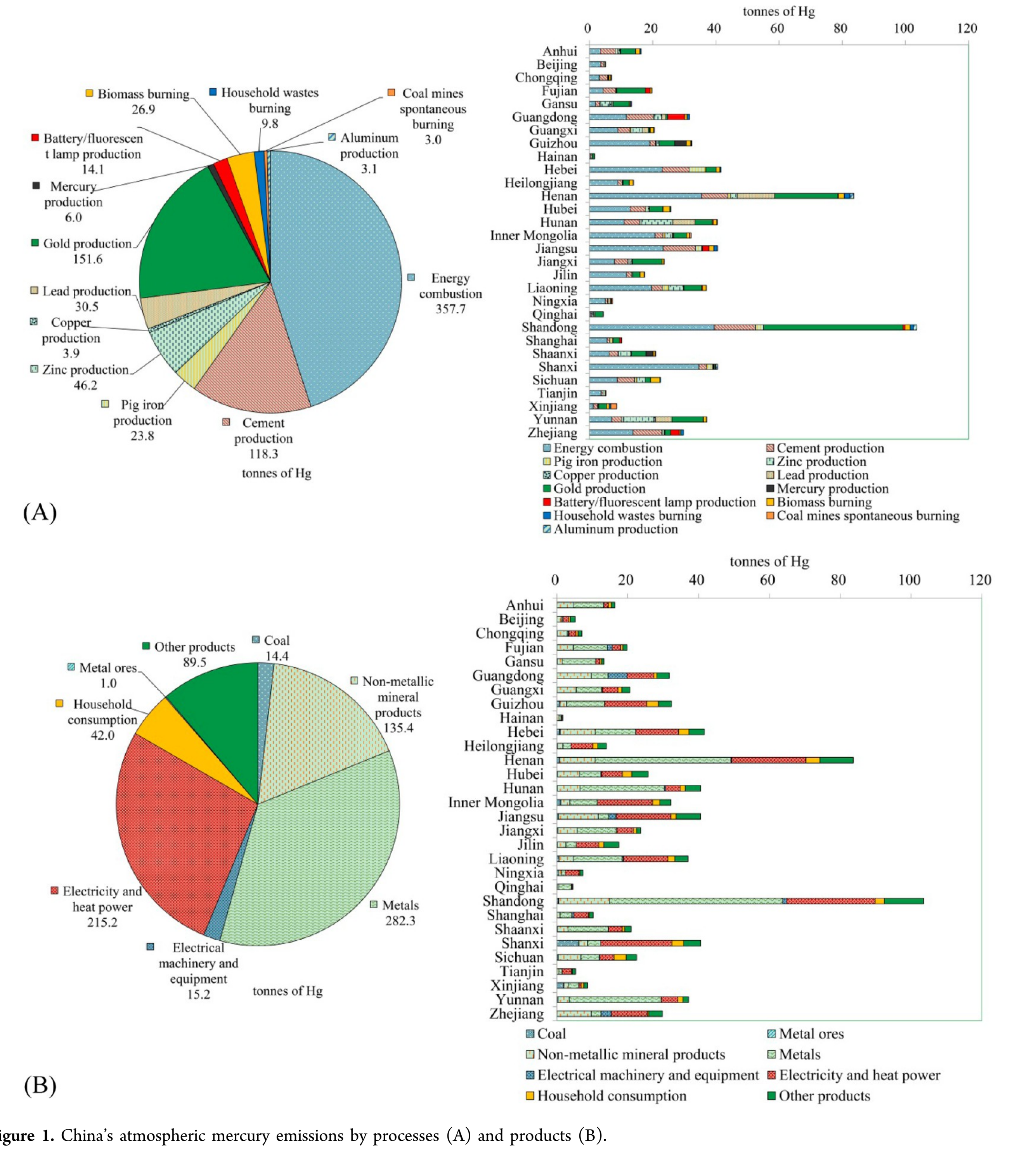

Figure 1. China's atmospheric mercury emissions by processes (A) and products (B).

