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RESEARCH AND ANALYSIS

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# Critical transmission sectors in embodied atmospheric mercury emission network in China

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## Abstract

Atmospheric mercury is a crucial pollutant that must be well-controlled to avoid damaging public health. It is thus necessary to understand from multiple perspectives the roles played by different industrial sectors, as well as their geographical distribution. Existing studies have overlooked the transmission sectors in the economic supply chains of the embodied atmospheric mercury emission network. In this paper, we offer a betweenness-based account (BBA) for Chinese regions and industrial sectors in transmitting embodied atmospheric mercury emissions and in doing so have identified the transmitting hubs. Our results show that the Henan province acts as the transmission hub of the embodied atmospheric mercury emission network in China. The metallurgy, chemical, and construction industries generally play important roles in the transmission of embodied atmospheric mercury emissions across China. Henan's metallurgy sector, the third highest of all, is more closely linked with inter-provincial sectors than the top two transmission sectors (the metallurgy industry of Jiangsu and the chemical industry of Shandong). This study can help policy makers improve mercury control measures by focusing on transmission processes for effective and comprehensive atmospheric mercury emission control.

**KEYWORDS**
betweenness-based accounting, embodied mercury emissions, hypothetical extraction, industrial ecology, input–output analysis, nodal network

# 1 | INTRODUCTION

Mercury is a critical pollutant emitted to the atmosphere from various human activities (Streets et al., 2011). It causes severe damage both to the ecosystem and to human health, producing neurocognitive and cardiovascular effects in humans (Axelrad Daniel et al., 2007; Bose-O'Reilly et al., 2010; L. Chen et al., 2019; Stern & Smith, 2003; Zeitz et al., 2002). Modern cases of massive mercury poisoning have left hundreds of victims fatally affected for generations (Harada, 1995; Skerfving & Copplestone, 1976; Yorifuji et al., 2018) via epigenetic transgenerational inheritance (Nilsson et al., 2018). The latest research suggests that human activities emit about 2000 Mg/year of mercury into the atmosphere globally. By contrast, only 76–300 Mg/year of mercury is emitted by natural sources globally (Streets et al., 2019). To alleviate the environmental cost incurred by mercury emissions, governments are working on mitigation policies that best fit their present circumstances. The signing of Minamata Convention on Mercury is a demonstration of a global joint effort to control mercury emissions.

China is a significant mercury emitter globally (UNEP, 2013). Wu et al. (2016) show that annual mercury emission in China has risen to 530 t by 2014. To help better understand the sectorial composition of Chinese mercury emissions, many researchers have tried to account for mercury emissions embodied in economic activities in China. Streets et al. (2003) have built the first comprehensive atmospheric emission inventory for China and other Asian countries. Some case studies of mercury emission from regional production, consumption, and capital formation activities have also been published (Li et al., 2009; Liang et al., 2013; S. Wang et al., 2005).

In recent research, the Environmentally Extended Input–Output (EEIO) Model is the common method used for emission analysis at the macro level (P. Zhang et al., 2018; Zhou et al., 2018). Concretely, EEIO studies use both consumption-based account (CBA) (Davis & Caldeira, 2010; Liang et al., 2015) and production-based account (PBA) (Liang et al., 2015; Peters, 2008) methods, in order to provide insights for policy design from both demand-side and production-side perspectives. Using the EEIO method, B. Chen et al. (2017) have identified coal mining and electrical machinery manufacturing as the hot spots for upstream and downstream mercury emissions respectively. Latest research by H. Zhang et al. (2018) has gone one step further to construct a virtual embodied mercury flow in a time series, and analyzed the contribution of different sectors towards mercury emissions. Using a recently developed Chinese provincial multi-regional input–output (MRIO) table, L. Chen et al. have analyzed the atmospheric mercury deposition embodied in inter-provincial trade in China and have simulated the consequent health impact (L. Chen et al., 2019; L. Chen et al., 2018).

Although the research mentioned above has contributed greatly to the understanding of both Chinese and global mercury emissions, producing useful production-side and demand-side policy recommendations, PBA and CBA can only account for emissions at the beginning and the end of supply chain path. The emissions happening at various transmission stages have yet to be analyzed in the literature. Liang et al. (2016) have proposed a betweenness-based account (BBA) to identify hotspots of embodied carbon emissions in transmission sectors. Representing a development from nodal analysis techniques, BBA can provide a scientific indicator for the importance of sectors in linking upstream and downstream embodied mercury emission. This concept is used to describe the influence of a node in information transmission (Newman, 2005) and has many real-life applications by revealing what is obscured in conventionalinterregional planning studies. For example, betweenness analysis is applied in a case study on hypothetical disruption of Beijing subway lines (Yin et al., 2016). It is also used as a tool to assess the vulnerability of power systems (Deka et al., 2017; Rout et al., 2016). Environmental researchers have applied the BBA method to account for environmental impacts in complex and self-circulating supply chain networks. B. Chen et al. (2019) have accounted for the BBA of embodied rare earths consumption in China. Huang et al. (2019) have accounted for the BBA of embodied carbon emissions in China. Globally the embodied mercury emission network has also been studied using BBA (X. Wang et al., 2017). However, there is not yet any study that investigates Chinese provincial embodied mercury emissions using a comparative analysis of PBA, CBA, and BBA. Furthermore, by taking one further step in conducting the hypothetical extraction method (HEM) (Schultz, 1977) analysis of BBA results, we simulated a "what-if" scenario to see what the changes in BBA will be if the highest BBA sectors are removed. Thus, the inter-linked regional and sectorial impact of mercury emission mitigation policies targeting those transmission hot spots can also be proposed. In parallel with PBA and CBA, BBA of embodied mercury emissions may help policy makers understand which sectors play more important roles in consuming from upstream and producing for downstream, so that differentiated-yet-targeted policies and monitoring strategies can be formulated. Our study only accounts for the historical accumulated atmospheric mercury emissions in China, without considering the atmospheric chemical processes taking place in reactive mercuries. This paper can offer Chinese policy makers a much-needed extra dimension for consideration in facilitating the successful implementation of the Minamata Convention in China.

