Spatially explicit global hotspots driving China's mercury related health impacts

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ABSTRACT

Over 100 nations signed the *Minamata Convention on Mercury* to control the adverse effects of mercury (Hg) emissions on human beings. A spatially explicit analysis is needed to identify the specific sources and distribution of Hg-related health impacts. This study maps China's Hg-related health impacts and global supply chain drivers (i.e., global final consumers and primary suppliers) at a high spatial resolution. Here we show significant spatial heterogeneity in hotspots of China's Hg-related health impacts. Approximately 1% of the land area holds only 40% of the Chinese population but nearly 70% of the fatal heart attack deaths in China. Moreover, approximately 3% of the land area holds nearly 60% of the population but 70% of the intelligence quotient (IQ) decrements. The distribution of hotspots of China's Hg-related health impacts and global supply chain drivers are influenced by various factors including population, economy, transportation, resources, and dietary intake habits. These spatially explicit hotspots can support more effective policies in various stages of the global supply chains and more effective international cooperation to reduce Hg-related health impacts. This can facilitate the successful implementation of the *Minamata Convention on Mercury*.

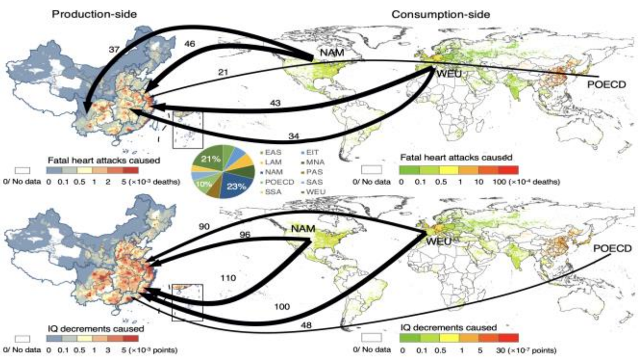
KEYWORDS

Mercury; health impacts; supply chain; input-output analysis; spatially explicit analysis; trade; footprint; Minamata Convention

SYNOPSIS

Spatially explicit analyses for China's Hg-related health impacts and relevant global economic drivers can facilitate the smooth implementation of the Minamata Convention on Mercury.

GRAPHICAL ABSTRACT/ TOC



1. INTRODUCTION

Mercury (Hg) is a global pollutant that can be transported worldwide and is difficult to be removed from the environment.[1, 2] One of its forms, methylmercury (MeHg), is highly toxic to the nervous, digestive, and immune systems of human body, as well as the development of the child in utero.[3, 4] Given the adverse impacts of Hg on human beings, the World Health Organization (WHO) has listed Hg as one of the top ten chemicals with primary public health concern.[3] To control global anthropogenic Hg emissions and their adverse effects on human beings, over 100 nations signed the *Minamata Convention on Mercury* (*Minamata Convention*)[5]. This convention entered into force on 16 August 2017, which is the first global agreement to protect human health and the environment in the recent decade.[6]

In order to reduce the human health damage of global Hg pollution, lots of studies have been conducted to evaluate Hg-related health impacts via MeHg intake and dose-response relationship of MeHg exposure.[7, 8] Studies on prenatal MeHg exposure indicate that MeHg intake can have severe impacts on neurodevelopment in children, thus affecting their intelligence quotient (IQ) and cognitive levels.[9] In addition, MeHg exposure is closely associated with the risks of cardiovascular diseases.[10] Given the long-distance transport of Hg, the assessment of Hg-related health impacts should be based on a complete Hg cycle (e.g., atmospheric Hg emissions[11-13], atmospheric Hg transport and deposition[14, 15], MeHg bioaccumulation[4, 16], and Hg-related health risks[17, 18]). Recently, studies have combined the economic systems with traditional biogeochemical Hg cycle to identify the impacts of economic activities and international trade on Hg emissions and related health impacts. For example, previous studies have characterized the impacts of local Hg emissions on domestic human health in the U.S and China.[17, 19,20] In addition to local Hg emissions, remote economic activities can also influence local Hg emissions through global supply chains[17, 21, 22] and subsequently influence human health[13,17,18]. For instance, our recent study has revealed China's regional Hg-related health impacts driven by the economic activities of other regions in China.[17] In addition to domestic economic drivers, international economic activities also influence domestic Hg-related health impacts via global supply chains. This requires international cooperation which is an important component of the

Minamata Convention[5]. However, the global economic drivers (including global final consumers and primary suppliers) of local Hg-related health impacts have not been well characterized yet.

Moreover, Hg-related health impacts and economic activities are both highly localized and have significant spatial heterogeneity.[23] Existing studies have nationally or sub-nationally averaged out the spatial characteristics of Hg-related health impacts and economic activities.[17, 19] However, they ignored the identification of Hg-related health impacts and economic drivers at a high spatial resolution. It is important to develop a highly resolved inventory to explicitly spatialize the supply chain hotspots of Hg-related health impacts (including the occurrence of Hg-related health impacts, global final consumers, and global primary suppliers). This effort can more accurately locate the hotspots for Hg control measures and effectively facilitate the implementation of the *Minamata Convention*.

This study fulfils the above knowledge gaps, taking China as a representative case. China is important in global biogeochemical Hg cycle due to its largest atmospheric Hg emissions and population in the world.[24] Atmospheric Hg deposition over China has been proven to adversely affect human health through the intake of Hg-containing foods (e.g., rice, fish, vegetables, and meat).[25, 26] The MeHg intake has resulted in approximately 0.14 points of per-foetus IQ decrements and 7,360 deaths from fatal heart attacks in China in 2010.[17] Moreover, China participates in intensive trade of commodities with other nations and plays the role of world factory in global supply chains.[27] Identifying the hotspots for China's Hg-related health impacts and global supply chain drivers plays an important role in global Hg control.

