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Mercury Flows in China and Global Drivers

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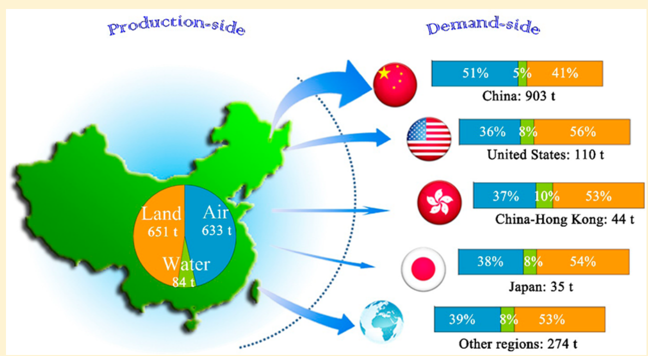
S *Supporting Information*

ABSTRACT: Mercury (Hg) pollution control has become an urgent need at global and national scales. This study, for the first time, comprehensively examines Hg flows in Mainland China and uncovers domestic and external causal drivers of China's Hg emissions/releases. Results show that China's Hg input reaches 2643 t in 2010. China discharges 1368 t of Hg to the environment (to air, 633 t; water, 84 t; and land, 651 t). Embedded Hg transfers across production sectors via waste/byproduct flows reduce Hg releases to land, but lead to secondary Hg emissions to air. Such revelations of embedded Hg transfers adjusts China's comprehensive Hg control that would otherwise only tackle primary emitters. Domestic consumption causes 67% of China's Hg emissions/releases, and external consumption induces the remaining 33%. Besides traditional production-side Hg control measures, demand-side measures and international joint efforts are required to effectively combat Hg pollution. Uncovering embedded and embodied Hg flows within the global economy can assist a paradigm shift necessary to make real progress in global Hg control and the implementation of the *Minamata Convention on Mercury*.



■ INTRODUCTION

Mercury (Hg), an element that can cycle across major environmental compartments, is widely distributed in the biophysical environment and can be transported globally.[1−4] Hg contamination is persistent and highly toxic to wildlife and human beings.[5,6] For example, methylmercury can accumulate in wildlife and human beings and then cause central nervous system diseases.[6] Anthropogenic activities since 2000 BC have increased background levels of Hg in the biophysical environment by 5−10 times.[2] To reduce global Hg emissions to the environment, 128 nations have signed the *Minamata Convention on Mercury*.[7] Mainland China (termed as China in this study) plays an important role in global Hg cycle, given that its atmospheric Hg emissions account for 27% of the global total.[8]

Scholars have taken extensive efforts to quantify China's atmospheric Hg emissions from primary emission sources.[8−15] However, production activities in these inventories, which are closely interconnected through waste/byproduct flows, are assumed to be independent from one another.[9,10,14,15] Ignoring the links between different production activities will potentially overlook secondary atmospheric Hg emissions.[16−18] For example, Hg captured from coal combustion flue gas to fly ash will probably be discharged to the air again, if fly ash is used to produce cement clinker.[18] On the other hand, tracking Hg in the waste/byproduct flows will help identify sources of Hg releases to water and land.[8,16,18,19] For example, the disposal process of waste acid is a significant source of aquatic Hg releases from zinc smelters, when we track Hg flows in waste

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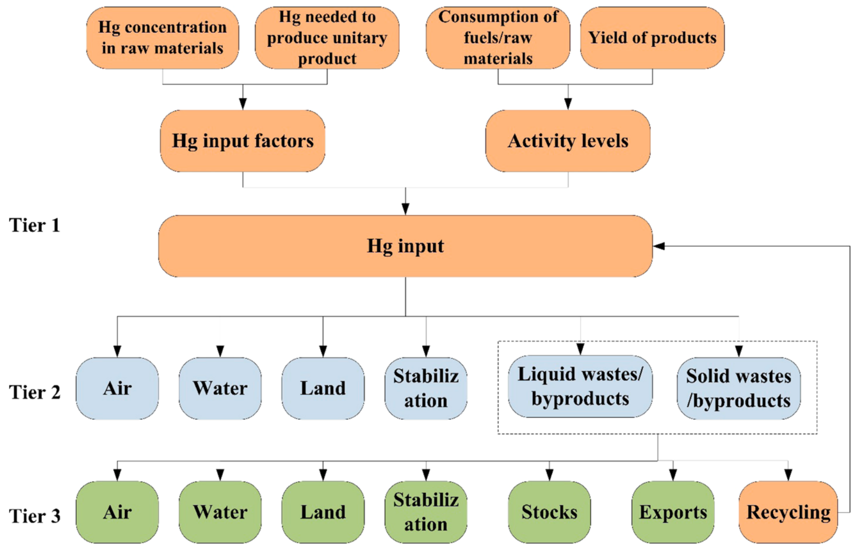

Figure 1. Conceptual framework for Hg flow analysis in China.

disposal processes.[18] Therefore, it is urgent to link all production activities together by considering Hg flows in both production activities and waste/byproduct disposal processes. Existing studies have examined Hg flows within other countries (e.g., the U.S.,[20,21] Europe,[22] and India[23]) as well as several specific Chinese sources (e.g., zinc, lead, and copper smelting).[16−18] However, a comprehensive national Hg flow map for China is still left unknown. Such a flow map can help effective policy decisions to identify critical Hg emission/release sources and avoid secondary atmospheric Hg emissions.