emission network by unraveling the Leontief inverse matrix using its Taylor expansion:[35,39]

$$(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + ... + \mathbf{A}^n, \quad \lim_{n\to\infty} (\mathbf{A}^n) = 0 \tag{5}$$

Coupling with atmospheric mercury emission data, the EE-MRIO model essentially describes a virtual atmospheric mercury emission network in which nodes are sectors in regions and directional links represent atmospheric mercury emissions embodied in products bought by a sector from another sector. SPA can extract important supply chains within the virtual atmospheric mercury emission network:

$$\begin{aligned} \text{mercury emissions} &= \mathbf{F}(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + ... + \mathbf{A}^n)\, \text{diag}(y_i) \\ &= \mathbf{FI}\, \text{diag}(y_i) + \mathbf{FA}\, \text{diag}(y_i) + \mathbf{FA}^2\, \text{diag}(y_i) + ... \\ &\quad + \mathbf{FA}^n\, \text{diag}(y_i) \end{aligned} \tag{6}$$

where column vector y_i indicates the final demand for products from sector i. We define each term in the right-hand side of eq

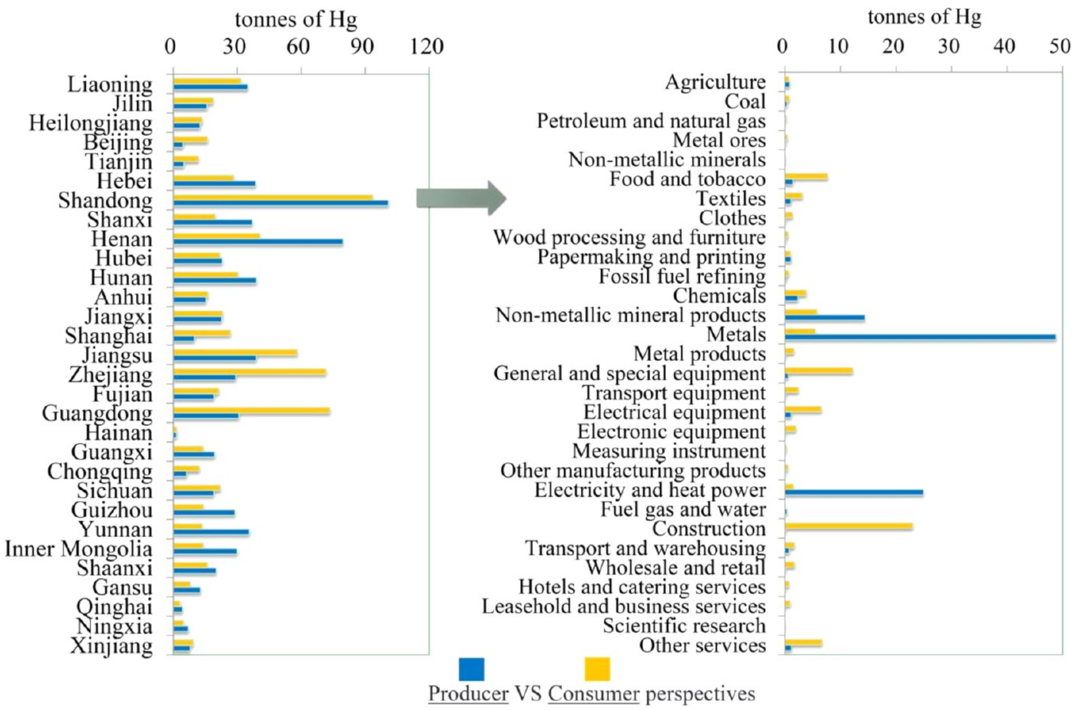

Figure 2. Regional atmospheric mercury emissions in China from the producer and consumer perspectives with details for Shandong.

6 as a production layer (PL). PLs for atmospheric mercury emissions in China are listed in Table S2.