To effectively identify the global supply chain hotspots driving China's Hg-related health impacts at a high spatial resolution, this study constructs a model for the Spatially Explicit Global Tracking of Hg-related Health Impacts (SEGTHI). This model integrates global economic supply chains with China's biogeochemical Hg cycle to track spatially explicit hotspots of global supply chains driving the spatially explicit health impacts of China's Hg emissions. We map China's Hg-related health impacts (including IQ decrements and deaths from fatal heart attacks) in 2010 caused by local production, global final demand, and global primary inputs at a high spatial resolution. In this way, we can identify key hotspots of Hg-related health impacts and global supply chain drivers at a finer scale than the national and sub-national levels. These findings can facilitate distinct Hg control strategies and international cooperation to reduce Hg-related health impacts more effectively. It is worth noting that there is a time lag between MeHg intake and the response of heart attacks (generally 6 years). Moreover, the data on population structure (i.e., the Sample Survey Data of 1% of National Population[28]) used to calculate the fatal heart attack deaths are only updated to 2015. Consequently, we use the global MRIO data in 2010 and estimate China's Hg-related health impacts in 2010.

2. METHODS AND DATA

The SEGTHI model consists of three components, including (1) the global environmentally extended multi-regional input-output (EE-MRIO) model, (2) the biogeochemical Hg cycle, and (3) the spatially explicit mapping for Hg-related health impacts of China caused by domestic production, global final demand, and global primary inputs. This study evaluates the roles of 30 Chinese provinces and 140 nations as primary suppliers, direct emitters, and final consumers for China's Hg-related health impacts at a high spatial resolution. Tables S1 and S2 in the Supporting Information (SI) present the list of Chinese provinces, world nations, and aggregated regions. The framework of the SEGTHI model in this study is illustrated in Figure S1. Here we provide the simplified methods and the detailed methods and data can be found in section S1 of the SI.

2.1 Global EE-MRIO model

We use the global EE-MRIO model to evaluate the roles of nations and Chinese provinces as primary suppliers, direct emitters, and final consumers for atmospheric Hg emissions in China. The global EE-MRIO model has been widely used to investigate environmental issues related to interregional trade, such as resource extraction[29] and atmospheric emissions[27,30,31]. The global EE-MRIO model is constructed with a global multi-regional input-output (MRIO) table and a satellite account of environmental issues (i.e., atmospheric Hg emissions in China in this study). This model is used to calculate production-based, consumption-based, and income-based emissions of nations and Chinese provinces for atmospheric Hg emissions in China. We use the Chinese atmospheric Hg emission inventory compiled in our previous work[14] to construct the satellite account of the global EE-MRIO model. The atmospheric Hg emission inventory is compiled by multiplying energy uses or product yields with corresponding emission factors.[14] The global MRIO table is constructed by Mi et al.[32], which links the Chinese MRIO data to the Global Trade and Analysis Project (GTAP) database. The base year in this study is set as 2010.

The production-based Hg emissions are direct geographic Hg emissions from the physical emitters. They are the satellite account of the global EE-MRIO table. We define the Hg emission intensity of each sector using Eq. (1).

The notation indicates production-based Hg emissions of sectors in province *n*. The row vector *q* indicates the direct Hg emission intensity of each province sector, which represents Hg emissions for unitary output of each province sector. The column vector represents the total output of sectors in province *n*.

Consumption-based Hg emissions of nations and Chinese provinces are calculated by the Leontief MRIO model, which regards the economy as demand-driven. Consumption-based Hg emissions represent China’s Hg emissions directly and indirectly driven by the final demand of nations and Chinese provinces[31, 33], as shown in Eq. (2).

The notation represents consumption-based Hg emissions of nation/province *n*. The row vector *q* indicates the direct Hg emission intensity of each province sector.

The column vector represents the final demand of nation/province *n*. The matrix is the direct input coefficient matrix, in which each element equals to direct input from sector *i* to sector *j* divided by the total output of sector *j*. The matrix **I** is an identify matrix. The matrix is the Leontief Inverse matrix, which describes both direct and indirect inter-sectoral relationships of the outputs and unitary final demand[34].

Income-based Hg emissions of nations and Chinese provinces are calculated by the Ghosh MRIO model, which regards the economy as supply-push. Income-based Hg emissions represent China's Hg emissions directly and indirectly enabled by primary inputs of nations and Chinese provinces[35, 36], as shown in Eq. (3).

The notations represents income-based Hg emissions of nation/province *n*. The row vector indicates the primary inputs of nation/province *n* (values for sectors of nation/province *n* are non-zero and values for other nation/province sectors are zeros). The column vector q' represents the transposition of the Hg emission intensity vector q. The matrix **B** is the direct output coefficient matrix, in which each element equals to direct input from sector *i* to sector *j* divided by the total output of sector *i*. With an identity matrix **I**, the matrix is the Ghosh Inverse matrix, which represents both direct and indirect inter-sectoral relationships of the outputs and unitary primary inputs.[34]

2.2 Biogeochemical cycle of Hg

The methods for modelling the biogeochemical cycle of Hg in this study refer to those in our previous work[17]. Here we give a brief overview of each component, while specific methods are described in SI S1.2. We also provided the details on related methods and data on our website (https://www.cgeed.net/cmstm-model). The biogeochemical cycle of Hg consists of five components which occur over mainland China and the coastal seas, including a Chinese anthropogenic Hg emission inventory, an atmospheric transport model, changes in food MeHg resulting from atmospheric deposition, a human intake inventory of MeHg, and human health impacts due to MeHg intake. Meanwhile, two external components include Hg emissions from natural sources and foreign anthropogenic sources, and imports of food products from foreign nations.