Existing studies and above discussions primarily focus on China's Hg emissions/releases from the production side. From a supply chain perspective, Hg emissions/releases arising from the production side are ultimately caused by consumption activities.[24−27] Revealing underlying drivers from a consumption viewpoint is important to develop demand-side measures. Limited studies have uncovered consumption drivers of China's Hg emissions to air,[25,28] but no attention to Hg releases to water and land. In addition, existing studies mainly focus on domestic supply chains of China.[25,28] Given China's increasingly important role in international trade, both domestic and external consumption drivers of China's Hg emissions/releases to all environmental media must be uncovered if Hg abatement is to be effective.

In this study we combine substance flow analysis (SFA) and a global environmentally extended multiregional input−output (EE-MRIO) database for the year 2010 (containing 190 regions and ∼15 000 sectors;[29,30] sectors classified based on the System of National Accounts[31]) to identify Hg emission/release sources to multiple environmental media and uncover their domestic and external consumption drivers. This study, for the first time, comprehensively examines Hg flows in China to support effective production-side and demand-side policy decisions. Uncovering global consumption drivers of China's Hg emissions/releases will assist a paradigm shift necessary to make real progress in China's Hg control and the implementation of the *Minamata Convention on Mercury*.

■ METHODOLOGY

In this study we link the SFA method with the EE-MRIO model to comprehensively examine Hg flows in China and to uncover global consumption drivers. The SFA method can directly identify Hg emission/release sources from the production side, while the EE-MRIO model can analyze China's Hg emissions/releases driven by global consumption activities.

SFA Method. The SFA is suitable to trace the fate of Hg in a production system.[21−23,32] This approach enables the identification and quantification of Hg into a given system, its temporal storage in the system, and its final fates.[22,33] Generally, four major steps are required to conduct the substance flow analysis, including goal and system definition, data acquisition, material balances and modeling, and the interpretation. In this study, the system boundary is Mainland China (abbreviated as China in the following text). Hg flows are measured in tonnes in 2010. Our goal is identifying China's Hg flows from primary input to final fates. We obtain Hg flow information through multiple ways: literature review, field experiments, site investigations, best estimations, and expert judgements. Site investigation means direct interviews in the plants to obtain data, such as coal/limestone consumption per clinker produced. Best estimation means that the data are estimated by authors based on raw data or similar situations in other industries. Expert judgment means that the raw data are provided by experts with their experience. Detailed data collection methods are listed in the Supporting Information (SI) (Excel). Our flow model comprises three tiers (Figure 1): Hg input tier (Tier 1), Hg distribution tier (Tier 2), and Hg redistribution tier (Tier 3). In Tier 1, we consider Hg inputs to 8 sectors (further divided into 31 subsectors) (Data set S1). For sectors where Hg is an impurity in raw materials, we calculate Hg inputs by multiplying activity levels with Hg input factors. For intentional Hg use sectors, we collect Hg input data from China's national investigation reports[34] (SI section S1.1,). In Tier 2, the Hg inputs from Tier 1 flow to multiple destinations: Hg emissions to air, Hg releases to water, Hg releases to land, Hg stabilization, Hg releases to liquid wastes/byproducts, and solid wastes/byproducts (SI section S1.2). In this tier, if liquid wastes/byproducts are released to wastewater without disposal, Hg contained in them is regarded to be released to water. Otherwise, such Hg is distributed to liquid wastes/byproducts and then flow to Tier 3. For solid wastes/byproducts, if they are reused or treated, Hg is regarded as

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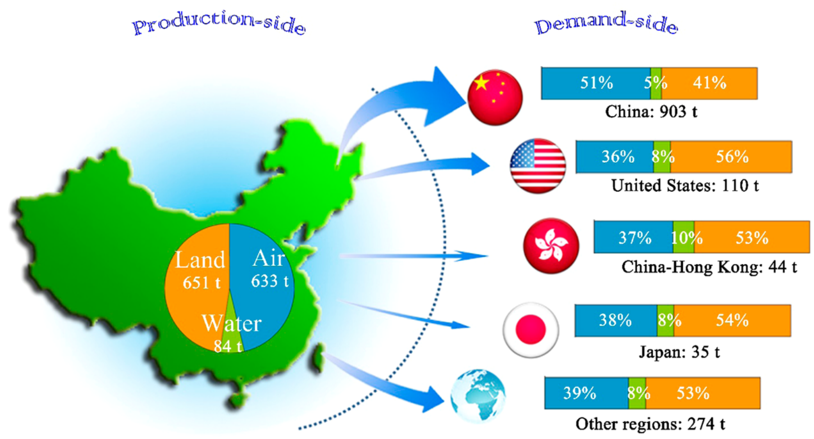