# 2 | METHODS

## 2.1 | Structural path betweenness

Betweenness is a concept developed in network analysis that measures the total quantity of flow passing through a certain node (Freeman, 1978; Freeman et al., 1991; Freeman et al., 1979). Basically, a network consists of nodes linked by edges with different magnitudes/strength. By accounting for the weighted strength of all edges connecting the nodes, the importance of the nodes in the network transmission can be understood. Considering the Internet as a network, search engine giants such as Google bear high-weighted edge strength since they are pointed by and direct to many other sites. Some of the other sites also have high-weighted edge strength, hence cascading the total betweenness of search engine giants. Hence search engine giants behave as the transmission hub according to the accounting of betweenness. Many more betweenness studies investigate problems on social, trade, and scientific collaboration networks.

In the work of Liang et al. (2016), a method of hybridization is introduced to bring betweenness into EEIO analysis. Essentially, the sectors in EEIO tables can be treated as very similar to nodes in networks. The only difference is that the flow of production and consumption between sectors is directed, unlike in many networks where they are undirected. The hybridization takes that into consideration by integrating path analysis, a method widely used for specific supply chain environmental impact analysis (Q. Zhang et al., 2017), with betweenness calculation to develop a new method named as structural path betweenness. The structural path betweenness method can quantitatively compare sectors in terms of their importance in embodied emission transmission. Since the focus of this research is to provide an aggregated account for the responsibilities of sectors in transmitting the embodied mercury emissions, we have chosen the structural path betweenness method over the structural path analysis that is better suited for analysis on a specific sector for case analysis.

Concretely, the classic EEIO can be expressed in Taylor Expansion form as follows (Skelton et al., 2011; Suh & Heijungs, 2007).

$$\begin{aligned} e &= f(I-A)^{-1}y \\ &= f\left(I + A + A^2 + A^3 + \cdots\right) y \\ &= fy + fAy + fA^2y + \cdots \ldots . \end{aligned} \tag{1}$$

In Equation (1), $e$ is a scalar representing total environmental pressure. It is also denoted as the CBA of environmental pressures if converted into vector from. $f$ is a vector of environmental pressure intensities of all the sectors accounted for, or PBA as denoted in other research (Z.-M. Chen et al., 2018; Lindner et al., 2013; Södersten et al., 2018; H. Zhang et al., 2019). $I$ is an identity matrix. $A$ is the technical coefficient matrix with element $a_{ij}$, which represents the amount of input needed from sector $i$ to produce a unitary output in sector $j$. In the last line of Equation (1), each of the terms can be interpreted as a production layer (Skelton et al., 2011). At a certain production layer, the weight of a production path passing through $r$ sectors can be given as follows.

$$w\ (s, t | k_1, k_2, \ldots, k_r) = f_s\, a_{sk_1} a_{k_1k_2} \ldots a_{k_rt} y_t \ldots . \tag{2}$$

In Equation (2), $s$ is the starting sector and $t$ is the ending sector of the production path. Since betweenness is the sum of all weights of all edges passing through a node, the betweenness of a sector $i$ with $l_1$ sectors extending upstream and $l_2$ sectors extending downstream is denoted as $b_i(l_1, l_2)$ and given as follows (step-wise derivation can be found in the referenced work (Liang et al., 2016)).

$$\begin{aligned} b_i\ (l_1, l_2) &= \sum_{1 \le k_1, \ldots, k_{l_1} \le n} \left( \sum_{1 \le j_1, \ldots, j_{l_2} \le n} \left( f_{k_1} a_{k_1k_2} \ldots a_{k_{l_1}i} a_{ij_1} \ldots a_{j_{l_2-1}j_{l_2}} y_{j_{l_2}} \right) \right). \\ &= fA^{(l_1)} J_i A^{(l_2)} y \ldots \end{aligned} \tag{3}$$

In Equation (3), $n$ stands for the number of sectors in the EEIO model, so that the summation operation sums up all possible paths of the EEIO network. Rewriting the betweenness $b_i(l_1, l_2)$ into matrix form, the last line of Equation (3) is obtained, where $J_i$ is a selection matrix with its $(i, i)$th element as 1 and other elements as 0.

Theoretically, the production layers will be extended by infinitely many times, just as we have demonstrated with the Taylor expansion in Equation (1). Betweenness of sector $i$ is thus changed from Equation (3) to Equation (4) as follows.

$$\begin{aligned} b_i &= \sum_{l_1=1}^{\infty} \sum_{l_2=1}^{\infty} fA^{l_1} J_i A^{l_2} y \\ &= f \left( \sum_{l_1=1}^{\infty} A^{l_1} \right) J_i \left( \sum_{l_2=1}^{\infty} A^{l_2} \right) y^{\cdot} \\ &= fTJ_iTy \ldots \end{aligned} \tag{4}$$

Here we define $T = (I-A)^{-1} A = A + A^2 + A^3 + \cdots$. Using Equation (4), we can then determine the most important intermediate nodes in an EEIO network, which in our case is embodied mercury emission network in China.

Unlike PBA and CBA, the accounting method of BBA will not sum up to the total emissions given in the inventory (Liang et al., 2016). Hence, the BBA emissions are adjusted to the actual total emissions according to Equation (5) in part of this study for a fair comparison among the three accounted results. It is worth noting that adjusted BBA accounting does not imply physical mercury emissions, but rather a special way to allocate mercury emission responsibilities according to the importance of transmissions among sectors.

$$b_i^{\text{adjusted}} = b_i * \frac{\sum_{j=1}^{n} f_j}{\sum_{j=1}^{n} b_j} \dots . \tag{5}$$

## 2.2 | Hypothetical extraction method

Once we know the most important intermediate embodied mercury emission sectors, we then investigate the impacts of the induced linkage of these sectors in the EEIO network. HEM offers the best method for this purpose (Ali, 2015; Schultz, 1977). HEM has been used in many studies to investigate the linkages of a certain sector in an EEIO network (Guerra & Sancho, 2010; Y. Wang et al., 2017; Zhao et al., 2015). Concretely, HEM removes the sectors to be investigated from $A$ and $y$ on a hypothetical basis and performs the EEIO calculations as usual to obtain a virtual situation as if the investigated sector does not exit. Taking the sector to be investigated as the $k$th sector, $A$ and $y$ can be originally written as follows.