We use the Chinese atmospheric Hg emissions inventory complied in our previous work as the production-based emission inventory.[14] The production-based emissions are distributed as point and non-point sources, which serve as the input of an atmospheric transport model. Then, we use the GEOS-Chem chemical transport model (version 9-02; http://geos-chem.org) to simulate atmospheric Hg cycle over China. A nested simulation at a horizontal resolution of 1/2°×2/3° over China is conducted in a boundary condition provided by a global simulation at a horizontal resolution of 4°×5°. Changes in Hg deposition simulated by the model are used as a measure of changes in Hg concentrations in Hg-containing food products, including ten categories of food products (i.e., rice, wheat, beans, vegetables, pork, poultry, milk, eggs, marine fish, and freshwater fish) referred from previous studies[25, 37]. Next, we compile an intake inventory at the provincial scale to present a map of MeHg intake for the population over China in the model. The data regarding the compilation of intake inventory of MeHg and the evaluation of human health impacts are from our previous study[17]. In addition to the intake inventory, the model involves the dose-response relationships between dietary intake of MeHg and Hg-related health impacts to evaluate the health impacts. The dose-response relationships referred to in previous studies are based on epidemiological studies.[10,19,38]

2.3 Spatially explicit mapping

The spatially explicit mapping of Hg-related health impacts in China includes the impacts caused by domestic production, global final demand, and global primary inputs. The grid maps of Hg-related health impacts in China caused by domestic production show the occurrence of foetal IQ decrements and deaths from fatal heart attacks. For grid maps of Hg-related health impacts in China caused by global final demand and primary inputs, data in each grid represent the foetal IQ decrements and deaths from fatal heart attacks occurring in China caused by the final demand and primary inputs in this grid.

For Hg-related health impacts in China caused by domestic production, we use the gridded food consumption expenditure data in China as the proxy to spatialize the foetal IQ decrements and deaths from fatal heart attacks in China. Due to the lack of basic gridded data, we multiply the per-capita food consumption expenditure data of China at the city level with gridded population to obtain the gridded data for food consumption. We select China's gridded population in 2010 and 2015 at the 1km × 1km grid scale as the basic grid data, which are from the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences[39]. The gridded population in 2010 is used in the evaluation of the foetal IQ decrements, and the gridded population in 2015 is used to investigate Hg-related fatal heart attacks to reflect the time lag between MeHg intake and the response of heart attacks.[17] The gridded population data are calibrated with the official demographic statistics[40,28]. Notably, when calculating the foetal IQ decrements, we multiply the birth rate in 2010 to the gridded population data to obtain the gridded data of new-born population. The birth rate data can be obtained from the China Statistical Yearbook[40].

For grid maps of China's Hg-related health impacts driven by global final demand, we construct a grid map for global final demand as the proxy to spatialize the health impacts. The grid map for global final demand is constructed with the final demand of nations and Chinese provinces in the global MRIO table and the global nighttime lights data at the 1km × 1km grid scale in 2010. The grid data for global nighttime lights can be obtained from the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) Nighttime Lights Time Series[41]. They can directly reflect the intensity of human activities and describe the socioeconomic development level of a region.[42] We simulated the relationship between the global final demand and the values of nighttime lights. We observed a significant positive correlation relationship between them, and the fitting degree is high (SI Figure S5). Therefore, we assume that the spatial distribution of nighttime lights is consistent with that of the final demand. Subsequently, we use the values of nighttime lights at the 1km × 1km grid scale as the proxy variable to spatialize global final demand at the national/subnational scale. In this way, we can investigate global final consumers driving China's Hg-related health risks at a higher spatial resolution to support more targeted policy decisions.

The primary inputs are also called value added, whose sum in each region is equal to the Gross Domestic Product (GDP). The main variable that influences the primary inputs is GDP. Thus, for grid maps of Hg-related health impacts in China enabled by global primary inputs, we use the global gridded GDP data at the 1km × 1km scale in 2010 developed by United Nations Environment Programme[43] as the proxy variable to spatialize the health impacts. See section S1.3 of the SI for specific methods.

3. RESULTS AND DISCUSSION

3.1 Spatially explicit health impacts of atmospheric Hg emissions in China

Overall, anthropogenic atmospheric Hg emissions in China led to 8.48×10^{-2} points of per-foetus IQ decrements and 4,593 deaths from fatal heart attacks in 2010. These impacts generally increase from northwestern inland areas to southeastern coastal areas (Figure 1a-b). Figure 1c shows that atmospheric Hg emissions of Central China lead to the most national health impacts, with 2.19×10^{-2} points of per-foetus IQ decrements and 1,196 deaths from fatal heart attacks. In terms of sectoral sources, the electricity and heat power sector is the major sectoral source of national Hg-related health impacts in eastern regions (including the Northeast, Beijing-Tianjin Region, Central Coast, and South Coast), contributing approximately 40% in each region. The metallurgy industry plays a dominant role in western regions, including the Northwest and Southwest. In addition, for the North and Central, the nonmetal products, metallurgy, and electricity and heat power sectors are all important sources of national Hg-related health impacts. Specially, a significant spatial heterogeneity was observed in hotspots of China's Hg-related health impacts. Approximately 1% of the land area holds 40% of the Chinese population but nearly 70% of the deaths from fatal heart attacks in China. Moreover, approximately 3% of the land area holds nearly 60% of the Chinese population but 70% of the IQ decrements. For example, approximately 80% of the hotspots in Sichuan Province are located in the Chengdu-Chongqing District (occupying only 32% of the land area in Sichuan) of eastern Sichuan. Few hotspots have been observed in western Sichuan because western Sichuan is mountainous with lower population and less industrial activities. This indicates the necessity of spatially explicit mapping to accurately identify the hotspots and effectively reduce Hg-related health impacts in China. Moreover, it shows that the hotspots of economic activities and Hg-related health impacts are driven by various factors, not just the population density.

The spatial distribution of Hg-related health impacts is affected by many factors, including population, economy, resources, and dietary intake habits. Many hotspots of Hg-related health impacts are distributed in urban agglomerations. This pattern is the most obvious in the Yangtze River Delta (including Shanghai, South Jiangsu, North Zhejiang, and some regions in Anhui), Beijing-Tianjin-Hebei Region, Pearl River Delta (including Guangzhou, Foshan, Shenzhen, and Zhuhai in Guangdong Province), and Chengdu-Chongqing District. For example, the land area of the Yangtze River Delta and Pearl River Delta urban agglomerations accounts for only 4% of the whole country, but holds approximately 30% of China's Hg-related health impacts. Most of these cities are provincial capitals or municipalities, such as Beijing, Shanghai, Nanjing, Hangzhou, Guangzhou, and Chengdu (see SI Figure S5a for provincial boundaries). These cities have large populations and high levels of socioeconomic development, inducing large amounts of anthropogenic Hg emissions. Meanwhile, their populations consume large amounts of marine fish and meat with relatively high Hg concentration. This subsequently results in high Hg-related health impacts in these cities.