■ BOTTOM-UP REGIONAL ATMOSPHERIC MERCURY EMISSION INVENTORY ANALYSES

China totally discharged 794.9 tonnes (t) of atmospheric mercury emissions in 2007 (Figure 1). Primary emitters are energy combustion (357.7 t), gold production (151.6 t), cement production (118.3 t), zinc production (46.2 t), lead production (30.5 t), biomass burning (26.9 t), and pig iron production (23.8 t), accounting for 45.0%, 19.1%, 14.9%, 5.8%, 3.8%, 3.4%, and 3.0% of the national total, respectively (Figure 1A). We also find that battery and fluorescent lamp production, mainly located in China's coastal areas, such as Guangdong, Zhejiang, Jiangsu, and Fujian, discharges 14.1 t of atmospheric mercury emissions (1.8% of the national total). On the other hand, atmospheric mercury emissions are discharged due to the production of metals (282.3 t), electricity and heat power (215.2 t), and nonmetallic mineral products (135.4 t), accounting for 35.5%, 27.1%, and 17.0% of the national total, respectively (Figure 1B).

Shandong, Henan, and Hebei discharged 103.6 t, 83.7 t, and 41.6 t atmospheric mercury emissions, respectively, representing the top three emitters of atmospheric mercury in China (Figure 1). Production of metals (pig iron, lead, and gold) and electricity and heat power dominates atmospheric mercury emissions in these regions.

Figure 1 also shows that the atmospheric mercury emission profile varies across regions. For example, gold production is a major contributor to atmospheric mercury emissions in Shandong and Henan, but not in Hebei. Similarly, zinc production is a major contributor to atmospheric mercury emissions in Hunan and Yunnan, but not in Hubei.

In general, China's atmospheric mercury emissions are mainly from energy consumption and material manufacturing, mainly due to China's increasing demand for energy[40] and industrial materials during 2002–2007.[19,41]

■ TOP-DOWN REGIONAL ATMOSPHERIC MERCURY EMISSIONS AND PRIMARY SUPPLY CHAINS

Regional Atmospheric Mercury Emissions from Both the Producer and the Consumer Perspectives. Top-down regional atmospheric mercury emissions are presented from both the producer and the consumer perspectives. The producer perspective analyzes direct contributors to atmospheric mercury emissions by assigning emissions to sectors and regions from which emissions first enter the environment. The consumer perspective relates atmospheric mercury emissions to underlying drivers that cause the emissions throughout entire supply chains. The detailed top-down atmospheric mercury emission inventory is shown in the Supporting Information (SI).

At regional level, Liaoning, Hebei, Shandong, Shanxi, Henan, Hunan, Guizhou, Yunnan, and Inner Mongolia, who mainly produce primary products (e.g., fossil fuels and mineral ores) and semimanufactured products (e.g., metals and nonmetallic mineral products), locate in the upstream of China's economic supply chains. These regions cause more atmospheric mercury emissions from the producer perspective than that from the consumer perspective (Figure 2). Shandong and Henan are top two atmospheric mercury emitters from the producer perspective, discharging 101.0 and 79.7 t of atmospheric mercury emissions, respectively (Figure 2). Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, and Guangdong locate in the downstream of China's economic supply chains. They mainly produce finished products such as clothes, equipment, and services. These regions cause more atmospheric mercury emissions from the consumer perspective than that from the producer perspective (Figure 2). Shandong, Guangdong, Zhejiang, and Jiangsu are top four contributors to atmospheric mercury emissions from the consumer perspective, causing 93.6

t, 73.6 t, 71.8 t, and 58.3 t of atmospheric mercury emissions, respectively (Figure 2).

At sectoral level, Table 1 lists top 30 sectors contributing to China's atmospheric mercury emissions. From the producer perspective, major contributors to China's atmospheric mercury emissions are production activities of metals, nonmetallic mineral products, and electricity and heat power. From the consumer perspective, major contributors are construction activities and equipment manufacturing, which directly discharge few atmospheric mercury emissions but have large indirect emissions associated with their intermediate material inputs such as metals, nonmetallic mineral products, and electricity and heat power. We find similar situation for particular regions, such as Shandong—the largest contributor to atmospheric mercury emissions from both the producer and the consumer perspectives (Figure 2).