$$A = \begin{bmatrix} A_{11} & \cdots & A_{1(k-1)} & A_{1k} & A_{1(k+1)} & \cdots & A_{1n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ A_{(k-1)1} & \cdots & A_{(k-1)(k-1)} & A_{(k-1)k} & A_{(k-1)(k+1)} & \cdots & A_{(k-1)n} \\ A_{k1} & \cdots & A_{k(k-1)} & A_{kk} & A_{k(k+1)} & \cdots & A_{kn} \\ A_{(k+1)1} & \cdots & A_{(k+1)(k-1)} & A_{(k+1)k} & A_{(k+1)(k+1)} & \cdots & A_{(k+1)n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ A_{n1} & \cdots & A_{n(k-1)} & A_{nk} & A_{n(k+1)} & \cdots & A_{nn} \end{bmatrix},$$

$$y = \begin{bmatrix} y_1 \\ \cdots \\ y_{(k-1)} \\ y_k \\ y_{(k+1)} \\ \cdots \\ y_n \end{bmatrix}.$$

After hypothetical extraction, we set the $k$th row and $k$th column of $A$, and $k$th element of $y$ to be 0. The resulted $A'$ and $y'$ will be as follows.

$$A' = \begin{bmatrix} A_{11} & \cdots & A_{1(k-1)} & 0 & A_{1(k+1)} & \cdots & A_{1n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ A_{(k-1)1} & \cdots & A_{(k-1)(k-1)} & 0 & A_{(k-1)(k+1)} & \cdots & A_{(k-1)n} \\ 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ A_{(k+1)1} & \cdots & A_{(k+1)(k-1)} & 0 & A_{(k+1)(k+1)} & \cdots & A_{(k+1)n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ A_{n1} & \cdots & A_{n(k-1)} & 0 & A_{n(k+1)} & \cdots & A_{nn} \end{bmatrix},$$

$$y' = \begin{bmatrix} y_1 \\ \cdots \\ y_{(k-1)} \\ 0 \\ y_{(k+1)} \\ \cdots \\ y_n \end{bmatrix}.$$

Substituting $A'$ and $y'$ into Equation (4), we can then calculate the resulting sectorial betweenness $b_i'$ under the hypothetical circumstance where the investigated sector does not exist. By calculating the difference of $b_i$ and $b_i'$ given in Equation (5), we can calculate the change in betweenness of all sectors (i.e., changes in the importance of sectors in acting as transmitting nodes) after removal of $k$th sector.

$$D_i = b_i - b_i' \dots . \tag{6}$$

## 2.3 | Data sources

To implement the proposed research with the method described above, a Chinese provincial MRIO table is needed. We chose the China Emission Accounts and Datasets (CEADs) 2012 MRIO table (Mi et al., 2017; Mi et al., 2018) as the source of our data. Changes in inventory are registered as final consumption in the MRIO table, which may be negative if capital investment in the current year is less than depreciation. Exports are not differentiated from final demand and total output items in the MRIO table, while imports rows associated with value-added items are not used in the Leontief inversion in Equation (1). Although it may be possible to map imports and exports to foreign countries for a global nodal analysis, such an extension would entail significant work with a different research objective relating to international trade. Since the focus of this research is to provide policy implications for trans-provincial domestic mercury emissions in China, we have not performed a global BBA nodal analysis.

A mercury emission inventory for China in 2012 is compiled according to L. Chen et al. (2018). L. Chen et al. (2018) used a technology-based approach to compile the latest comprehensive estimate of provincial emission factors for primary anthropogenic Hg sources. Then emissions are estimated by multiplying the emission factors by energy usage or product yields. Emission factors are updated based on the updates of air pollution control devices implementation rate provided in Wu et al. (2016). Emission factors and inventories of 2012 are compiled in Tables S1 and S2 in Supplementary Information together with 2010 emission factors and inventories for readers' reference. The energy usage or product yield is collected from the *China Energy Statistical Yearbook 2013* and other relevant industrial statistical yearbooks. The *China Energy Statistical Yearbook 2013* reports data on energy usage or product yield for the year 2012. In terms of primary emissions, coal-fired industrial boilers were the largest emitter before 1998 and were replaced by zinc smelting from 1999 to 2004 and coal-fired power plants from 2005 to 2008. Cement production has been the largest emitter since 2009 (Wu et al., 2016). In this study, 145.1 Mg of Hg is emitted from the cement industry, which serves as the largest emitter in 2012.

In addition to these primary sources of mercury emission, the secondary mercury emissions from the disposal of waste/by-products (i.e., the use of mercury-added products) are also used in this study. However, due to limited information on temporal changes, the levels of secondary mercury emissions (106 Mg) in 2012 are assumed to be same as the numbers in 2010 derived from L. Chen et al. (2018); these account for roughly 16% of total mercury emission in 2012. On the other hand, large uncertainties have been reported for the secondary mercury emissions (e.g., [−31%, 54%] for waste disposal in cement plants) due to data limitations (L. Chen et al., 2018; Hui et al., 2017). More reliable measurements and annual statistics are needed in future studies. Consequently, a mercury emission inventory of 30 provinces and 30 sectors (multiplied out to be 900) is compiled to match with CEADs MRIO table with the same resolution, which corresponds to the PBA vector $f$ in Equation (1). The emission inventory is attached in Supporting Information S2 for readers' reference.

# 3 | RESULTS

A nodal network of Chinese embodied intermediate mercury emission (Figure 1) illustrates the interactions among provincial sectors. If more mercury emission is embodied between two nodes, the two nodes will be drawn closer to each other and vice versa. In this way, we are able to see the clustering effect among sectors and provinces for embodied mercury emissions. A modularity class algorithm is also implemented to identify and color different clusters in the network (Blondel et al., 2008). Results show that clusters group up based upon provinces, with each of the clusters resembling arm-branches in the nodal network plot. It is because sectors from different provinces have smaller mercury emissions embodied in trades and transections, while sectors from the same provinces have larger embodied mercury emissions. It can thus be deduced that geographical factors play a bigger role in embodied mercury emissions in general than sectorial factors.

Sectors in Henan and Jiangsu provinces tend to cluster more towards the center of the network, showing the two provinces' importance in acting as transitional hubs for embodied mercury emissions. In addition, the sectors that are concentrated in the center of the network are metallurgy, the chemical industry, construction, and electrical equipment of various provinces. This suggests that these sectors embodied more mercury emissions from upstream and downstream interactions. In other words, these sectors overcome the geographical boundaries and are more closely linked among themselves.