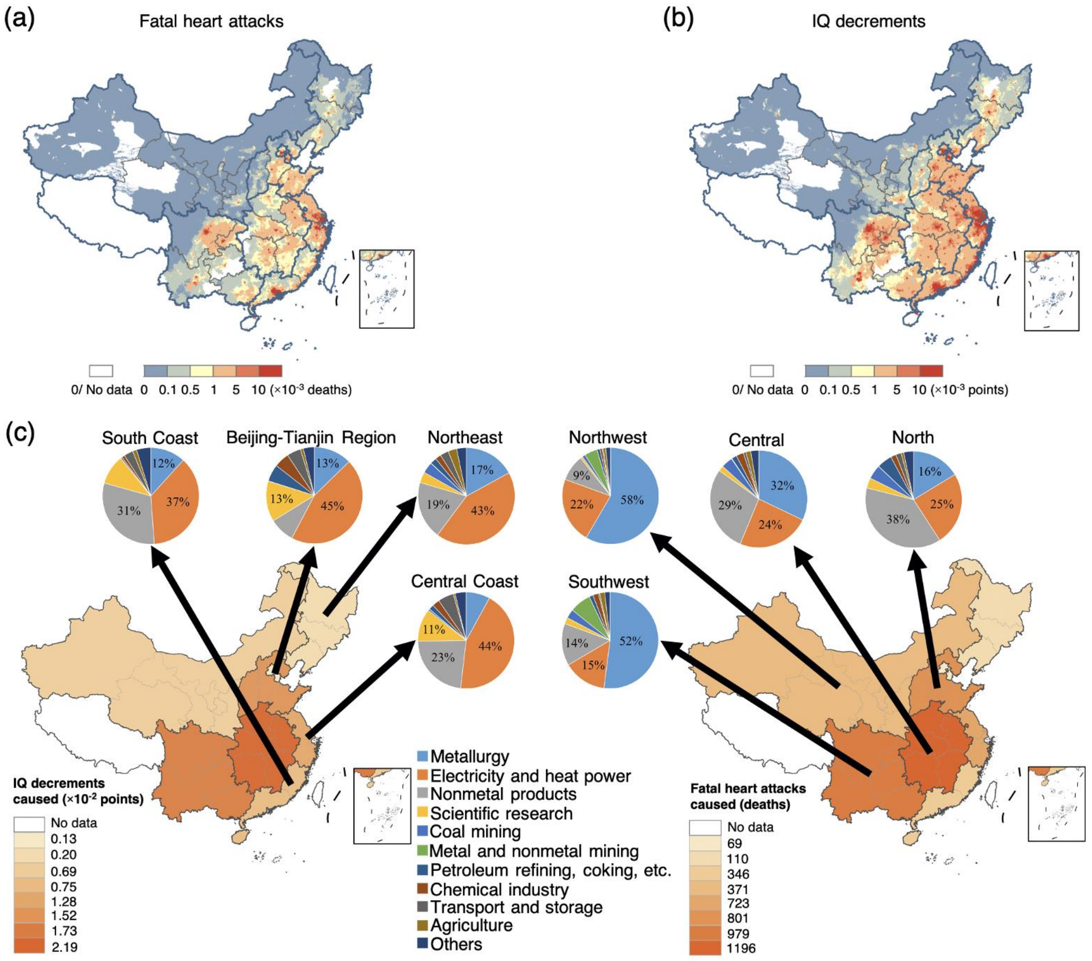


Figure 1. Spatially explicit human health impacts caused by anthropogenic atmospheric Hg emissions in China in 2010. Graphs *a* and *b* describe spatially explicit deaths from fatal heart attacks due to methylmercury intake and total foetus IQ decrements in each grid. It is worth noting that graph *b* shows the total IQ decrements for the total new-born population in each grid. Graph *c* shows national per-foetus IQ decrements and deaths from fatal heart attacks caused by anthropogenic atmospheric Hg emissions in each region of China. The pie chart shows the contributions of sectors in each region to the national health impacts caused by atmospheric Hg emissions in this region.

Moreover, parts of the hotspots of China’s Hg-related health impacts are associated with the distribution characteristics of mineral and water resources. China's mineral resources are mainly distributed in the North, Northwest, and Southwest,[44] where many hotspots of Hg-related health impacts are located. Famous metal mining areas include iron mines in Panzhihua of Sichuan, Hg mines in Tongren of Guizhou, and gold mines in Zhaoyuan of Shandong (SI Figure S5b). For fossil fuels, Shanxi, Xinjiang, and Sichuan are the major producers of coal, oil, and natural gas, respectively. These resource-abundant areas discharge large amounts of atmospheric Hg emissions due to intensive mining, smelting, and energy combustion activities. This subsequently results in significant Hg-related health impacts. Figure 1c shows that the *metallurgy* industry is an important source of national Hg-related health impacts for these resource-based regions, including the Northwest (58%), Southwest (52%), and North China (16%). In addition to mineral resources, Hg-related health impact hotspots are also associated with water resources because water resources are essential for industrial production.[45] For instance, many hotspots are located in areas of the Yellow River catchment across the Gansu, Ningxia, and Shanxi provinces (SI Figure S5b). Moreover, Hg-related health impacts in southeast coastal areas are generally higher than other areas. This situation might be related to the higher consumption of fish, because fish consumption is a major pathway of MeHg exposure[37].