Table 1. Top 30 Sectors Contributing to China's Atmospheric Mercury Emissions

rank	producer perspective		consumer perspective	
1	Shandong	metals	Zhejiang	construction
2	Henan	metals	Shandong	construction
3	Yunnan	metals	Jiangsu	construction
4	Shandong	electricity and heat power	Guangdong	electrical equipment
5	Hunan	metals	Guangdong	construction
6	Henan	electricity and heat power	Hunan	construction
7	Shanxi	electricity and heat power	Jiangxi	construction
8	Inner Mongolia	electricity and heat power	Shandong	general and special equipment
9	Jiangsu	electricity and heat power	Sichuan	construction
10	Shandong	nonmetallic mineral products	Shaanxi	construction
11	Liaoning	metals	Liaoning	construction
12	Liaoning	electricity and heat power	Henan	construction
13	Hebei	electricity and heat power	Henan	general and special equipment
14	Guizhou	electricity and heat power	Zhejiang	general and special equipment
15	Hebei	metals	Yunnan	construction
16	Shaanxi	metals	Hubei	construction
17	Jiangsu	nonmetallic mineral products	Shandong	food and tobacco
18	Jiangxi	metals	Hebei	construction
19	Guizhou	metals	Shanxi	construction
20	Zhejiang	electricity and heat power	Guangxi	construction
21	Henan	nonmetallic mineral products	Anhui	construction
22	Hebei	nonmetallic mineral products	Shanghai	construction
23	Guangdong	nonmetallic mineral products	Zhejiang	transport equipment
24	Fujian	metals	Shandong	other services
25	Zhejiang	nonmetallic mineral products	Heilongjiang	construction
26	Gansu	metals	Shandong	electrical equipment
27	Anhui	metals	Chongqing	construction
28	Inner Mongolia	metals	Beijing	construction
29	Guangdong	electricity and heat power	Guangdong	electronic equipment
30	Guangxi	metals	Jiangsu	general and special equipment

Supply chains connect direct atmospheric mercury emitters from the producer perspective with underlying drivers from the consumer perspective. Table S3 lists top 30 supply chains contributing to atmospheric mercury emissions identified through the SPA. These primary supply chains are mostly associated with metals, nonmetallic mineral products, equipment, and construction activities. The largest supply chain is located in Shandong who is the largest atmospheric mercury emitter: "Shandong-Metals → Shandong-Construction" (causing 5.8 tonnes of atmospheric mercury emissions). From the consumer perspective, capital formation, urban household consumption, and exports are primary drivers (Figure S1). This reflects China's large-scale infrastructure construction, rapid urbanization, and export-oriented economy. In particular, exports are main drivers of atmospheric mercury emissions in coastal areas such as Guangdong, Fujian, Shanghai, Jiangsu, Zhejiang, and Shandong (Figure S1). Table S3 lists top 30 supply chains for atmospheric mercury emissions caused by capital formation, urban household consumption, and exports. Primary supply chains for atmospheric mercury emissions caused by capital formation are mainly related with construction materials (metals and nonmetallic mineral products) and construction activities, with "Shandong-Metals → Shandong-Construction" as the largest contributing one. Atmospheric mercury emissions driven by urban household consumption are mainly contributed by supply chains related with electricity and heat power. The largest contributing one is the generation of electricity and heat power in Inner Mongolia directly consumed by urban households. Exports drive atmospheric mercury emissions mainly through supply chains associated with metals, nonmetallic mineral products, and equipment, with the largest contributing one being "Shandong-Metals" directly exported.

Interregional Atmospheric Mercury Emission Spillovers. We observe differences between production-based and consumption-based atmospheric mercury emissions in each region (Figure S2), indicating interregional atmospheric mercury emission spillovers. The spillover here means the transfer of atmospheric mercury emissions embodied in interregional trades. We aggregate results of interregional atmospheric mercury emission spillovers from the 30-region format into an 8-region format for easier interpretation (Figure S3), based on economic structure similarity and spatial location of these 30 regions.[25,42]