An overview of the top 20 provincial sectors that have the highest BBA mercury emission is presented in Table 1 alongside with the corresponding PBA and CBA values and ranks. The complete record for 900 provincial sectors is presented in the Supporting Information S2. Results show that metallurgy of Jiangsu, Henan, and Shandong are the top three ranked BBA mercury emission provincial sectors, with corresponding PBA and CBA ranks as 38, 1, 14 and 96, 211, 572, respectively. Among the top 20 mercury BBA provincial sectors, 11 are metallurgy sectors, suggesting the importance of metallurgy in embodied mercury emission transmission. For similar reasons to the high metallurgy PBA, the nature of metallurgical industrial process contributes to embodied mercury emissions. By contrast although 7 in the top 20 mercury PBA provincial sectors are metallurgy sectors, electricity and hot water production and supply appears 8 times, which is much more than the 2 times it appears in the BBA top 20 list. For the top 20 mercury CBA provincial sectors, construction appeared 15 times, indicating the importance of its consumption in inducing embodied mercury emission.

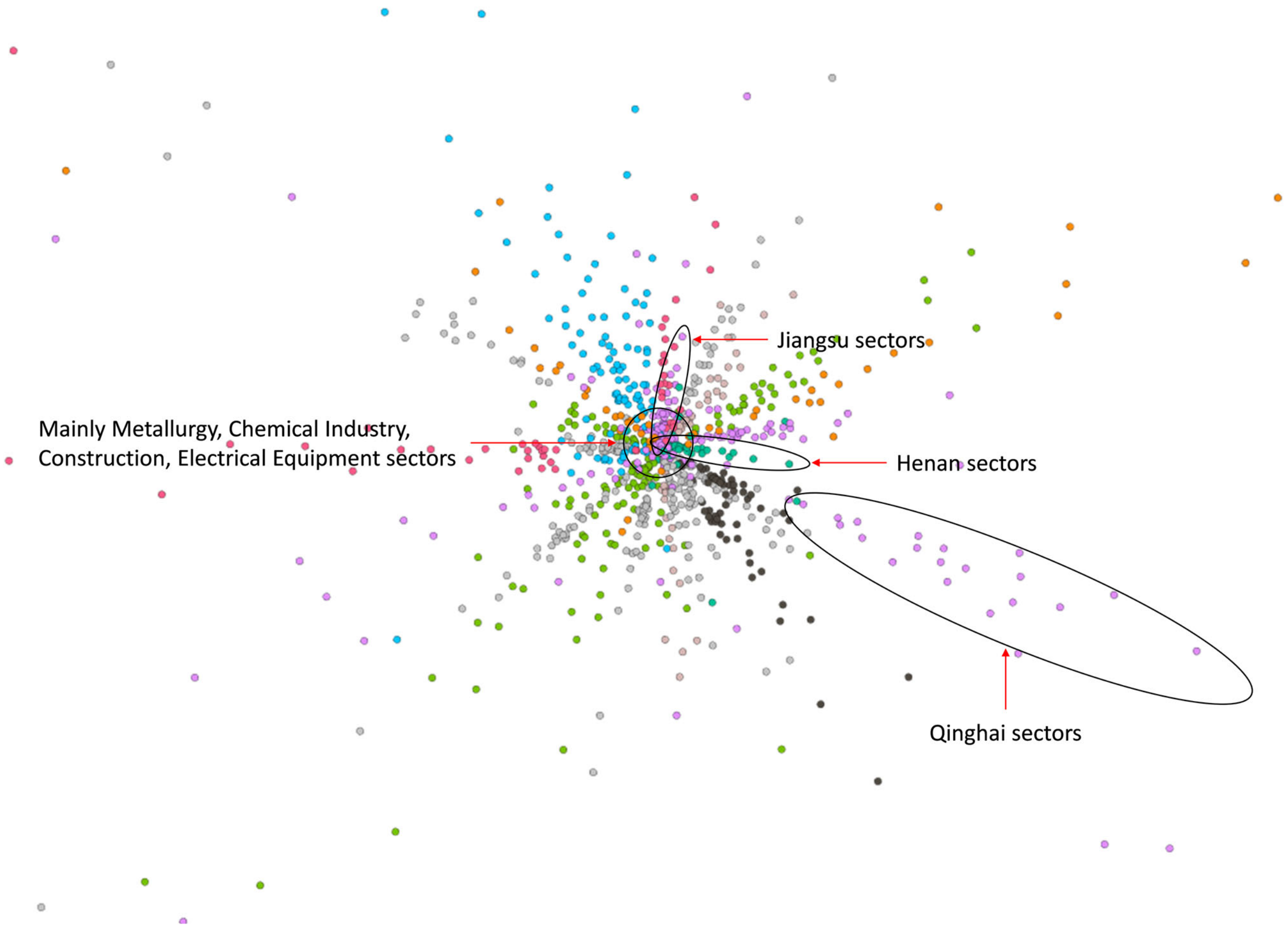


**FIGURE 1** Nodal network of embodied mercury emissions in Chinese provincial sectors. Distance between nodes shows the strength of their links. The further apart means less connected and vice versa. Different colors highlight 15 clusters identified by modularity class algorithm. The clusters show nodes that are more closely located to each other, indicating closer linkages among certain nodes. It is clearly shown that metallurgy, the chemical industry, and construction sectors are more closely connected to each other in the embodied mercury emission network. Provinces such as Jiangsu and Henan are located toward the center of the network, suggesting their importance in mercury emission transmission, unlike Qinghai province that is located toward the outer ring of the network. Due to limitation on resolution, labels are not given in Figure 1. Readers may refer to Supporting Information S1 and S2 for details

To present the results in a comparative and clear manner, we produced Figure 2 as a scatter plot of mercury emission BBA, PBA, and CBA of different provinces by the same sectors. As introduced in the *Methods* section, BBA is adjusted for a fair comparison with PBA and CBA. This clearly shows that metallurgy, nonmetal products, the chemistry industry, electricity and hot water production and supply, and construction are the sectors with higher accounted mercury emissions across provinces. Nonmetal products and metallurgy sectors have both higher BBA (avg. 2.2 Mg and 6.0 Mg, respectively) and PBA (avg. 5.1 Mg and 7.4 Mg, respectively) emissions, but the chemical industry and electronic equipment (avg. 2.0 Mg and 0.5 Mg, respectively) apparently have higher BBA compared to the other two methods of accounting (avg. PBA 0.4 Mg and 0.0 Mg, respectively; avg. CBA 0.5 Mg and 0.5 Mg, respectively; numbers are given in one decimal place). The vast differences in BBA show that the chemical industry and electronic equipment industry are relatively more important in the transmission of embodied mercury emissions. In addition, mercury emissions of electricity and hot water production and supply sectors appear to be high regardless of the method of accounting, suggesting their importance at all stages of the Chinese mercury emission network.