Figure 2. China's Hg emissions/releases to air, water, and land due to local production activities (left China map) and global consumption drivers (right bars).

flowing to Tier 3. Otherwise, Hg in solid wastes/byproducts is regarded to be released to land, when the wastes are open-dumped without environmental protection or stabilized in controlled landfill sites. In Tier 3 (SI section S1.3), Hg in wastes finally flows to different fates. We classify Hg outputs into six categories: Hg emissions to air, Hg releases to water, Hg releases to land, Hg exports, Hg stabilization, and Hg stocks. Hg emissions/releases in this study do not consider Hg transportation across different environmental media through biogeochemical cycling. The term "stabilization" means that Hg is properly treated with little potential environmental risks. The term "stock" implies that Hg is stored in wastes/byproducts due to the delay of sales or disposal (over 1 year), such as the Hg stored in the acid slags produced in nonferrous metal smelters. The term "export" indicates Hg flowing abroad by embedding in exported products. For example, Hg in the exported Hg-containing thermometers is regarded as Hg exports.

One significant challenge to construct China's Hg flows is the identification of suitable input factors and distribution factors which are related with specific emission sources, production technologies, and pollution control devices. The Hg distribution factor represents the percentage of Hg to wastes/byproducts or media in total Hg of an upstream material. We first construct the database of Hg input factors from field experiments for 763 raw coal samples,[13,35] 167 limestone samples,[36] 83 iron concentrate samples,[37] 207 copper concentrate samples,[12,18,38] 381 zinc concentrate samples,[12,18,38] 198 lead concentrate samples,[12,18,38] and 27 gold concentrate samples.[39] For sectors without on-site samplings and tests, we collect their Hg input factors through literature review (data set S2). We also establish a technology-based database on Hg distribution and redistribution factors (data set S3, S4, and S5). Those distribution and redistribution factors are determined according to Hg distributions in different production technologies and pollution control devices as well as the application status of technologies and devices (SI sections S1.2 and S1.3).

To consider uncertainties of results, we introduce the Monte Carlo simulation into Hg flow analysis. The Monte Carlo simulation considers probabilistic distributions of key input parameters and examines statistical distributions of Hg emissions/releases (SI section S1.4). We plot distribution curves of Hg emissions/releases based on 20 000 simulations. Key characteristics of the simulation curves include P10, P50, and P90 values. The P10, P50, and P90 mean that the probabilities of actual results lower than corresponding values are 10%, 50%, and 90%, respectively. The P10 and P90 values of distribution curves are assigned as the lower and upper limits of simulation results, respectively. The (P50 − P10)/P50 and (P90 − P50)/P50 values are the lower and upper limits of uncertainties with 80% confidence degree.

Global EE-MRIO Model. We use the global EE-MRIO model (containing 190 regions and ∼15 000 sectors) to quantify China's Hg emissions/releases caused by final consumption activities of each nation/region,[40−42] as shown in eqs 1 and 2.

$$c_r = e(\mathbf{I} - \mathbf{A})^{-1} f_r \quad (1)$$

$$e = m(\hat{x})^{-1} \quad (2)$$

The notation c_r stands for China's Hg emissions/releases caused by final consumption activities of nation/region r. Row vector e indicates the amount of Hg emissions/releases for unitary output of each Chinese sector (i.e., only Chinese sectors have values, while values for sectors of other nations/regions are zeroes). The matrix **I** is an identity matrix. The matrix **A** is the direct input coefficients matrix.[43] The element a_{ij} of matrix **A** indicates direct requirement of products from nation-sector i to produce unitary output of nation-sector j. The matrix $(\mathbf{I} - \mathbf{A})^{-1}$ is the *Leontief inverse* matrix.[43] The element l_{ij} of matrix $(\mathbf{I} - \mathbf{A})^{-1}$ indicates both direct and indirect requirements of products from nation-sector i to satisfy unitary final demand on products of nation-sector j. Column vector f_r stands for region r's final demand on products from all nation-sectors; row vector m indicates the amount of Hg emissions/releases from Chinese sectors (i.e., only Chinese sectors have values, while values for sectors of other nations/regions are zeroes); and column vector x represents the total output of each nation-sector. The hat over x means diagonalizing vector x.