China's embodied atmospheric mercury emissions are generally moving from the inland with lower per capita GDP to the east coast with higher per capita GDP. Beijing−Tianjin and South Coast are two largest regions with net embodied atmospheric mercury inflows (Figure 3). Total net inflows of embodied atmospheric mercury emissions into Beijing−Tianjin are 4.8 t, among which 1.6 t come from North, 1.3 t from Northwest, 0.7 t from Central, and 0.7 t from Northeast. South Coast has 3.3 t of net embodied atmospheric mercury inflows, which mainly originate from Central (1.1 t), Central Coast (1.0 t), and Northwest (0.6 t). In contrast, the North is the largest region with net embodied atmospheric mercury outflows (5.3 t). We also observe large flows of embodied atmospheric mercury emissions from North to Central Coast (1.7 t), from Central to Northwest (0.8 t), from Northeast to Central (0.8 t), and from Central Coast to Southwest (0.7 t). Major origin−destination pairs at the provincial level supporting these large

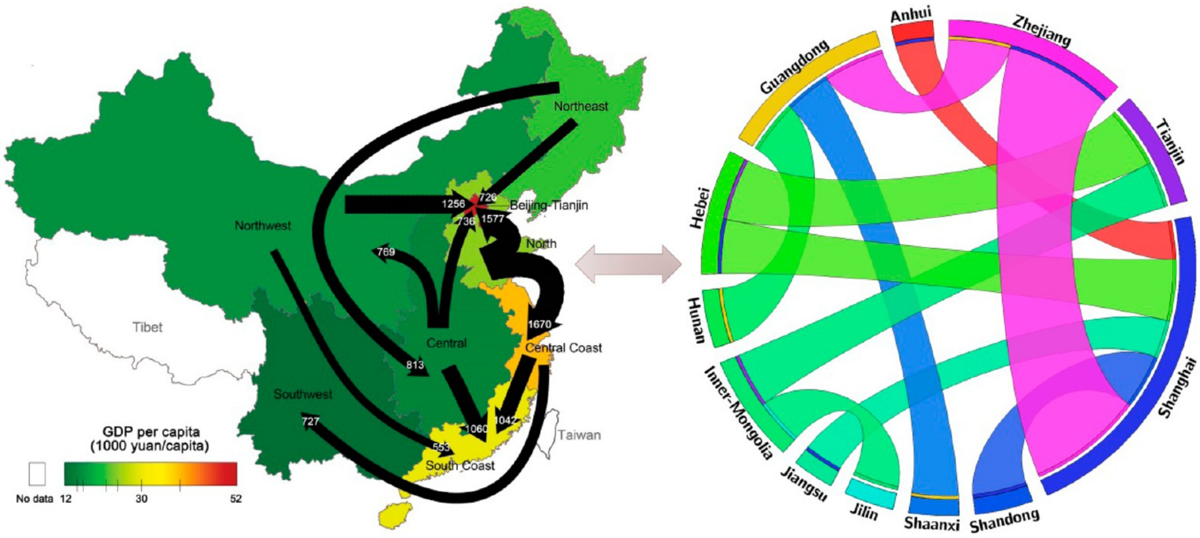

Figure 3. Interregional atmospheric mercury emission spillovers within China. The numbers expressed by arrows in China map, whose unit is kilogram atmospheric mercury emissions, indicate the amounts of net flows of embodied atmospheric mercury emissions. The circular graph, created using Circos,[43] represents major interregional atmospheric mercury emission spillovers within China at the provincial level. Lines in the circular graph are colored by starting regions, with larger width indicating larger values. Detailed data on interregional atmospheric mercury emission spillovers within China at the provincial level are listed in Table S4.