Among the top three BBA mercury emission sectors, metallurgy appeared three times for Jiangsu, Shandong, and Henan. HEM is thus performed on these three sectors to investigate the consequent impact on the BBA mercury emissions of other sectors (Figure 3). Figure 3a,c clearly shows that metallurgy of Jiangsu and Shandong mostly influence the sectors in their own provinces. In fact, 49.7 Mg of changes in BBA is observed in Jiangsu province by removing the Jiangsu metallurgy sector, comprising 72% of the total changes in BBA in China after HEM. Metallurgy of Shandong induces 56.4 Mg of changes in BBA mercury emissions within the Shandong province, comprising 91% of the total changes in BBA in China after HEM. By contrast, Figure 3b suggests a different pattern of linkage for metallurgy of Henan. Although 47.2 Mg of changes in BBA mercury emissions are induced by metallurgy of Henan within its own provincial boundaries, it only comprises 53% of the total changes in BBA in China after HEM. In

**TABLE 1** Top 20 provincial sectors in adjusted betweenness-based account (BBA) and their corresponding production-based account (PBA) and consumption-based account (CBA) values and ranks. Comprehensive results given in the Supporting Information S2

| Provincial sectors | Betweenness-based account, Hg emissions (Mg) | Rankings | Production-based account, Hg emissions (Mg) | Rankings | Consumption-based account, Hg emissions (Mg) | Rankings |
|---|---|---|---|---|---|---|
| Jiangsu metallurgy | 24.89 | 1 | 3.90 | 38 | 1.41 | 96 |
| Henan metallurgy | 18.24 | 2 | 44.18 | 1 | 0.55 | 211 |
| Shandong metallurgy | 17.67 | 3 | 9.93 | 14 | 0.06 | 572 |
| Shandong chemical industry | 16.22 | 4 | 1.23 | 87 | 2.87 | 49 |
| Henan nonmetal products | 13.30 | 5 | 29.71 | 4 | 1.03 | 126 |
| Shandong nonmetal products | 11.39 | 6 | 21.86 | 7 | 5.17 | 30 |
| Hebei metallurgy | 11.22 | 7 | 9.11 | 16 | 0.76 | 158 |
| Zhejiang metallurgy | 10.70 | 8 | 1.07 | 94 | 0.55 | 209 |
| Gansu metallurgy | 9.73 | 9 | 38.57 | 2 | 1.52 | 87 |
| Jiangxi metallurgy | 7.62 | 10 | 3.99 | 36 | 0.15 | 425 |
| Guizhou metallurgy | 7.17 | 11 | 1.70 | 73 | 0.17 | 396 |
| Shaanxi metallurgy | 7.07 | 12 | 15.82 | 8 | 2.16 | 63 |
| Hunan metallurgy | 6.85 | 13 | 22.95 | 6 | 1.02 | 128 |
| Shandong general and specialist machinery | 6.61 | 14 | 0.14 | 252 | 8.22 | 15 |
| Beijing electricity and hot water production and supply | 6.54 | 15 | 1.00 | 100 | 0.28 | 323 |
| Jiangsu nonmetal products | 6.35 | 16 | 10.14 | 13 | 1.22 | 112 |
| Hebei nonmetal products | 6.24 | 17 | 23.74 | 5 | 2.34 | 59 |
| Guangdong electricity and hot water production and supply | 6.22 | 18 | 8.89 | 18 | 1.63 | 78 |
| Yunnan metallurgy | 6.15 | 19 | 29.80 | 3 | 0.15 | 434 |
| Jiangsu chemical industry | 6.14 | 20 | 0.62 | 134 | 1.13 | 122 |

fact, 41.7 Mg of changes in BBA mercury emissions are induced by metallurgy of Henan in all metallurgy sectors across China, accounting for 47% of the total changes in BBA mercury emissions, almost equivalent to that of the total changes in BBA within the boundaries of the Henan province.

To better understand the underlying linkages of the embodied mercury emission network among Chinese provinces, we aggregated 30 sectors in each of the provinces into one and reperformed the same steps to form a network of 30 nodes. We identify the top three provinces with the highest BBA mercury emissions to be Shandong, Henan, and Jiangsu, with BBA mercury emissions of 74.1, 72.0, and 46.7 Mg, respectively. As in the previous investigation, we performed HEM on these three provinces, and plotted Figure 4 to show the impact on BBA mercury emissions in other provinces. Since changes in BBA mercury emissions on provinces themselves are too large compared to other provinces, the self-induced BBA mercury emission changes are removed for better visualization. Figure 4 obviously shows that changes in BBA in other provinces are strongly related to closeness in locations. However, the magnitudes of induced changes vary from case to case. Specifically, Figure 4a shows that Shandong induces significantly less BBA mercury emission changes in its neighboring compared to Jiangsu and Henan, suggesting a higher dependency of Shandong on mercury emissions within itself during transmitting stages. While Henan shown in Figure 4b and Jiangsu shown in Figure 4c induce reciprocal changes in BBA mercury emissions on each other, the impact on other provinces are not symmetrical. For instance, Henan induces 2.8 Mg changes in BBA mercury emission in Anhui, but Jiangsu induces 5.1 Mg changes in BBA mercury emission in Anhui. This phenomenon suggests that the supply chain between Anhui and Henan embodies more mercury emissions than that between Anhui and Jiangsu.