Constructing the global EE-MRIO model requires two types of data: global multiregional input−output (MRIO) data and Hg emissions/releases from Chinese sectors. We use the global MRIO data from the Eora database (version v199.82) which currently has the highest resolution for nations/regions and sectors.[29,30] This database has been widely used to analyze global consumption drivers of biodiversity changes,[44] resource flows,[45−47] nitrogen pollution,[48] and greenhouse gas emis-

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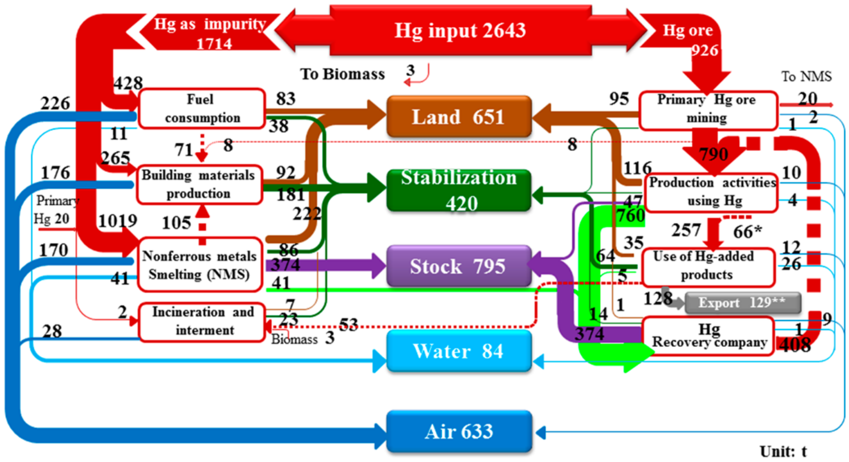

Figure 3. Hg flows within China's production system in 2010 (unit: t). (Flows between sectors are shown in dotted lines. Refer to the SI Figure S2 for a more detailed flow map.).

sions.[49] The Eora database divides the world into 190 nations/regions and 14 839 sectors.[29,30]

Data for Hg emissions/releases from Chinese sectors come from the SFA. We connect Hg emission/release inventories of the SFA to the global MRIO model by two steps. We first calculate Hg emissions/releases from the combustion of coal, oil, and natural gas by methods described in the SFA. Primary results are in 44-sector format which is the formal sector classification of China's energy statistics. However, China is divided into 123 sectors in the Eora database. We disaggregate the 44-sector results into the 123-sector format using existing methods.[50,51] We then correspond Hg emissions/releases from production processes (excluding the combustion of coal, oil, and natural gas) in the SFA to Chinese sectors in the global MRIO data according to relationships described in data set S1. Finally, we construct the global EE-MRIO model that is used to quantify China's Hg emissions/releases caused by each nation/region's consumption activities.

■ RESULTS

Hg emissions/releases to air, water, and land from China's production activities are 633, 84, and 651 t, respectively (Figure 2). Domestic consumption is the dominant driver, accounting for 67% of China's Hg emissions/releases. The remaining 33% is due to external consumption activities (Figure 2) mainly in the United States (US, contributing 8.2%), China-Hong Kong Special Administrative Region (SAR, 3.3%), and Japan (2.6%). In particular, China's Hg emissions caused by consumption activities of China-Hong Kong SAR might be overestimated, as parts of exports from China to China-Hong Kong SAR are re-exported to the US.[52]

Hg Flows within China's Production System. Figure 3 shows Hg flows within China's production system for the year 2010. Out of the total Hg input of 2643 t, 1714 t is from non-Hg ores where Hg is an impurity, 926 t comes from primary Hg ores, and 3 t is from biomass combusted by rural households. China's Hg output is approximately 2709 t. The 66 t gap between Hg input and output results from the disposal of historical stocks of fluorescent lamps and the release of dental amalgam from interred human bodies. Hg in these stocks were inputted in previous years.[23] However, their emissions and releases mainly happen in 2010, and therefore belong to Hg outputs in 2010. Hg emissions/releases to air, water, and land are totally 1368 t, accounting for 51% of total Hg output. Product exports transfer 129 t of embedded Hg abroad. Approximately 420 t of Hg is stabilized in controlled landfill sites or fixed in building materials, of which 46% comes from cement plants. Hg stocks reach 795 t, in which Hg-containing wastes from nonferrous metal smelting processes and Hg recovery companies contribute 94%.