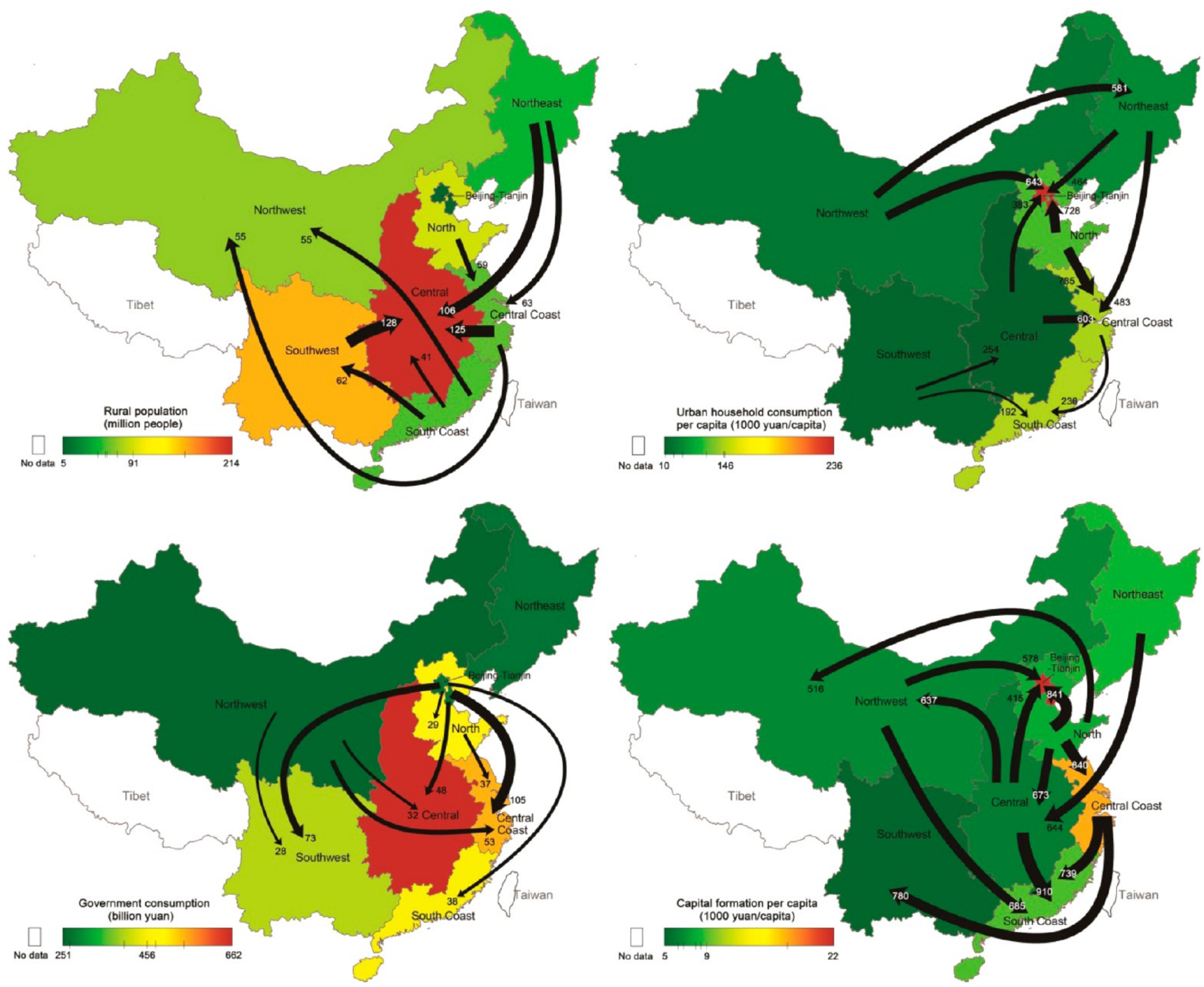

Figure 4. Interregional atmospheric mercury emission spillovers within China caused by rural household consumption (upper left), urban household consumption (upper right), government consumption (lower left), and capital formation (lower right). The numbers expressed by arrows, whose unit is kilogram atmospheric mercury emissions, indicate the amounts of net flows of embodied atmospheric mercury emissions.

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flows are Hebei–Tianjin, Inner Mongolia–Tianjin, Hebei–Shanghai, Shandong–Shanghai, Zhejiang–Guangdong, Hunan–Guangdong, and Shaanxi–Guangdong (Figure 3).

The interregional atmospheric mercury emission spillovers can be further related to various domestic final demands as drivers including rural household consumption, urban household consumption, government consumption, and capital formation. Specifically, interregional demands of capital goods and urban household consumption are the main drivers for atmospheric mercury emission spillovers (Figure 4).