## 4 | DISCUSSION

This study gives gives a general picture of the important roles that each Chinese provincial sector has played in a virtual embodied mercury emission network for year 2012 using the EEIO model and its nodal analysis variations. Unlike conventional PBA and CBA analysis that focuses on the

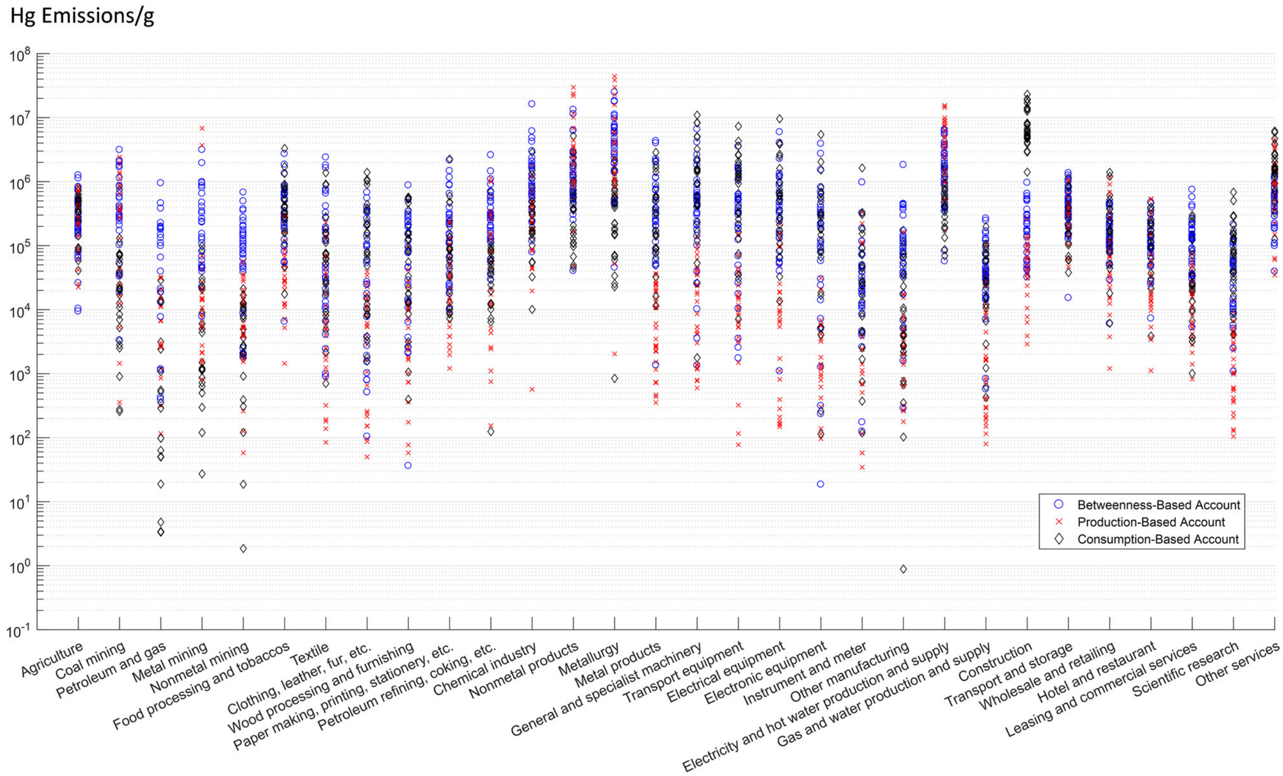


**FIGURE 2** Log distributed scatter plot of Chinese mercury emissions by sectors, provinces, and ways of accounting (BBA vs. PBA vs. CBA). BBA values are adjusted according to total actual emissions to compensate for overcounting issue associated with the method. Detailed numbers are given in Supporting Information S2

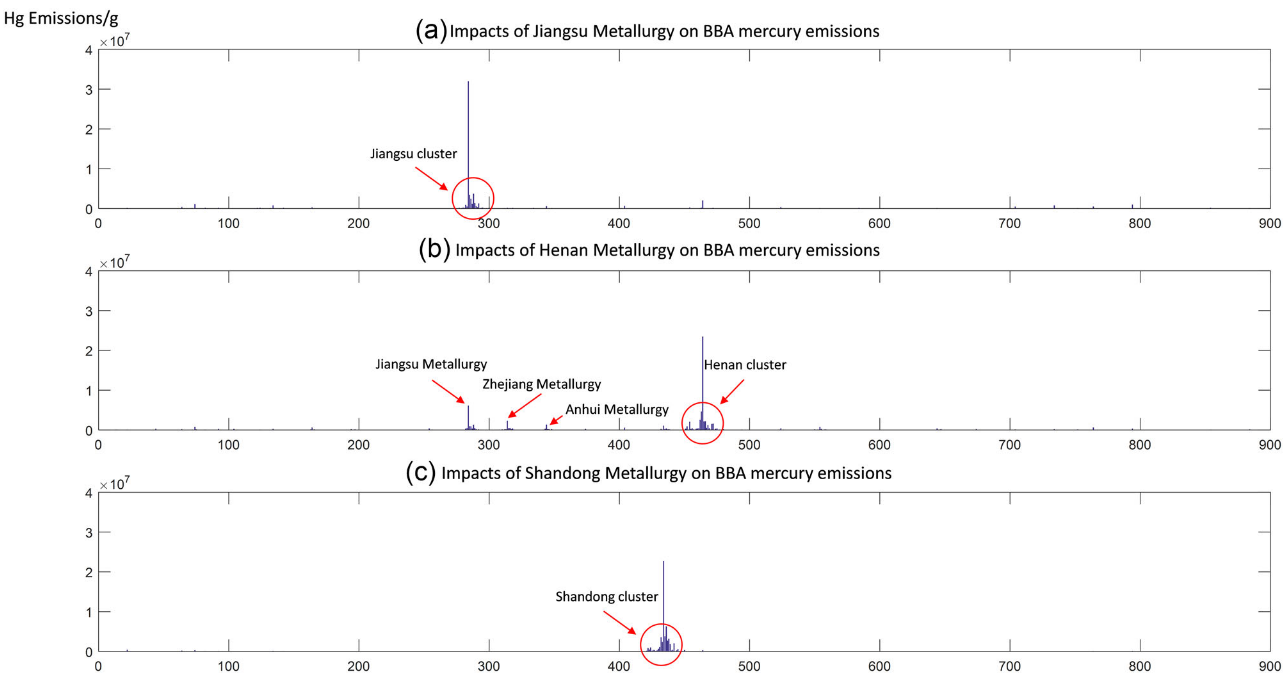


**FIGURE 3** Bar plots of the impacts on BBA mercury emissions of the top three BBA emitting sectors (metallurgy of Jiangsu, Henan, and Shandong) by performing HEM on them. Numbering on *x*-axes refers to the numbering of provincial sectors given in Supporting Information S2