Total atmospheric Hg emissions in China are 633 t (Figure 2), of which 531 t is from primary emission sources (Figure S2). Our primary Hg emissions to air are comparable with those in previous 2010 inventories, but Hg emissions from certain sectors, such as that from artisanal and small-scale gold mining (ASGM), cement production, and coal-fired industrial boilers, are significantly different (SI section S3 and Figure S3).[8,15] The difference between our study and the report of AMAP/UNEP[8] lies in Hg emissions from China's ASGM, 5 and 167 t, respectively. The 2010 activity data for China's ASGM in the AMAP/UNEP report are derived from China's 2001 data.[53,54] However, the Chinese government has conducted various strict measures to prohibit ASGM activities after 2001.[55,56] Thus, the practical situation for China's ASGM in 2010 is significantly different from the ASGM activity data used in the AMAP/UNEP report.[15,57] Moreover, we observe large differences in Hg emissions from cement production and coal-fired industrial boilers (termed as industrial coal combustion in Zhang et al.[15]) between our inventory and that of Zhang et al., due to different calculation patterns of coal combustion.

In addition to primary atmospheric Hg emissions (emissions from production processes of the studied sectors), we identify 102 t of secondary atmospheric Hg emissions (emissions from the disposal of wastes/byproducts). Dominant sources of secondary atmospheric Hg emissions are waste disposal processes in nonferrous metal smelters and cement plants, which lead to 54 and 25 t of atmospheric Hg emissions, respectively. Other secondary atmospheric Hg emissions are due to the use of Hg-added products (e.g., thermometer and gypsum) and the recovery of Hg from wastes (SI Figure S4).

China's national Hg releases to water and land are approximately 84 and 651 t, respectively (Figure 3 and data set S6). They constitute 54% of China's total Hg emissions/releases, which indicates that the conventional treatment of atmospheric Hg emissions pretty much misses the Hg releases into the environment and may lead to the underestimation of

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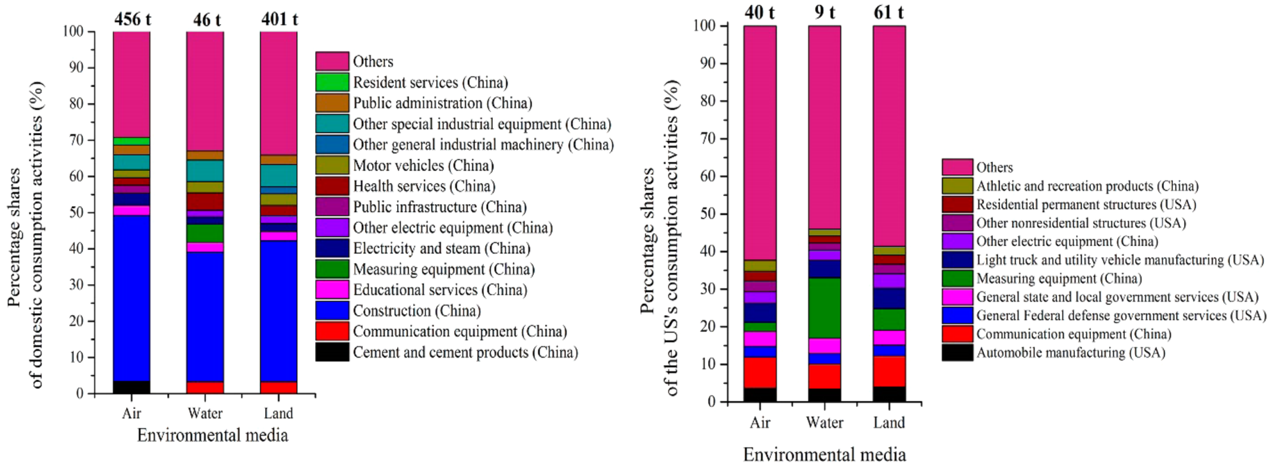

(a) China's Hg emissions/releases due to domestic consumption

(b) China's Hg emissions/releases due to the US's consumption

Figure 4. Consumption activities of China (a) and the US (b) leading to China's Hg emissions/releases to air, water, and land. (Nation names in the brackets refer to nations where consumed products are produced, and numbers on top of bars indicate the quantity of China's Hg emissions/releases to environmental media due to consumption activities of corresponding nations.

Hg burden in the global environment. Nonferrous metal smelting—the largest Hg release source to water—contributes 49% of national Hg releases to water (Figure 3). Hg releases from copper, lead, and zinc smelters to water are 2, 3, and 25 t, respectively, which are quite similar to our previous estimation.[18] The use of Hg-added products (e.g., thermometer) discharges 26 t of Hg to water. Other Hg release sources to water include fuel consumption sectors, primary Hg ore mining, production activities using Hg, and Hg recovery processes. All production activities examined in this study release Hg to land. Nonferrous metal smelting is the top one Hg emitter to land, whereas production using Hg, primary Hg ore mining, fuel consumption, and building materials production occupy similar shares in total Hg releases to land.