Embodied atmospheric mercury emissions caused by rural household consumption mainly flow from eastern areas to central and western areas, such as from Central Coast to Central (125 kg) and from Northeast to Central (106 kg) (Figure 4). A large proportion of China's rural population resides in central and western regions (Figure 4) which have lower per capita GDP and lower urbanization rates (Table S5). These regions are located in the low end of China's domestic supply chains, providing raw mineral materials and primary products. Deep-processed products and services consumed by rural households in those regions are mainly imported from eastern areas, leading to flows of embodied atmospheric mercury emissions from eastern to central and western regions.

The pattern of embodied atmospheric mercury emissions caused by urban household consumption is clearly shaped by three supercity communities in China: Beijing–Tianjin agglomeration, Yangtze River Delta agglomeration in Central Coast and Pearl River Delta agglomeration in South Coast. Major flows are from Northwest to Beijing–Tianjin (643 kg), from North to Beijing–Tianjin (728 kg), from North to Central Coast (735 kg), and from Central to Central Coast (603 kg) (Figure 4).

Embodied atmospheric mercury emission flows caused by government consumption mainly originate from Beijing–Tianjin (Figure 4). This is an interesting visualization of how embodied pollution flows reflect China's highly centralized political system. China's central government, located in Beijing, provides services to local government and households, such as education, scientific research, and financial services. Flows of these services from Beijing to other regions lead to the radial pattern of embodied atmospheric mercury flows originating from Beijing.

Embodied atmospheric mercury emission flows caused by capital formation mainly end at Beijing–Tianjin and South Coast which have higher capital formation per capita (Figure 4). The service industry dominates Beijing–Tianjin and South Coast (Figure S4). As a result, products related to capital formation, such as metals and mineral products, need to be imported from regions specializing in manufacturing such as North, Central, Central Coast, and Northwest. These product flows drive the flows of embodied atmospheric mercury emissions ending at Beijing–Tianjin and South Coast.

Along with China's rapid urbanization, interregional atmospheric mercury emission spillovers caused by urban household consumption may keep growing, while the amount of emission spillovers driven by rural household consumption will decrease. In addition, China's urbanization process is highly spatially uneven, in the way that coastal areas have much higher urbanization rate than other regions (Table S5). The interregional atmospheric mercury emission spillovers caused by urban household consumption and capital formation will be further strengthened if China continues such uneven urbanization processes.

■ POLICY IMPLICATIONS

Our results mainly have three policy implications with respect to China's atmospheric mercury reductions: identifying key direct emitters of atmospheric mercury emissions for implementing production-side controlling policies; directing key underlying drivers of atmospheric mercury emissions for implementing demand-side controlling policies; and reducing interregional atmospheric mercury emission spillovers.

First, our study identifies key direct emitters of atmospheric mercury emissions from the producer perspective, such as Liaoning, Hebei, Shandong, Shanxi, Henan, Hunan, Guizhou, Yunnan, and Inner Mongolia provinces (Figure 2) and sectors producing metals, nonmetallic mineral products, and electric and heat power (Table 1). Production-side controlling measures, such as end-of-pipe removal facilities (e.g., electrostatic precipitators, fabric filters, cyclone, and wet scrubber[12,26]) and enterprise cleaner production, should focus on these key direct emitters identified in this study. Chinese governments mainly rely on mandatory command and control tools, such as closing down enterprises with outdated technologies and conducting mandatory cleaner production for particular enterprises. Economic instruments, such as atmospheric mercury emission fee or tax, and financial subsidies, can usually play a more effective role in controlling atmospheric mercury emissions than mandatory tools. Thus, Chinese government should pay more attention to economic instruments. In addition, end-of-pipe removal facilities on soot and dust can also remove atmospheric mercury.[12,26] Production-side policy-making in atmospheric mercury reduction should pay attention to such kind of cocontrol opportunities.