3.2 Spatially explicit global final consumers driving Hg-related health impacts

Domestic consumption (mainly in Central China, Central Coast China, and Northwest China) contributes 82% of the Hg-related health impacts in China, while foreign consumption (mainly in North America, Western Europe, Japan, India, and the Middle East) contributes the remaining 18% of impacts (see SI Figure S6 for details of domestic and foreign consumers). The U.S. is the largest foreign consumer, contributing 3.2×10^{-3} points of per-foetus IQ decrements and 171 deaths from fatal heart attacks. At the sectoral level, domestic demand of construction activities is the largest source. In most foreign regions, the consumption of mechanical and electrical products is the largest source (contributing over 20%). However, in the Middle East and North Africa, the final demand of construction activities has the leading role (contributing 25%). The demand for building materials (e.g., cement, steel, and ceramic tiles) in the Middle East (especially Saudi Arabia) is highly dependent on China.[46]

Figure 2 shows a significant spatial heterogeneity in global consumers driving Hg-related health impacts in China. The consumption activities in approximately 0.1%

of the global land area holds nearly 10% of the global population but drives 70% of the Hg-related health impacts in China. Overall, the domestic consumption in China has driven the majority of China's Hg-related health impacts. Since domestic hotspots in China are much larger than other global hotspots, we have adopted another classification to obtain more details about hotspots in China (SI Figure S7). The hotspots in China are mainly concentrated in North China, South Coast China, Middle-Lower Yangtze Region, and Pearl River Delta. They are the most developed regions in China with large populations and intensive consumption activities. They drive large Hg-related health impacts in China through global supply chains. The details are shown in the section S2 of the SI for the consumption of specific Chinese regions driving China's Hg-related health impacts. In addition, we observe significant influences of transportation and resources on the distribution of hotspots, mainly in developing areas (e.g., Yunnan, Guizhou, Guangxi, Eastern Sichuan, and the Yellow River Basin). These hotspots distribute along roads and rivers.

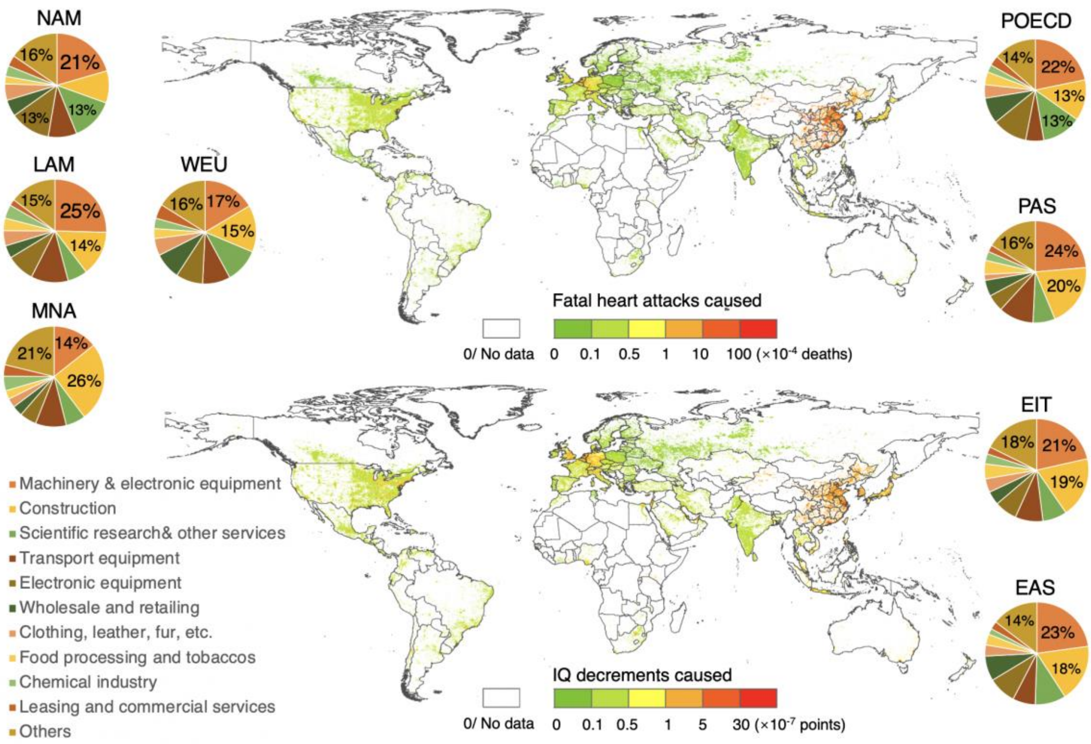


Figure 2. Spatially explicit global consumers driving China's Hg-related health impacts in 2010. Abbreviations: NAM – North America; LAM – Latin America and the Caribbean; WEU – Western Europe; MNA – the Middle East and North Africa; PAS – Southeast Asia and the Pacific; POECD – Pacific-OECD-1990 nations (including Japan, Australia, and New Zealand); EIT – Economies in Transition (including Eastern Europe and the former Soviet Union); EAS – East Asia (China excluded).

Foreign consumers driving China's Hg-related health impacts mainly include the U.S., Western Europe, Japan, and South Korea (See section S2 of the SI for more international pairs). They are developed nations and regions, where the hotspot locations are based on urban agglomerations centred on large cities. Cities are aggregation areas of consumption activities. They consume large amounts of commodities that directly and indirectly lead to atmospheric Hg emissions and related health impacts in China. For instance, in the eastern U.S., hotspots are concentrated in the megalopolises of New York, Boston, Washington D.C., Atlanta, and Chicago, forming a dotted distribution. The consumption of mechanical and electrical products in these regions results in significant Hg-related health impacts in China through global supply chains (Figure 2). In Western Europe, the consumption of Netherlands, Belgium, western Germany, and southern United Kingdom leads to the most Hg-related health impacts in China. In addition, some regions in Southeast Asia (e.g., Hanoi and Ho Chi Minh City in Vietnam, Bangkok in Thailand, Kuala Lumpur in Malaysia, and Singapore) have close trade ties with China. Their consumption has driven large Hg-related health impacts in China.