We also identify Hg recycling flows in China. Approximately 806 t of Hg embedded in wastes is sent to Hg recovery companies. These wastes are mainly from production processes using Hg and nonferrous metal smelting processes, accounting for 94% and 5% of Hg input to Hg recovery companies, respectively. However, only 408 t of Hg is recovered and then sent to production activities using Hg. Approximately 374 t of Hg is still left in wastes, implying a high recovery potential. During Hg recovery processes, 9, 1, and 1 t of Hg are discharged to air, water, and land, respectively.

Global Consumption Drivers of China's Hg Emissions/Releases. Domestic consumption leads to 74%, 56%, and 62% of Hg emissions/releases to air, water, and land, respectively (Figure 2 and data set S7). The remaining is caused by external consumption of products whose upstream suppliers involve Chinese production activities. Final consumption of the US is the largest external driver, leading to 6%, 10%, and 10% of China's Hg emissions/releases to air, water, and land, respectively. This finding informs decision makers to focus on both domestic consumers and external consumption drivers.

Major domestic consumption activities include construction, special industrial equipment, cement, electricity, etc. (Figure 4A and data set S8). Producing cement and electricity directly discharges Hg to environmental media, but construction and special industrial equipment lead to Hg emissions/releases mainly through upstream supply chain links. For example, as the largest driver among China's consumption activities, construction itself discharges few Hg emissions, it causes significant Hg emissions through Hg-intensive inputs such as nonferrous metals. The consumption viewpoint can reveal new critical activities leading to China's Hg emissions through global supply chains, which are unidentifiable by traditional production-side analyses.

We also investigate consumption activities of the US which is the largest external consumption driver. Major contributors include the US's demand on products not only imported from China (e.g., communication equipment) but also produced within the US (e.g., vehicles) (Figure 4B and data set S9). The production of these products leads to large Hg emissions/releases in China mainly through upstream Chinese suppliers facilitated by the US–China trade. The US's consumption also causes Chinese Hg emissions/releases through multiple-step global supply chains, involving third-party nations. For example, the US's demand on motor vehicles, trailers, and semitrailers from Canada (ranked 28th in data set S9) causes China's atmospheric Hg emissions, because the vehicle parts and related metals are produced in China. These findings reveal the necessity of appraising China's Hg emissions/releases in the context of global supply chains, instead of only counting domestic supply chains.

China's Hg emissions to air have been examined in previous demand-side studies.[25,28] Previous studies investigated critical regions/sectors the final consumption of which drives large upstream Hg emissions. However, these studies ignored China's Hg releases to water and land which are also important components of China's Hg emissions. In this study we find that some consumption activities are more important in China's Hg releases to water and land than emissions to air (data set S8). For example, China's final consumption of domestic communication equipment is ranked third in Hg releases to land, but ranked 11th in Hg emissions to air, because the producing upstream inputs (mainly nonferrous metals) of communication equipment production discharges more Hg to land than to air (data set S6). This finding reveals the importance of considering Hg releases to water and land in identifying critical consumption drivers of Hg emissions/releases. The demand-side policymaking on Hg control should focus on not only critical consumption activities leading to large

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atmospheric Hg emissions, but also critical consumption activities which may be insignificant atmospheric Hg emission sources but lead to large Hg releases to water and land.

The consumption of large and populous nations obviously leads to large Hg emissions/releases in China. However, China's Hg emissions/releases driven by per-capita consumption of major export destinations (Figure S5) show that significant global supply chains also point to small but wealthy importers of Chinese goods and services (e.g., Singapore).

■ DISCUSSION

Implications for Production-Side Hg Control. Hg control has been both national and global policy goals.[7,58,59] The Chinese government has already made large efforts in reducing atmospheric Hg emissions (e.g., emissions from power plants), mainly through measures such as improving energy efficiency and end-of-pipe control measures.[60−62] Approximately 1002 t of Hg (calculated by multiplying Hg input with Hg distribution factors for wastes captured by air pollution control devices (APCDs)) was removed by APCDs in 2010, which would otherwise have been directly discharged to air.

The removed gaseous Hg mainly enters wastewater and solid wastes, depending on the type of APCD applied.[63−66] Traditional aquatic pollutant control measures (e.g., chemical precipitation) further remove Hg from wastewater to solid wastes.[38,67] Even so, approximately 84 t of Hg is still released to water. Inorganic Hg can be converted into a more toxic form, methylmercury, which is a naturally occurring process in water.[5] Thus, the Hg shift from gas to water may cause larger environmental impacts. To reduce such cross-media Hg shifting, the Chinese government should pay special attention to controlling Hg releases to water, such as improving water pollution control measures and increasing wastewater recycling rates. Hg removed from waste gas and water is primarily migrated to solid wastes. Unfortunately, solid waste disposal is challenging China, given that large amounts of solid wastes have been left untreated in past years and mature disposal methods are limited in China. China is promoting comprehensive utilization of solid wastes in its recent socioeconomic development plans,[68−70] such as the collaborative disposal of solid wastes in building materials production (e.g., cement plants). Approximately 184 t of Hg is sent to building materials production primarily via desulfurization gypsum and fly ash, which would otherwise be released to land (SI Figure S2). Subsequently, only 4 t of Hg is released to land, and approximately 143 t of Hg is stabilized in building products (e.g., cement) where these solid wastes are used as raw materials. Such measures are capable of reducing Hg releases to land, but lead to 37 t of Hg emissions to air. Therefore, Hg control should consider the linkages among production activities, which can support effective policy decisions by avoiding the shifting of Hg from one environmental medium to another.