Second, our study identifies key underlying drivers of atmospheric mercury emissions from the consumer perspective, such as Shandong, Jiangsu, Zhejiang, and Guangdong provinces (Figure 2) and sectors on construction activities and equipment manufacturing (Table 1). These key underlying drivers from the consumer perspective are important for economy-wide and demand-side policies. For atmospheric mercury reductions, only production-side measures are not enough to ensure continuous emission cutting if downstream demand for mercury-intensive products still keeps growing. Demand-side measures should focus on the following three aspects to change demand patterns of mercury-intensive products: (1) limiting the usage of mercury-intensive materials and products in major downstream demand sectors, such as construction, by implementing compulsory regulations and setting mercury-related standards; (2) providing better information to consumers through mercury-free certification and labeling of end-use products to influence consumers' behaviors in product selection; and (3) using economic instruments, such as additional consumption tax on mercury-intensive products and subsidies on mercury-free products, to promote consumption style changes.

In particular, primary supply chains identified by the SPA (Table S3) associate direct emitters (the upstream stage) with underlying drivers (the downstream stage). Those supply chains not only illustrate major supply demand paths through which virtual atmospheric mercury emissions are transferred but also illustrate the paths through which production-side policies (passed from direct emitters to underlying drivers) and demand-side policies (passed from underlying drivers to direct emitters) interact with each other. Primary supply chains identified in this study can provide guidance for policy makers to trace the indirect effects of possible measures on controlling atmospheric mercury emissions.

Third, our results provide guidance for reducing interregional atmospheric mercury emission spillovers. Currently, Chinese central government accounts for each region's atmospheric mercury emissions from the producer perspective. If regions with net embodied atmospheric mercury inflows, such as Shanghai (Figure S2), choose to import more mercury-intensive goods from regions with net outflows such as Shandong, Jiangsu, and Zhejiang (Figure S2), atmospheric mercury reduction pressure of the net-inflow regions will be transferred to the net-outflow regions by increasing atmospheric mercury emissions due to increased production in the net-outflow regions. Such an increase in interregional atmospheric mercury emission spillovers will make it difficult to achieve atmospheric mercury reduction goals at the national level. Avoiding such spillovers requires the Chinese central government to consider both the production-based and consumption-based atmospheric mercury emissions of each region when assigning atmospheric mercury emission reduction responsibilities among regions. In every Five-Year Plan (FYP), the Chinese central government will propose mandatory emission reduction targets and disaggregate those targets to the regional level. Atmospheric mercury emissions have not been incorporated into current FYP. Using the ability of the Chinese central government to coordinate each region to share both production-based and consumption-based atmospheric mercury reduction responsibilities in FYPs is a possible way to reduce interregional atmospheric mercury emission spillovers. Two mechanisms are potentially useful for each region to take such responsibility assignment: conducting atmospheric mercury emission trading scheme and promoting final demand pattern changes. An emission trading scheme has been tested in China for traditional pollutants such as SO_2, NO_x, chemical oxygen demand, and ammonia nitrogen,[44] which can potentially be applied to atmospheric mercury emissions as well. Such a trading scheme can encourage the transfers of technologies and capital between regions.[25] On the other hand, changing the final demand pattern of regions with net embodied atmospheric mercury inflows, such as encouraging the usage of low-mercury products in household consumption, will help reduce atmospheric mercury emissions in regions with net embodied atmospheric mercury outflows. Changing the final demand pattern should integrate mandatory measures and economic instruments, as discussed in the second policy implications part on key underlying drivers from the consumer perspective.

While the results are specific for atmospheric mercury emissions in China, the framework presented in this study can be applied in other countries as well as the world. System analysis at the macroscopic level as presented in this study is particularly important for economy-wide and demand-side policy decisions.

■ ASSOCIATED CONTENT

Supporting Information

Detailed bottom-up and top-down atmospheric mercury emission inventories, the classification of economic sectors for Chinese regions, and additional results supporting the main text. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Authors

*E-mail: liangsai09@gmail.com; liangsai@umich.edu (S.L.).
*E-mail: mingxu@umich.edu. Phone: +1-734-389-9931. Fax: +1-734-936-2195 (M.X.).

Notes

The authors declare no competing financial interest.

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