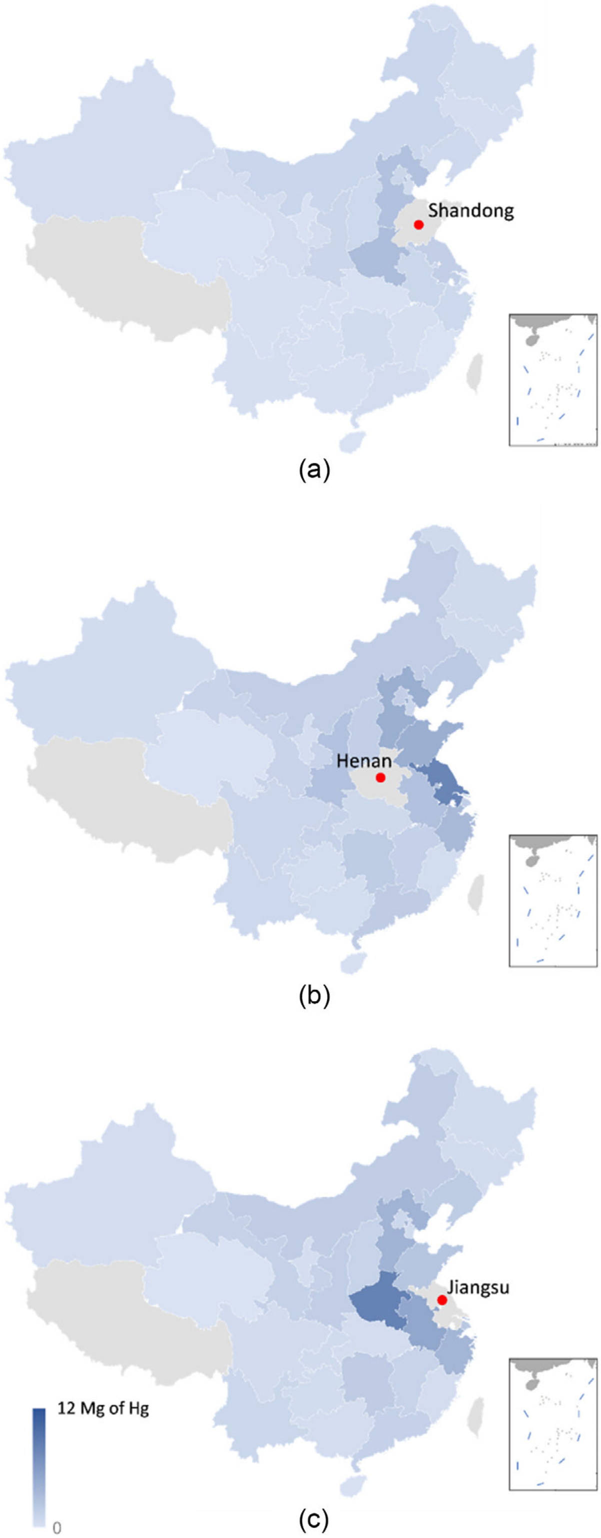


**FIGURE 4** Maps showing the intensities of BBA changes in other provinces after the indicated provinces are performed with HEM. Subfigures (a), (b), and (c) correspond to the effects of HEM being performed on Shandong, Henan, and Jiangsu, respectively. Due to data unavailability, the results shown here do not include Tibet or Taiwan. Detailed numbers are given in Supporting Information S2

**TABLE 2** Features of production-, consumption-, and betweenness-based account

| Method | Description | Advantages | Disadvantages |
|---|---|---|---|
| Production-based account (PBA) | Emissions produced directly by producers. Considers upstream terminus emission responsibility. | - Accurate raw data directly collected from industrial surveys. | - Constrained to geographic boundaries.<br>- Emission leakage overlooked. |
| Consumption-based account (CBA) | Emission induced by consumer activities. Considers downstream terminus emission responsibility. | - Consumer responsibilities fairly allocated | - Information on embodied emission transmission lost. |
| Betweenness-based account (BBA) | Emission embodied in upstream and downstream production and consumptions. Considers middle stream transmission hub emission responsibility. | - Identify sectors' responsibility in both production for downstream and consumption from upstream | - Does not correspond to total emission in emission inventory. Needs reconcilement when making comparison. |

upstream and downstream terminus, BBA focuses on the importance of sectors in transmitting embodied emissions in intermediate stages. Table 2 is formulated to illustrate the features of the three accounting methods. Using BBA as complementary to conventional PBA and CBA accounting for embodied mercury emissions, readers and hopefully policy makers will have a much-needed extra dimension for consideration when formulating mercury emission mitigation policies in China. It needs to be noted that the focus of this research is on the embodied mercury emission responsibilities of Chinese regions and economic sectors. Different forms, such as the gaseous element, gaseous reactive, and particulate mercury, are emitted simultaneously from direct industrial processes. These types of mercury emitted into the atmosphere also undergo complex chemical conversions. Hence, the interregional transmitting abilities and lifetimes of emitted mercury vary. As with other embodied emission research, the atmospheric chemical process is not touched upon in this study.

This study is based on the latest available data of 2012, which may limit its applicability of policy implications today. However, we believe that some observations can serve as references for policy makers today as no studies before have investigated embodied emissions of interregional Chinese sectors. By using BBA as complementary to conventional PBA and CBA accounting for embodied mercury emissions, readers and hopefully policy makers will have an added perspective for consideration when formulating mercury emission mitigation policies in China.

Uncertainty associated with EEIO analysis is also considered in this study. Instead of delving into comprehensive uncertainty investigations using techniques such as Monte-Carlo Simulations, we build our uncertainty analysis based on previous studies on the data used in this paper (L. Chen et al., 2018; Shan et al., 2016). L. Chen et al. (2018) showed the overall uncertainty for primary anthropogenic Hg estimates to be [−19%, 22%] ([460 Mg, 694 Mg]) in 2012. Meanwhile, due to the use of secondary emissions from the disposal of waste/by-products in 2010, the uncertainty for secondary emissions was the same as in L. Chen et al. (2018). Combining errors for primary and secondary anthropogenic Hg estimates, L. Chen et al. (2018) calculated an overall uncertainty of [−25%, 29%] for the production-based emissions. The uncertainty of activities, or input–output data, falls between [2.8%, 3.3%], negligible if compared to emission inventory uncertainty. We thus conducted a sensitivity analysis by changing every one of the 900 sectorial emissions by −25% and 29% to see how the final result might differ. As shown in Figure 5, uncertainties of each sectors are limited within −15% to 15% under most circumstances. Under the most extreme situation, uncertainty is estimated to be −25% and 25%. In reality, uncertainties may arise from much wider sources such as the limited capacity of statistical departments, price fluctuation, etc. The inherited uncertainties of EEIO model are not analyzed in this study. Hence, improving the accuracy of EEIO studies may be an important research direction for future investigation.