In the near future, end-of-pipe Hg control will still be an efficient action to control Hg emissions to air and Hg releases to water. For example, the use of end-of-pipe Hg control devices will contribute to 66% of total Hg reduction in coal-fired power plants under the maximum emission reduction scenario.[35] Hg releases to land via solid wastes can be reduced by increasing controlled landfills and strengthening solid waste recycling given that over 90% of Hg is released to land as undisposed wastes. If solid wastes containing Hg are treated through high temperature, we should either remove Hg from solid wastes before the treatment or strengthen Hg reduction of APCDs for treatment procedures. In the long term, the best way to control Hg emissions/releases is to reduce total Hg input, such as promoting clean energy substitution and using scrap metals to substitute primary ores in metal smelting, which will synchronously reduce Hg emissions and releases. For example, scrap metals substitution in Zn, Pb, and Cu smelting is expected to totally reduce 306 t Hg input to these sectors in 2030, which further contributes to 34% of atmospheric Hg emission reduction, 30% of aquatic Hg release reduction, and 36% of terrestrial Hg release reduction, respectively.[38]

Moreover, our results indicate that 926 t of Hg in the Hg ore was input to the primary Hg mining sector, which lead to 790 t of primary Hg in production activities using Hg as raw materials. This amount is much larger than the recycled Hg (408 t). From the viewpoint of the global Hg cycle, controlling current Hg input to primary Hg ore mining can help reduce Hg emissions/releases from downstream industries in the future. This study finds that using recycled Hg is an attractive way to reduce Hg input from primary Hg ore. China currently has large Hg recovery potentials. Approximately 374 t of Hg is stored in recovery companies as discarded activated carbon and Hg catalyst in 2010. These solid wastes can potentially produce 355 t of recycled Hg (equal to 38% of the Hg input from Hg ores in 2010), given that the Hg recovery rate can reach 95% in most companies.[71] Other potential sources for Hg recovery are waste acid from flue gas scrubber and calomel from specific Hg reclaiming towers in nonferrous metal smelting. Only 41 t of Hg in the calomel and waste acid slag is sent to Hg recovery companies, while 374 t of Hg is stocked in the smelters. However, Hg recovery is challenging, because there are many obstacle factors such as the market requirement for Hg and technology availability.[18,72] The Chinese government should propose new measures to promote Hg recovery, such as encouraging the development of innovative Hg recovery technologies to treat wastes with low Hg content and giving subsidies to Hg recovery companies to lower their product prices.

Implications for Demand-Side Hg Control. Besides production-side measures discussed above, demand-side actions are equally important. Domestic consumption is the largest driver of China's Hg emissions/releases. China has established standards for embedded Hg concentrations of domestic consumer goods.[73] Our study finds that, although products of particular sectors (e.g., educational services) do not contain Hg, the consumption of these products can lead to upstream Hg emissions/releases (not only through energy use, but also through the use of other products such as buildings, computers, and papers). Therefore, China should extend its Hg-related standards to take into account Hg emissions driven by consuming activities, such as using ecolables on consumer goods and services[74−78] and then place environmental taxes based on embodied Hg emissions. This measure can inform consumers about how many Hg emissions/releases will be induced by their purchases and hence probably influence consumption pattern of consumers (e.g., purchasing products with less embodied Hg emissions). Its smooth implementation highly depends on government auxiliary policies, such as incorporating embodied Hg emissions/releases in environmental tax rates on products. However, further studies are needed to determine the appropriate rates of environmental

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taxes and assess the effects of environmental taxes on other aspects such as gross domestic products and employment.