The transportation is also an important factor affecting the distribution of global consumers driving China's Hg-related health impacts. This distribution feature is mainly manifested as a coastal distribution. The geographical location of coastal areas facilitates international trade activities. For example, consumption hotspots on the west and east coast of the U.S., the west coast of Latin America and Caribbean, and the south coast of West Africa all follow the coastal distribution patterns. Another typical area of the transportation-based pattern is the Mid-Eastern of the U.S. There are major cities working as freight transportation nodes, and the hotspots are radiantly distributed on the dominating transportation arteries. For example, the Ohio state ranks second among all the U.S. states in terms of China's Hg-related health impacts driven by the final demand of various states in the U.S. However, the total value of Ohio's nighttime lights ranks only 7th. There are not too many nighttime lights in Ohio, but China's Hg-related health impacts caused by its final demand are high. One possible reason is the influence of transportation factors. As the third most developed state in manufacturing in the U.S., Ohio plays an important role as freight transportation hub.[47] For instance, the freight volume on the Ohio River is twice that of the Panama Canal.[48] Another area worthy of attention is Minnesota (especially Minneapolis and St. Paul). It ranks sixth among all the U.S. states in terms of China's Hg-related health impacts driven by the final demand of various states in the U.S. However, its population only ranks 21st among the U.S. states. Minnesota is adjacent to the Great Lakes and Mississippi River. It also borders Canada. This makes it an important port and rail transportation center.[48] These findings indicate that particular areas responsible for high Hg-related health impacts are not necessarily big cities with large populations or nighttime lights. Convenient traffic conditions can also make final demand activities gather here, resulting in high Hg-related health impacts in China through global supply chains.

3.3 Spatially explicit global primary suppliers enabling Hg-related health impacts

Figure 3 shows the spatially explicit global primary suppliers enabling China's Hg-related human health impacts in 2010. Domestic primary inputs (mainly in Central China, Northwest China, and North China) enable approximately 93% of the Hg-related health impacts in China, while foreign primary inputs (mainly in North America, Western Europe, and Japan) enable the remaining 7% of impacts (SI Figure S8). For relatively developed regions such as the Central Coast, major sectoral source enabling China's Hg-related health impacts is the *scientific research and other* *services* sector. For the Northwest with abundant mineral resources, primary inputs in the *metallurgy* sector takes the leading role. In the Central, primary inputs in the *nonmetal products* sector contributes the most to Hg-related health impacts in China (SI Figure S3). Foreign primary suppliers enabling significant Hg-related health impacts in China involve the Pacific-OECD-1990 nations (including Australia, Japan, and New Zealand), Latin America and the Caribbean, and the Middle East and North Africa. See section S2 of the SI for more international and intranational trade pairs inducing China's Hg-related health impacts. In particular, Australia is the largest primary supplier, enabling 1.6×10^{-3} points of IQ decrements and 85 deaths from fatal heart attacks in China. The *metal and nonmetal mining* sector and *petroleum and gas* sector are the major sectoral sources for foreign primary suppliers. The *metal and nonmetal mining* sector contributes nearly 50% of China's Hg-related health impacts enabled by primary inputs of Pacific-OECD-1990 nations, as well as Latin America and the Caribbean. The *petroleum and gas* sector contributes 76% for the Middle East and North Africa. The reason is that China imports large amounts of mineral resources from Australia and Latin America, and oil and gas resources from the Middle East.[49]

Figure 3 also shows a significant spatial heterogeneity in global primary suppliers enabling Hg-related health impacts in China. The distribution of global primary suppliers is significantly influenced by the distribution of resources, including mineral, oil, gas, and water resources. Similarly, we provide a spatially explicit map of domestic primary suppliers in China driving Hg-related health impacts (SI Figure S9).

In China, the resource-based distribution feature is obvious for hotspots in the Central (e.g., Henan), North (e.g., Hebei, and Shanxi), and Northwest (e.g., Shaanxi, Gansu, and Inner Mongolia). These regions have abundant fossil fuel and mineral resources (e.g., coal in Shanxi and Inner Mongolia, nonferrous metals in Henan and Hebei, and oil in Xinjiang). They provide raw materials to downstream producers and enable downstream Hg-related health impacts. There are also hotspots in the Yangtze River and Yellow River catchments driven by the availability of water resources. Moreover, hotspots in Jiangsu Province have a distinct distribution feature along the Yangtze River and Taihu Lake. For the rest of the world, hotspots also have obvious characteristics of resource-based distributions. For example, hotspots in the Middle East are associated with the distribution of oil fields along the Persian Gulf. Southeast Asia is abundant in minerals, including coal mines in Vietnam and large gold mines in Indonesia.[50] Thus, primary inputs in the *coal mining* and *metal and nonmetal mining* sectors are major hotspot sources in Southeast Asia. The distribution of foreign primary suppliers is also influenced by water resources (e.g., the Nile in Egypt, the Amazon in northern Latin America, and the Rhine in Germany).