## 5 | POLICY IMPLICATIONS

Contrary to production-side and demand-side policies backed by PBA and CBA accountings, transmission-bound policies can be developed in response to BBA accounting for mercury emissions. In addition, although intermediate products manufactured in these hubs may not deal with mercury physically, higher BBA mercury emissions suggest their role played in inducing upper and lower streams of embodied mercury emissions. Demand-side policies should better use public campaigns to raise awareness in sectors with higher CBA mercury emissions (e.g., scientific research, other services). Production-side policies such as direct emission monitoring and technical capacity building should be implemented in upstream industries that record higher PBA mercury emissions (e.g., metallurgy, nonmetal product) to improve emission efficiency. In contrast, sectors with higher BBA mercury emissions (e.g., chemical industry, manufacturing) should embrace transmission-bound mitigation policies. Specifically, embodied emission recording and labeling should be more strongly enforced at the transmission stage, as intermediate sectors know better what energy

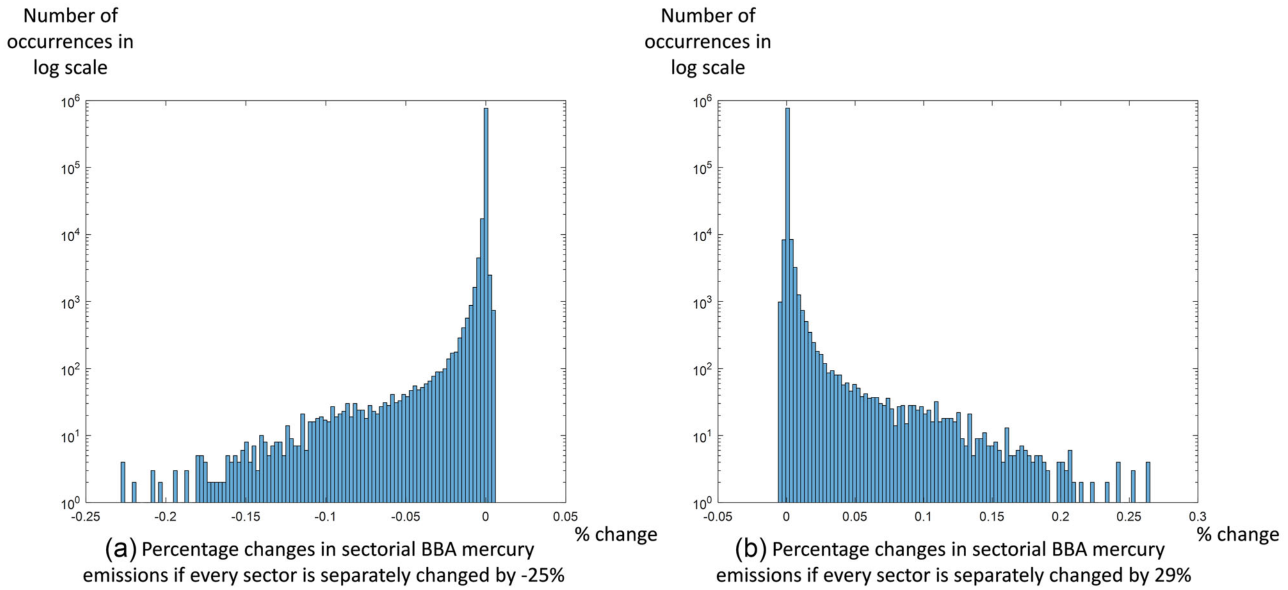


**FIGURE 5** Sensitivity analysis of China's provincial sectors' BBA mercury emissions. The analysis is done by changing every sector separately by −25% and 29% as informed by the mercury emission inventory data source

content they use. As our results suggest that higher BBA mercury emissions are identified in the metallurgy sectors of Shandong, Henan, and Jiangsu, the proposed measures in transmission-bound mitigation policies of emission content labeling will work better in these regions.

Most importantly, by referencing all three accounting results, the Environmental Protection Inspection Team dispatched by the Ministry of Ecology and Environment can devote limited resources in a better differentiated and more effective way. For example, the chemical industry in Shandong is higher in BBA (ranking 4) mercury emission, but much lower in PBA (ranking 87) mercury emission. Thus, the Environmental Protection Inspection Team dispatched to Shandong would know that chemical industry in Shandong is responsible in transmitting more embodied mercury emissions, so that the inspection work focus can be changed to forms of survey and interviews to determine if local plants are fulfilling their obligations in choosing emission efficient suppliers in their upstreams.

In addition, "spill-over" impacts of transmission-bound policy may also be revealed by our study. In other words, if one region introduces transmission-bound policies to mitigate embodied mercury emission, other regions may be loaded with the burden of transmission as a result due to the underlying linkages present. For instance, according to HEM result shown in Figure 3, transmission-bound mitigation in metallurgy of Henan will induce the most transmission-bound mitigation in the metallurgy of Jiangsu, Zhejiang, and Anhui. The same impact would not happen in the other two provincial sectors (i.e., metallurgy of Jiangsu and chemical industry of Shandong) in this study. Furthermore, our study also suggests that transmission-bound embodied mercury mitigation in Jiangsu and Henan will have a stronger impact on the neighboring provinces than that in Shandong. Hence, we suggest the National Development and Reform Committee and its auxiliary research institutions to take note of our development in EEIO methodology and findings in mercury emissions, and use them as a reference in developing specific policy recommendations. The Provincial Development and Reform Committee may also extend our research to analyze specific cases and prepare local sustainable development strategies toward a comprehensive approach to mercury emissions mitigation that encompasses the "spill-over" effects of policy instruments.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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