Improving production efficiency (e.g., using less upstream inputs to produce unitary output of a sector) is another promising way to reduce upstream Hg emissions/releases caused by consumption activities.[24,79−82] For example, improving the usage efficiency of metals in construction activities can reduce the demand on metals, which will further reduce Hg emissions/releases from metal smelting activities. Moreover, using less upstream inputs indicates the reduction of economic costs and can enhance market competitiveness of enterprises. China proposed the ambitious *Made in China 2025* strategy to encourage the development of high-end manufacturing sectors, aiming to improve economic quality and market competitiveness.[68] This study finds that domestic and external demands on products of high-end manufacturing sectors (e.g., equipment, machinery, and vehicles) are critical underlying drivers of China's Hg emissions/releases. Currently, the *Made in China 2025* strategy only takes into account the usage efficiency of energy and water resources, but overlooks the usage efficiency of other Hg-intensive upstream inputs to manufacturing sectors (e.g., ferrous and nonferrous metals usage in vehicle manufacturing). Rapid development of high-end manufacturing sectors in the future can increase the demand on Hg-intensive upstream inputs (e.g., nonferrous metals, iron and steel, and electricity) and will probably increase Hg emissions/releases. To control this part of Hg emissions/releases, both upstream measures (e.g., establishing Hg removal devices in enterprises producing metals and electricity) and downstream measures (e.g., improving production efficiency) are required. It is crucial for the *Made in China 2025* strategy to take into account the usage efficiency of all critical upstream inputs, instead of only energy and water resources. This can mitigate not only China's Hg emissions/releases but also resource demands (e.g., metal ores for metals smelting) and other pollutant emissions (e.g., CO_2 and particulate matter), indicating cobenefits of China's emission control policies.[83,84] Subsidies from Chinese governments to high-end manufacturing enterprises are good incentives to the improvement of production efficiency.

In addition, the contribution of external consumption cannot be ignored. This indicates that reducing China's Hg emissions/releases will require globally joint efforts. First, external regions can help reduce China's Hg emissions/releases by demand-side measures such as influencing consumption behaviors (e.g., placing environmental taxes on consumer products based on embodied Hg emissions) and improving production efficiency of finally consumed products. Accounting for Hg emissions/releases caused by external consumption (not only the absolute amount but also per capita amount) in the *Minamata Convention on Mercury* framework can stimulate external regions to take demand-side measures to reduce Hg emissions/releases of a specific nation (e.g., China in this study). Second, dedicated Hg removal devices are relatively expensive, and China's Hg-intensive enterprises do not have sufficient capital to implement these devices.[85] Developed regions (e.g., the US, Japan, and Singapore), which are major external consumption drivers of China's Hg emissions/releases, have advanced technologies and sufficient capital. Transferring technologies and capital from these developed regions to China's Hg-intensive enterprises can help efficient reduction of China's Hg emissions/releases. The emissions trading scheme widely discussed for carbon dioxide mitigation[86] is a promising way to encourage technology and capital transfers for Hg control. Demand-side measures and the emissions trading scheme can complement production-side measures and make a nation's Hg control more efficient. Findings in this study provide scientific foundations for the implementation of the *Minamata Convention on Mercury*.

Uncertainties and Recommendations. We investigate uncertainties in China's Hg emissions/releases by sectors (data set S1). The overall uncertainties of Hg emissions to air, Hg releases to water, and Hg releases to land are in the ranges of (−49%, 68%), (−63%, 81%), and (−74%, 97%), respectively. The uncertainty ranges of our atmospheric Hg emissions are substantially smaller than those (−51%, 131%) of the inventories provided by global mercury assessment report.[8] The Hg concentration of raw materials and Hg removal efficiencies of pollution control devices are two dominant factors, the uncertainties of which contributed 61% and 21% of the overall uncertainties of our atmospheric Hg emission inventory. The large range of Hg concentrations of raw coal/ores is a natural property of the coal/ores. The result uncertainty caused by the uncertainty of Hg removal efficiencies can be reduced through more field experiments. Major emitters with large uncertainties are zinc smelting, lead smelting, and coal-fired industrial boilers. We observe that uncertainties of Hg releases to water and land are much larger than those of Hg emissions to air, which indicates that more information on the waste/byproduct disposal processes is needed to constrain Hg redistribution factors and enhance the accuracy of results.

In addition, we use the Eora MRIO database[29,30] to analyze consumption drivers of China's Hg emissions/releases. There are also many other global MRIO databases (such as WIOD[87,88] and GTAP[89]), and scholars observed data quality differences across these databases.[90−92] We choose the Eora database due to its highest resolution for nations and sectors in the world economy, given that the aggregation of sectors and nations has non-negligible effects on MRIO results.[93] It is important to harmonize the data quality of different global MRIO databases in the future.

In general, revealing embedded Hg flows of an economy from the production side helps uncover secondary Hg emissions and improve production-side measures, while revealing embodied Hg flows within global supply chains from the consumption side helps uncover underlying drivers and make demand-side measures. The analytical framework in this study can assist a paradigm shift necessary to make real progress in global Hg control and the implementation of the *Minamata Convention on Mercury*. Although this study takes China as the case, the framework developed can be widely applied in other nations/regions. The findings of our study will provide not only better inputs for Hg pollution modeling community, but also scientific foundations for both production-side and demand-side policy decisions on global Hg pollution control.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b04094.

Additional text, tables, and figures supporting the main text (PDF)

Detailed data collection methods and data sets (XLS)

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