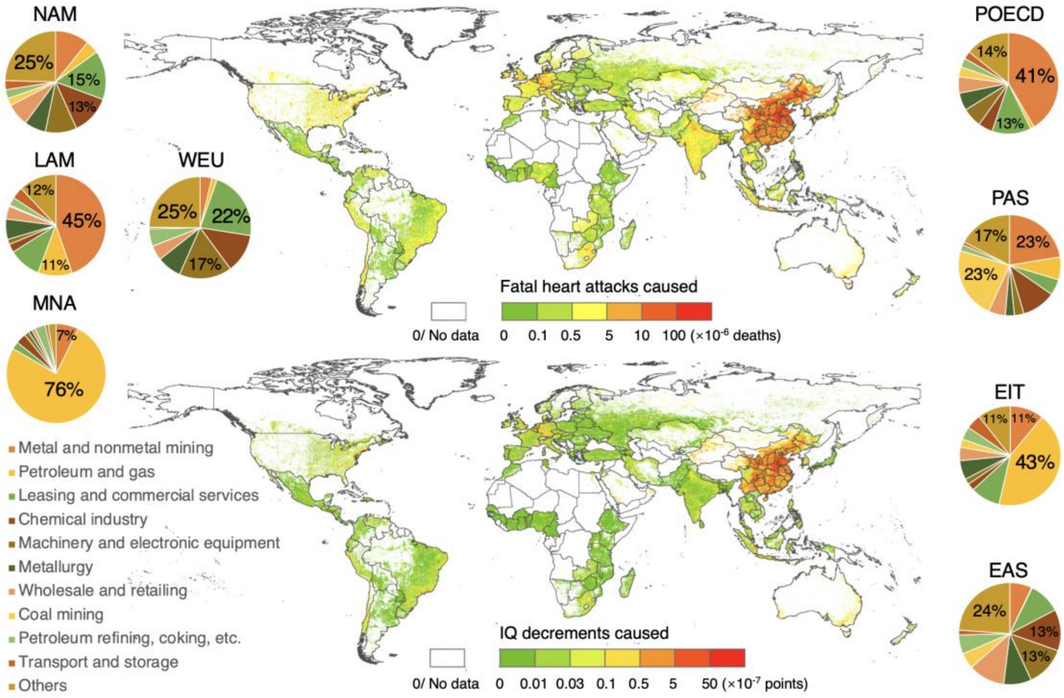


Figure 3. Spatially explicit global primary suppliers enabling China's Hg-related health impacts in 2010. Abbreviations: NAM – North America; LAM – Latin America and the Caribbean; WEU – Western Europe; MNA – the Middle East and North Africa; PAS – Southeast Asia and the Pacific; POECD – Pacific-OECD-1990 nations (including Japan, Australia, and New Zealand); EIT – Economies in Transition (including Eastern Europe and the former Soviet Union); EAS – East Asia (China excluded).

In addition, many hotspots of primary suppliers are distributed based on urban agglomerations, dominated by the service industries. The *leasing and business services* sector in Beijing-Tianjin Region, Chengdu-Chongqing District, North America and Western Europe provides leasing and business services to downstream production activities and enables large Hg-related health impacts in China through global supply chains. Moreover, hotspots in the east coast of Australia and the northeast and west coasts of Latin America form the transportation-oriented distribution. Hotspots in coastal areas provide transportation services to downstream producers and enable large Hg-related health impacts in China through global supply chains. This indicates the significant role of transportation in the distribution of primary suppliers.

4. IMPLICATIONS

This study constructs a SEGTHI model, which integrates global economic supply chains with China's biogeochemical Hg cycle. We map China's Hg-related health impacts, associated global final consumers, and global primary suppliers at a high spatial resolution. We observed significant spatial heterogeneity in hotspots of China's Hg-related health impacts and global supply chain drivers. Results show that approximately 1% of the land area holds 40% of the population but nearly 70% of the fatal heart attack deaths in China. This indicates that the distribution of hotspots may be influenced by many factors, such as economy, transportation, resources, and dietary intake habits, not just the population density. This finer-scale study can help more accurately locate the hotspots of Hg-related health impacts and economic activities. It can facilitate more targeted policy decisions for the implementation of the *Minamata Convention*.

Comparisons with previous studies. We compared our results with previous studies. Compared with the gridded Hg emissions in China in 2010[51], we find that Hg emissions in the southeast coastal areas are relatively low, but their Hg-related health impacts are relatively high. This is related to the high consumption of marine fish in coastal areas and also reflects the Hg outflow from inland areas to coastal areas through atmospheric transport. Conversely, Hg emissions in Henan province are high, but the Hg-related health impacts are not so serious. This may explain the role of atmospheric Hg transport and may be related to the low-rice and high-wheat dietary habit in Henan province. The consumption of rice is one of the most important pathways to MeHg exposure.[25]

Moreover, compared with our previous study, spatially explicit results help identify the specific sources and distribution of global hotspots. They can guide more accurate and effective measures to reduce Hg-related health impacts. Compared with the sub-national results in our previous study, this study observed many areas where Hg-related health impacts are overestimated or underestimated (SI Figure S12). For example, the total Hg-related health impacts in Beijing, Tianjin, and Shanghai are relatively low. However, they have many spatially explicit hotspots of Hg-related health impacts. In addition, the total Hg-related health impacts in Hebei and Shandong are not much high. However, special attention should be paid to Shijiazhuang, Tangshan, Jinan, and other industrial cities, because of their large Hg emissions and high Hg-related health impacts. On the other hand, although the total Hg-related health impacts in Jiangsu, Zhejiang, Guangdong, and Sichuan are relatively high, most of the hotspots in these regions are concentrated in limited areas including the Yangtze River Delta, Pearl River Delta, and Chengdu-Chongqing District. The spatially explicit findings of this study can support the successful implementation of the *Minamata Convention* from two aspects: providing spatially explicit hotspots for policy decisions in various stages of global supply chains and for international cooperation.

Spatially explicit policy implications. Three perspectives are widely recognized to identify hotspots of global supply chains, comprising production-side, demand-side, and supply-side perspectives. Production-side control measures are effective for Hg emissions and related health impact hotspots, including improving energy use efficiency, promoting low-Hg energy sources, and establishing Hg removal facilities.[52] Spatially explicit measures should focus on hotspots including power plants in the Yangtze River Delta and Pearl River Delta, the *nonmetal products* sectors of urban agglomerations in the middle reaches of the Yangtze River (especially in Wuhan, Changsha, and Nanchang), and the *metallurgy* sector in certain large mining areas.

Demand-side control measures, mainly aiming at the optimization of consumption behaviours through economic instruments, are effective in hotspot areas where the final demand induces significant upstream health impacts through global supply chains.[53] According to the results of this study, consumption behaviour optimization should focus on the *construction* sector in the urban agglomerations of Beijing-Tianjin Region, Middle-Lower Yangtze River, and Pearl River Delta in China. For foreign hotspots, relevant measures should be aimed at the eastern U.S. (mainly New York, Boston, Washington D.C., and Chicago), Cologne and Munich in Germany, and London and Manchester in the United Kingdom. Moreover, the demand and productivity of construction activities in Saudi Arabia should be concerned.

Supply-side measures, focusing on the optimization of primary input behaviours such as the adjustment of tax rates and financial incentives on selling low-Hg products, are effective in critical geographic and sectoral sources whose primary inputs enable large downstream health impacts.[35] Decision makers could limit loan supply and subsidies to the *metal and nonmetal mining* and *metallurgy* sectors in the coastal areas of Australia and Latin America (mainly in Brisbane, Melbourne, Rio de Janeiro, and Santiago). For the Persian Gulf coast in the Middle East and the large oil fields in Eastern Europe, authorities can choose to invest in dominant petroleum and gas enterprises with less income-based Hg-related health impacts. In addition, primary inputs of the *leasing and commercial services* sector in Western Europe (especially southwest Germany) enable large amounts of Hg-related health impacts in China. These regions could encourage their leasing and commercial enterprises to preferentially serve enterprises with lower income-based Hg-related health impacts.

Different from previous studies, the findings of this study can identify spatially explicit geographical and sectoral hotspots for the implementation of these three types of measures. Considering the spatial heterogeneity of hotspots, control strategies should be conducted in regions where hotspots are relatively concentrated (e.g., developed urban agglomerations). Notably, almost all of the Hg-related health impacts in Sichuan are concentrated in its eastern part and connected with Chongqing. Thus, measures in this region can only focus on Chengdu, Chongqing, and their surrounding areas. This can significantly improve the effectiveness of measures controlling Hg-related health impacts across the whole province. Moreover, some hotspots distribute along the transportation arteries and large rivers, which are not limited to administrative boundaries. Thus, the measures should consider cross-boundary cooperation and may potentially be coordinated with city, transportation, and resource management.

International cooperation is an important component of the *Minamata Convention*[5]. The results of this study provide scientific foundations for this component by identifying spatially explicit international trade pairs from the demand and supply perspectives (SI S2). From the demand perspective, measures should focus on the international pair of east-central U.S. and coastal areas in China (mainly the Yangtze River Delta and Pearl River Delta). From the supply perspective, international cooperation should focus on the interconnections between resource-exporting regions and corresponding Chinese areas, such as coastal areas in Australia – Chengdu-Chongqing District and the Middle East – Yangtze River Delta. Potential measures include transferring technologies and related capital from these global consumers and primary suppliers to hotspots of Hg-related health impacts in China. For instance, dominant enterprises of the *metal and nonmetal mining* sector in the coastal areas of southeastern Australia could transfer technologies and related capital to the Chengdu-Chongqing District in China to reduce Hg-related health impacts there. In addition, intranational cooperation is critical for reducing the overall Hg-related health impacts in China. Herein, we find that Northwest (mainly in the Yellow River Basin) – Southwest (mainly in Chengdu-Chongqing District) is an important trade pair leading to the most Hg-related health impacts in China. Intranational cooperation between these two regions should be promoted by national governments.

Limitations and uncertainties. The methods of this study have certain limitations. On one hand, due to the limitation of computing resources and the lack of high-resolution meteorological data, the resolution of this SEGTHI model is limited by the horizontal resolutions in the chemical transport model. To analyze China's Hg-related health impacts and the economic drivers at a higher spatial resolution, we spatialize these factors based on certain regional heterogeneity features (e.g., population, socioeconomic status, food consumption, and income). Therefore, our finer-scale model is a parametric model developed with multiple parameters. It can reflect the influence of multiple factors, not just population. Specifically, we use the gridded population data at the 1km × 1km scale and city-level dietary intake data to spatialize the production-based Hg-related health impacts in China, reflecting the influence of population density and dietary intake. In terms of China's Hg-related health impacts driven by global final demand and primary inputs, we use gridded data of global nighttime lights and GDP at the 1km × 1km scale as the proxy variables to spatialize global final demand and primary inputs, respectively. This can reflect the influence of socioeconomic factors and reveal the global economic drivers at a finer scale than the national/subnational level. This study can reveal the spatially explicit features of global final consumers and primary suppliers (e.g., city-level, basin-based, and cross-boundary features of global economic drivers). Our SEGTHI model is currently refined and improved at the output terminal of Hg-related health impacts, while the front-end emission data and mid-end transport model are limited by the lack of gridded data, computing resources, and the background of meteorological data. It is difficult to unify the resolution of the whole model. Improving this limitation depends on the refinement of Hg emission data and meteorological data. On the other hand, at present, there are debates about whether Hg-related heart attacks are fatal. Some scholars believe that MeHg intake may lead to deaths from fatal heart attacks, while other scholars hold objections. Giang and Selin[19] calculated both the non-fatal heart attacks and fatal heart attacks in the U.S., while Chen et al.[17] evaluated the deaths from fatal heart attacks in China. According to the data availability, this study uses the deaths from fatal heart attacks to characterize Hg-related health impacts.

This study is subject to certain uncertainties. Uncertainties mainly originate from the estimations of China's atmospheric Hg emissions, global MRIO data, chemical transport model simulations, the intake inventory of MeHg, and the evaluation of human health impacts. We conducted a Monte Carlo simulation with 10,000 samples of these factors. The P10 and P90 values of the statistical distributions are set as the lower and upper limits of the uncertainty range. For example, ranges for the national Hg-related health impacts of per-foetus IQ decrement points caused by atmospheric Hg emissions from Central China are (0.39×10^{-2}, 4.31×10^{-2}). For deaths from fatal heart attacks, the uncertainties are estimated at (433, 2693). The uncertainties in the points of per-foetus IQ decrements and deaths from fatal heart attacks driven by the final demand of the U.S. are (0.06×10^{-2}, 0.61×10^{-2}) and (70, 374). From the supply perspective, the uncertainties enabled by the primary inputs of Australia are

(0.03×10^{-2}, 0.30×10^{-2}) and (35, 182). See SI S3 for more details of the uncertainties, including the specific sources and related improvement measures.

AUTHOR CONTRIBUTIONS

Conceptualization, S.L.; Methodology, S.L., Y.L., L.C., and J.Q.; Investigation, Y.L., L.C., J.Q., and H.Z.; Writing and revisions, all authors; Supervision, S.L.

COMPETING INTERESTS

The authors declare no competing interests.

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SUPPORTING INFORMATION

Additional information on (1) the complete methods and data sources (S1); (2) international and intranational trade inducing Hg-related health impacts in China (S2); (3) the limitations and uncertainties of this study (S3); (4) supplementary data and results (S4, Figures S4-S12); (6) the list of aggregated Chinese and world regions, as well as regions in the GATP 9 Database (Tables S1 and S2). This information is available free of charge via the Internet at http://pubs.acs.org.

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